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16.1 Introduction and Framing

16.1.1 Objective of the Chapter

Anthropogenic climate change poses risks to many human and ecological systems. These risks are increasingly visible in our day-to-day lives, including a growing number of disasters that already bear a fingerprint of climate change. There is increasing concern about how these risks will shape the future of our planet—our ecosystems, our well-being and development opportunities. Policymakers are asking what is known about the risks, and what can be done about them. Many people, especially youth, around the world are calling for urgency, ambition and action. Companies are wondering how to manage new threats to their bottom line, or how to grasp new opportunities. On top of this growing concern about climate change, the coronavirus disease 2019 (COVID-19) pandemic has exposed vulnerabilities to shocks, significantly aggravated climate-related risks, and posed new questions about how to achieve a green, resilient and inclusive recovery (see Cross-Chapter Box COVID in Chapter 7).

The three synthesis chapters of this report (Chapters 16, 17 and 18) aim to address these concerns. They synthesise information from across all thematic and regional chapters of the Working Group II (WGII) IPCC Sixth Assessment Report (AR6) and the recent IPCC Special Reports on Global Warming of 1.5°C, on Climate Change and Land, and on Ocean and Cryosphere in a Changing Climate (SR15 (IPCC, 2018a), SRCCL (IPCC, 2019a) and SROCC (IPCC, 2019b)), but also include an independent assessment of the literature, especially literature that cuts across sectors and regions.

Chapter 16 lays the groundwork by synthesising the state of knowledge on the observed impacts of climate change (Section 16.2) and ongoing adaptation responses (Section 16.3), the limits to adaptation (Section 16.4), and the key risks we should be concerned about, how these risks evolve with global temperature change, and also how they depend on future development and adaptation efforts (Sections 16.5, 16.6). It thus brings together elements that were assessed in different chapters in previous assessments, especially the Third, Fourth and Fifth Assessment Reports (TAR, AR4 and AR5, respectively). Background on specific methodological aspects of this chapter is provided in Supplementary Material (SM).

The strong link between risks, adaptation and development connects this chapter closely to Chapters 17 and 18. Chapter 17 assesses decision -making: what do we know about the ways to manage risks in a warming climate (including in the context of the key risks and limits to adaptation identified in this chapter)? Chapter 18 puts all of this information into the perspective of climate resilient development pathways: how can we achieve sustainable development given the additional challenges posed by climate change?

16.1.2 Risk Framing

In the IPCC AR6, 'risk' is defined as the potential for adverse consequences for human or ecological systems, recognising the diversity of values and objectives associated with such systems. Relevant adverse consequences include those on lives, livelihoods, health and well-being, economic, social and cultural assets and investments, infrastructure, services (including ecosystem services), ecosystems and species (Chapter 1 this volume, SR15 (IPCC, 2018a)). The AR6 definition explicitly notes that 'risks can arise from potential impacts of climate change as well as human responses to climate change.'

The main risks assessed here relate to the potential *impacts* of climate change. In recent years, the growing visibility of current climate impacts has resulted in a stronger focus on understanding and managing such risk across time scales, rather than just for the longer-term future. Examples include the rapid growth in attribution of specific extreme weather events, the use of scientific evidence of climate change impacts in legal cases, and the context of the Paris Agreement's Article 8 on 'averting, minimising and addressing loss and damage' associated with climate change, but also the stronger links between adaptation and disaster risk reduction, including early-warning systems, wider discussions on how to build resilience in the face of a more volatile climate, and attention for limits to adaptation that are already being reached.

Of course, the scale of these risks is also determined by the *responses* to climate change, mainly in how they reduce risk, but also how they may create risks (sometimes inadvertently, and sometimes to others than those who implement the response, in other places, or later in time). Our focus is on adaptation responses, given that mitigation is covered in Working Group III (WGIII) AR6, but we acknowledge certain important interactions, such as biomass production as an alternative to fossil fuels which can compete with food production and thus aggravate adaptation challenges. Given that SRM could also be considered a response with significant implications for climate risks across scales, this chapter also includes Cross-Working Group Box SRM.

This assessment focuses primarily on *adverse* consequences of climate change. However, climate change also has *positive* implications (benefits and opportunities) for certain people and systems, although there are gaps in the literature on these positive effects. Some risks assessed in this chapter are actually about a balance between positive and negative effects of climate change (and of response options, especially adaptation). In those contexts, we assess the combined effect of both, aiming to identify not only the aggregate impacts (the balance between positive and negative effects) but also the distributional aspects (winners and losers). A more comprehensive discussion of the decision-making related to such trade-offs in relation to adaptation is provided in Chapter 17.

This chapter's assessment takes a global perspective, although many risks and responses materialise at the local or national scale. We use case studies to illustrate the ways these risks aggregate across scales, again with particular concern for distributional aspects.

16.1.3 Storyline of the Chapter, and What's New Compared with Previous Assessments

Figure 16.1 illustrates the elements covered by the chapter, which can be summarised as four key questions.

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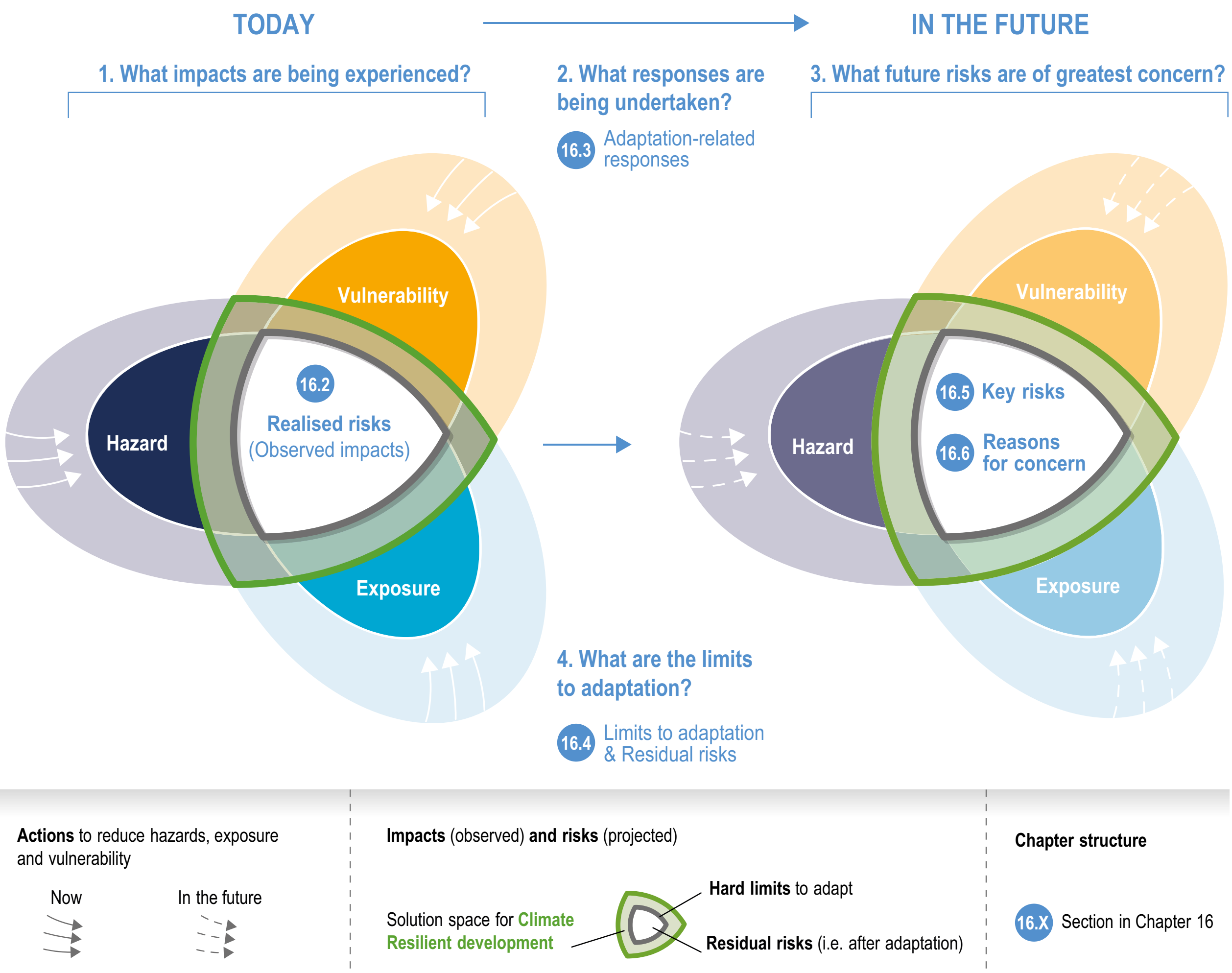

Figure 16.1 | Illustrative storyline of the chapter highlighting the central questions addressed in the various sections, from realised risks (observed impacts) to future risks (key risks and reasons for concern), informed by adaptation-related responses and the limits to adaptation. The arrows illustrate actions to reduce hazard, exposure and vulnerability, which shape risks over time. Accordingly, the green areas at the centre of the propeller diagrams indicate the ability for such solutions to reduce risk, up to certain adaptation limits, leaving the white residual risk (or observed impacts) in the centre. The shading of the right-hand-side propeller diagram compared with the non-shaded one on the left reflects some degree of uncertainty about future risks. The figure builds on the conceptual framework of risk–adaptation relationships used in SROCC (Garschagen et al., 2019).

16.1.3.1 What Impacts Are Being Experienced?

This assessment of climate-related impacts that are already taking place is covered in Section 16.2, which aims to differentiate between observed changes in climate hazards (also called 'climate impact drivers' in IPCC Working Group I) and the exposure and vulnerability of human and ecological systems.

Observed impacts of climate change were synthesised in the TAR, AR4 and AR5. The TAR found that recent regional climate changes had already affected many physical and biological systems, with preliminary indications that some human systems had been affected, primarily through floods and droughts. AR4 found *likely*[2] discernible impacts on many physical and biological systems, and more *limited evidence* for impacts on human environments. AR5 devoted a separate chapter to observed impacts, which found growing evidence of impacts on human and ecological systems on all continents and across oceans (Cramer et al., 2014).

2 In this Report, the following terms have been used to indicate the assessed likelihood of an outcome or a result: virtually certain 99–100% probability, very likely 90–100%, likely 66–100%, about as likely as not 33–66%, unlikely 0–33%, very unlikely 0–10%, and exceptionally unlikely 0–1%. Additional terms (extremely likely 95–100%, more likely than not >50–100%, and extremely unlikely 0–5%) may also be used when appropriate. Assessed likelihood is typeset in italics, e.g., *very likely*). This Report also uses the term '*likely* range' to indicate that the assessed likelihood of an outcome lies within the 17–83% probability range.

Section 16.2 reports on the expanded literature since then, generally reflecting a growing and more certain impact of climate change on humans and ecological systems.

16.1.3.2 What Responses Are Being Undertaken?

Section 16.3 provides, for the first time, a comprehensive synthesis of observed adaptation-related responses to the rising risks.

Such adaptation responses were first covered in the TAR, and further developed in the AR4 and AR5. For instance, AR5 Chapter 15 notes that adaptation to climate change was transitioning from a phase of awareness to the construction of actual strategies and plans in societies (Mimura et al., 2014) but did not include a comprehensive mapping of responses.

Based on such a comprehensive mapping, Section 16.3 finds growing evidence of adaptation-related responses, although these are dominated by minor modifications to usual practices or measures for dealing with extreme weather events, and there is *limited evidence* for the extent to which they reduce climate risk.

16.1.3.3 What are the limits to adaptation?

The literature on limits to adaptation, which is covered in Section 16.4, has strongly evolved since AR5, including links to discussions on loss and damage in the United Nations Framework Convention on Climate Change (UNFCCC). While the Summary for Policymakers (SPM) of AR4 noted that there was no clear picture of the limits to adaptation, or the cost, AR5 Chapter 16 (Klein et al., 2014) reported increasing insights emerging from the interactions between climate change and biophysical and socioeconomic constraints, and highlighted the fact that limits could be both hard and soft. It also noted that residual losses and damages will occur from climate change despite adaptation and mitigation action. However, AR5 Chapter 16 still found that the empirical evidence needed to identify limits to adaptation of specific sectors, regions, ecosystems or species that can be avoided with different greenhouse gas (GHG) mitigation pathways was lacking.

Section 16.4 provides a more comprehensive assessment of limits to adaptation, highlighting again that limits to adaptation are not fixed, but are properties of dynamic socio-ecological systems. They are shaped not only by the magnitude of the climate hazards (e.g., the amount of sea level rise in low-lying coasts and islands) and the exposure and vulnerability to those hazards (e.g., people and assets in those areas), but also by physical, infrastructural and social tolerance thresholds and adaptation choices of actors in societies (e.g., the decision to migrate from locations strongly impacted by climate change). The evolution of such socioeconomic systems over time, including their interaction with the changing physical climate, determines the evolution of limits to adaptation.

16.1.3.4 What Future Risks Are of Greatest Concern?

The fourth and final element of the chapter is the question about the risks we face, and which ones we should be most concerned about. This is addressed in Sections 16.5 and 16.6.

Section 16.5.1 presents a full discussion of 'key risks', synthesised from across all chapters, defined as those risks that are potentially severe and therefore especially relevant to the interpretation of 'dangerous anthropogenic interference with the climate system' in the terminology of UNFCCC Article 2.

In 2015, the Paris Agreement established the goal of 'holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels'. However, assessment of key risks across a range of future warming levels remains a high priority for several reasons: (1) understanding risks at higher levels of warming can help prepare for them, should efforts to limit warming be unsuccessful (UNEP, 2017); (2) understanding risks at higher levels can inform the benefits of limiting warming to lower levels; (3) in addition, there is continued debate about whether warming limits should be at or rather somewhere below 2°C (in particular at 1.5°C); and (4) there is a more explicit recognition that key risks can result not only from increased warming, but also from changes in the exposure and vulnerability of society, and from a lack of ambitious adaptation efforts. Thus, relatively limited warming does not automatically imply that key risks will not occur. In assessing key risks, we have applied four criteria: magnitude of adverse consequences, likelihood of adverse consequences, temporal characteristics of the risk, and ability to respond. Of course, this is an aggregated approach to what is dangerous; it should be noted that in practice, 'dangerous' will occur at a myriad of temperature levels depending on who or what is at risk (and their circumstances), geographic scale and time scale.

A new element is that we particularly look at a set of eight 'representative key risks' that exemplify the underlying set of key risks identified in the earlier chapters: risk to the integrity of low-lying coastal socio-ecological systems, risk to terrestrial and ocean ecosystems, risk to critical physical infrastructure and networks, risk to living standards (including economic impacts, poverty and inequality), risk to human health, risk to food security, risk to water security, and risk to peace and human mobility (Section 16.5.2.3).

Another increased focus relates to the issue of compound risks. This includes risks associated with compound hazards (Working Group I AR6 Chapter 11, Seneviratne et al., 2021), but also implications for future risk when repeated impacts erode vulnerability, as well as through transboundary effects (including effects both from one system to a neighbouring one, as well as from one system to a distant one), also discussed in the cross-chapter box on inter-regional risks and adaptation (Cross-Chapter Box INTEREG in this Chapter).

Section 16.6 maps the representative key risks in Section 16.5 to the SDGs, noting both direct and indirect implications for climate resilient development as assessed in Chapter 18.

Finally, Section 16.6 presents an updated assessment of the so-called Reasons for Concern (RFC): risks related to unique and threatened systems, extreme events, distribution of impacts, aggregate impacts (including the cross-chapter box on the global economic impacts of climate change and the social cost of carbon, Cross-Working Group Box ECONOMIC) and the risk of irreversible and abrupt transitions.

The AR4 and AR5 each also evaluated the most important climate risks, framed firstly in terms of the state of knowledge relevant to Article 2 of the UNFCCC. The TAR first synthesised this knowledge in five RFCs. AR4 identified a set of 'key vulnerabilities' and provided an update of the RFCs. AR5 further refined a new risk framework developed in the IPCC Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation (SREX), and used it to assess 'key risks' and provide another update of the overarching RFCs, drawing as well on Cramer et al.'s (2014) assessment of observed changes.

Our risk assessment also further builds on risk assessments from the Special Reports that are part of the AR6 cycle, that is, SR15, SRCCL and SROCC. While since AR4 the RFC assessment framework has remained largely consistent, refinements in methodology have included the consideration of different risks, the role of adaptation, use of confidence statements, more formalised protocols and standardised metrics (Zommers et al., 2020). In subsequent assessment cycles, the risk level at a given temperature has generally increased, reflecting accumulating scientific evidence (Zommers et al., 2020).

16.1.4 Drivers of Exposure and Vulnerability

Climate-related impacts, risks and responses all take place against a backdrop of trends in exposure and vulnerability driven by demographics, socioeconomic development (including inequalities) and ecosystem degradation. Other global trends that are shaping climate risks include technological innovation, shifts in global power relations, and resource scarcity (Retief et al., 2016). Note that these global trends may *increase* but also *reduce* exposure and/or vulnerability, for instance when growing incomes, savings and social protection systems increase resilience in the face of shocks and stresses. Drivers and future trends in vulnerability and exposure—next to climate-induced changes in natural hazards—therefore need to be considered in comprehensive risk assessments and eventually adaptation solutions, but empirical research suggests that they remain to be underemphasised in current national adaptation planning (Garschagen et al., 2021a).

While these risk drivers are often listed separately, they are often closely interconnected, including between human and ecological systems, and increasingly also through climate risks and responses (e.g., Simpson et al., 2021). Climate impacts increasingly affect these drivers, and may compete with financial resources that could otherwise be applied for development, mitigation, adaptation and resilience building, also affecting inequalities (e.g., Taconet et al., 2020).

16.1.4.1 Demographics

Population growth (or decline) can result in increasing (or decreasing) pressure on natural resources (e.g., soils, water and fish stocks) (IPBES, 2019), and can result in the expansion of densely populated areas (Cardona et al., 2012; Day et al., 2016). The majority of the population in the coming decades will be in urban areas. While urbanisation can have many benefits that reduce vulnerability, such as employment opportunities and increased income, better access to healthcare and education, and improved infrastructure, unsustainable urbanisation patterns can create challenges for resource availability, exacerbate pollution levels (Rode et al., 2015) and increase exposure to some risks. For example, ~10% of the global population live in low-elevation coastal zones (in 2000; areas <10 m of elevation) (McGranahan et al., 2007; Neumann et al., 2015), which is expected to increase by 5% to 13.6% by 2100 depending on the population scenario (Neumann et al., 2015; Jones and O'Neill, 2016). Building assets and infrastructure in naturally risk-prone areas are also projected to increase (Magnan et al., 2019), which may also lead to environmental degradation that can further aggravate risk, such as destruction of wetlands that buffer against floods (Schuerch et al., 2018; Oppenheimer et al., 2019). Demographic trends, coupled with changes in income, can also result in increasing demands for land, food, water and energy, and therefore in major changes in land use and cover change (Arneth, 2019). The observed and projected population decline in some rural areas also has implications for vulnerability and exposure. In addition, demographic changes such as ageing may increase vulnerability to some climate hazards, including heat stress (Byers et al., 2018; Rohat et al., 2019a; Rohat et al., 2019b).

16.1.4.2 Biodiversity and Ecosystems

Rapidly accelerating trends in human impacts on global ecosystems and biodiversity, especially in the past five decades, have resulted in precipitous declines in the numbers of many wild species on land and in the ocean, transformation of the terrestrial land surface for agricultural production, and the pervasive spread of alien and invasive species (IPBES, 2019). As a result, the capacity of ecosystems to support human society is thought to be coming under threat. For instance, the fraction of all primary production being appropriated for human use has doubled over the course of the 20th century (to about 25% in 2005), although it has grown at a slower rate than human population (Krausmann et al., 2013). Future projections significantly depend on bioenergy production, signalling one of the feedbacks between responses to climate change and climate risks.

16.1.4.3 Poverty Trends and Socioeconomic Inequalities within and across Societies

Poverty contributes to exposure and vulnerability by limiting access of individuals, households and communities to economic resources and restraining adaptive capacities (e.g., for food and energy supply, or for financing adaptation responses) (Hallegatte and Rozenberg, 2017). Over the past decades, until the COVID-19 pandemic, global poverty rates have declined rapidly. Between 1981 and 2015, the share of global population living in extreme poverty (under the international poverty line of USD 1.90 d^{-1}) declined from 42% to 10%, leaving 736 million people in extreme poverty, concentrated in South Asia and Sub-Saharan Africa (World Bank, 2018). This general reduction in poverty across the world is accompanied by a decrease in vulnerability to many types of climate change impacts (*medium confidence*). However, the COVID-19 pandemic has significantly increased extreme poverty by about 100 million people in 2020, with disproportionate economic impacts on the poorest, most fragile and smaller countries (World Bank, 2021) and significant implications for vulnerability to climate change (see also Cross-Chapter Box COVID in Chapter 7).

The majority of the population in poverty are smallholder farmers and pastoralists, whose livelihoods critically depend on climate-sensitive natural ecosystems, such as through semi-subsistence agriculture where food consumption is primarily dependent on households' own food production (Mbow et al., 2019). A significant share of this population is affected by armed conflict, which deters economic development and growth and increases local dependence on subsistence agriculture (Serneels and Verpoorten, 2015; Braithwaite et al., 2016; Tollefsen, 2017), and aggravating humanitarian challenges (e.g., ICRC, 2020). Extreme weather events, particularly droughts, can result in poverty traps keeping people poor or making them poorer, resulting in widening inequalities within and across countries.

Climate risks are also strongly related to other inequalities, often but not always intersecting with poverty. AR5 found with *very high confidence* that differences in vulnerability and exposure arise from multi-dimensional inequalities, often produced by uneven development processes. These inequalities relate to geographic location, as well as economic, political and socio-cultural aspects, such as wealth, education, race/ethnicity, religion, gender, age, class/caste, disability and health status (Oppenheimer et al., 2014). Since AR5, a number of studies have confirmed and refined this assessment, especially also regarding socioeconomic inequality and poverty (Hallegatte et al., 2016; Hallegatte and Rozenberg, 2017; Pelling and Garschagen, 2019; Hallegatte et al., 2020). Poor people more often live in exposed areas such as wastelands or riverbanks (Garschagen and Romero-Lankao, 2015; Winsemius et al., 2018). Also, poor people lose more of their total wealth to climatic hazards, receive less post-shock support from their often-times equally poor social networks, and are often not covered by social protection schemes (Leichenko and Silva, 2014; Hallegatte et al., 2016). Countries with high inequality tend to have above-average levels of exposure and vulnerability to climate hazards (BEH UNU-EHS, 2016). Many socioeconomic models used in climate research have been found to have a limited ability to capture and represent the poor at a larger scale (Rao et al., 2019; Rufat et al., 2019). However, an analysis of 92 countries found that relative income losses and other climate change impacts were disproportionately high among the poorest (Hallegatte and Rozenberg, 2017, see Section 16.2.6). There have also been advances in detecting and attributing the impacts of climate change and vulnerability at household scale and specifically on women's agency and adaptive capacity (Rao et al., 2019). The distribution of impacts and responses (adaptation and mitigation) affects inequality, not just between countries but also within countries (e.g., Tol, 2020) and between different people within societies. Distribution has so far largely been thought of in a geographical sense, but identifying those most at risk requires an additional focus on the social distribution of impacts, responses, and resilience, as influenced for instance by differential social protection coverage (Tenzing, 2020).

Many climate responses interact with all of these global risk drivers. Some raise additional equity concerns about marginalising those most vulnerable and exacerbating social conflicts (Oppenheimer et al., 2019), leading to wider questions about the governance of climate risks (and impacts) across scales. Hence, our assessment of impacts, responses and risks is complemented by the assessment of governance and the enabling environment for risk management in Chapter 17, and of climate resilient development in Chapter 18.

16.2 Synthesis of observed impacts of changes in climate related systems

This section synthesises the observed impacts of changes in climate-related systems (Section 16.2.1) on different natural, human and managed systems (outlined in Chapters 2–8) and regions (outlined in Chapters 9–15). To stay as specific as possible given the required level of aggregation, we decided in favour of a summary along specific prominent indicators such as 'crop yields' or 'areas burned by wildfires' instead of an assessment across broad categories such as 'food production' which could include a broad range of measures ranging from climate-induced changes in growing seasons to impacts on livestock and fisheries, etc., or 'wildfires' which could also cover impacts on the frequency, intensity, timing, or emissions and health impacts of wildfires. This decision for specificity certainly implies a decision against comprehensiveness. In addition, the level of specificity has to be adjusted given the literature basis which is quite broad regarding crop yields but still limited and less harmonised regarding indicators when it comes to, for example, conflicts. A broader discussion can be found in the sectoral or regional chapters that all cover 'observed impacts' individually. Section 16.2.1 provides key definitions, followed by recent advances in available methods and data for climate impact attribution (Section 16.2.2), and the assessment of observed impacts of changes in climate related systems (Section 16.2.3). It is important to note that the assessment is primarily based on peer-reviewed literature, that is, it is limited to the regions and phenomena for which such studies are available. So 'no assessment' in a certain region does not imply that the considered type of impact did not occur in this region.

16.2.1 Definitions

The section adopts the general definition of **detection** as 'demonstration that a considered system has changed without providing reasons for the change' and **attribution** as 'identifying the causes of the observed long-term change in an impact indicator or of the change in the temporal or spatial extent, the intensity or frequency of a specific event' (see Glossary (Annex II)).

Based on these general definitions and following the approach applied in WGII AR5 Chapter 18 (Cramer et al., 2014), we define an **observed impact** as the difference between the observed state of a **natural, human or managed system** and a counterfactual baseline that characterises the system's state in the absence of changes in the **climate-related systems**, defined here as climate system including the ocean and the cryosphere as physical or chemical systems.

The difference between the observed and the counterfactual baseline state is considered the change in the natural, human or managed system that is attributed to the changes in the climate-related systems (**impact attribution**). The counterfactual baseline may be stationary or may change over time, for example due to direct human influences such as changes in land use patterns and agricultural or water management affecting exposure and vulnerability to climate-related hazards (see Section 16.2.3 for methods on how to construct the counterfactual baseline).

In line with the AR5 definition, 'changes in climate-related systems' here refer to any long-term trend, irrespective of the underlying causes; thus, an observed impact is not necessarily an observed impact of anthropogenic climate forcing. For example, in this section, sea level rise is defined as relative sea level rise measured against a land-based reference frame (tide gauge measurements), meaning that it is driven not only by thermal expansion and loss of land ice influenced by anthropogenic climate forcing, but also by vertical land movements. As attribution of coastal damages to sea level rise does not distinguish between these components, it does not imply attribution to anthropogenic forcing. Where the literature does allow attribution of changes in natural, human or managed systems to anthropogenic climate forcing ('joint attribution', Rosenzweig et al., 2007), this is highlighted in the assessment. Often the attribution of changes in the natural, human or managed systems to anthropogenic forcing can be done in a two-step approach where (i) an observed change in a climate-related system is attributed to anthropogenic climate forcing ('climate attribution') and (ii) changes in natural, human or managed systems are attributed to this change in the climate-related system ('impact attribution').

For climate attribution, the main challenge is the separation of externally human forced changes in the climate-related systems from their internal variability, while for impact attribution it often is the separation of the effects of other external forcings (i.e., direct human influences or natural disturbances) from the impacts of the changes in the climate-related systems. Direct influences not related to changes in the climate-related systems could, for example, be pollution and land use changes amplifying biodiversity losses, intensification of fishing reducing fish stocks, and increasing protection reducing losses due to river floods. The direct human or natural influences may counter the impacts of climate change (e.g., climate change may have reduced flood hazards, but exposure may have increased as people have moved to flood-prone areas, resulting in no change in observed damages). Given the definition of impact attribution, this means that there may be an observed impact of climate change without the detection of a change in the natural, human or managed system. This is different from 'climate attribution', where detection and attribution usually are consecutive steps.

Changes in climate-related systems can certainly also affect natural, human and managed systems through indirect effects on land use, pollution or exposure. However, these indirect effects are barely addressed in existing studies.

In addition to impact attribution, there is research on the identification of natural, human or managed systems' response to short-term (typically daily, monthly or annual) weather fluctuations or individual *extreme weather events*. As different from impact attribution, we separately define:

'Identification of weather sensitivity' refers to the attribution of the response of a system to fluctuations in weather and short-term changes in the climate-related systems including individual *extreme weather events* (e.g., a heatwave or storm surge).

Typical questions addressed include: 'How much of the observed variability of crop yields is due to variations in weather conditions compared to contributions from management changes?' (e.g., Ray et al., 2015; Müller et al., 2017) and 'Can weather fluctuations explain part of the observed variability in annual national economic growth rates?' (e.g., Burke et al., 2015). Identification of weather sensitivity may also address the effects of individual *climate extremes*, for example asking, 'Was the observed outbreak of cholera triggered by an associated flood event?' (e.g., Rinaldo et al., 2012; Moore et al., 2017b). It is important to note that sensitivity could be described in diverse ways and that, for example, the fraction of the observed variability in a system explained by weather variability differs from the strength of the systems' response to a specific change in a weather variable. Nevertheless, all these different measures are integrated in the 'identification of weather sensitivity' assessment, where 'sensitivity' should not be considered a quantitative one-dimensional mathematical measure.

In this chapter, we explicitly distinguish between assessment statements related to 'climate attribution' (listed in Table SM16.21), 'impact attribution' (listed in Table SM16.22) and 'identification of weather sensitivity' (listed in Table SM16.23). The identification of 'weather sensitivity' does not necessarily imply that there also is an impact of long-term changes in the climate-related systems on the considered system. However, if the probability or intensity of an *extreme weather event* has increased due to anthropogenic forcing ('climate attribution') (NASEM, 2016; WGI AR6 Chapter 11 Seneviratne et al., 2021) and the event is also identified as an important driver of an observed fluctuation in a natural, human or managed system ('identification of weather sensitivity'), then the observed fluctuation is considered (partly) attributed to long-term climate change ('impact attribution') and even to anthropogenic forcing.

16.2.2 Methods and Data for Impact Attribution Including Recent Advances

By definition, the counterfactual baseline required for impact attribution cannot be observed. However, it may be approximated by impact model simulations forced by a stationary climate, for example derived by de-trending the observed climate (Diffenbaugh et al., 2017; Mengel et al., 2021), while other relevant drivers (e.g., land use changes or application of pesticides) of changes in the system of interest (e.g., a bird population) evolve according to historical conditions. To attribute to anthropogenic climate forcing, the anthropogenic trends in climate are estimated from a range of different climate models and subtracted from the observed climate (e.g., Abatzoglou and Williams, 2016, for changes in the extent of forest fires or Diffenbaugh and Burke, 2019, for effects on economic inequality) or the 'no anthropogenic climate forcing' baseline is directly derived from a large ensemble of climate model simulations not accounting for anthropogenic forcings (e.g., Kirchmeier-Young et al.., 2019b, for the extent of forest fires). In any case, it has to be demonstrated that the applied impact models are able to explain the observed changes in natural, human or managed systems by, for example, reproducing the observations when forced by observed changes in climate-related systems and other relevant drivers.

In a situation where an influence of other direct human drivers can be excluded (e.g., by restriction to remote areas not affected by

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direct human interventions), the 'no climate-change' baseline can also be approximated by data from early observational periods with no or minor levels of climate change. In particular, the contribution of climate change to the observed changes in ecosystems is often also determined by a 'multiple lines of evidence' approach where the baseline is not formally quantified but the observed changes are identified as a signal of climate change compared with a no-climate-change situation based on process understanding from, for example, palaeo data and laboratory or field experiments in combination with individual long-term observational records and the large-scale spatial or temporal pattern of observed changes that can hardly be explained by alternative drivers (Parmesan et al., 2013).

To date, explicit accounting for direct human or natural influences is often hampered by an incomplete understanding of the processes and limited observational data. There are, however, first studies demonstrating the potential of detailed process-based or empirical modelling that explicitly accounts for known variations in direct human or natural drivers and separate their effects from the ones induced by changes in the climate-related systems. Examples are Butler et al. (2018) for the separation of growing season adjustments from within growing season climate effects on US crop yields; Wang and Hijmans (2019) separating effects of shifts in land use from climate effects; Jongman et al. (2015); Formetta and Feyen (2019) and Tanoue et al. (2016) for the separation of changes in exposure and vulnerability from climate effects on river floods; Kirchmeier-Young et al. (2019b) for wildfire attribution; and Venter et al. (2018) for the attribution of ecosystem structural changes to climate change versus other disturbances.

There also has been significant progress in the compilation of fragmented and distributed observational data (e.g., Cohen et al., 2018, for phenological ecosystem changes; Poloczanska et al., 2013, for distributional shifts in marine ecosystems; Andela et al., 2019, with the new global fire atlas including information about individual fire size, duration, speed and direction) as well as in the regional disaggregation (e.g., Ray et al., 2015, for crop yields) allowing for the identification of an overall picture of the impacts of progressing climate change. Given the ever-increasing body of literature on observed changes in natural, human and managed systems, there also is a first machine learning approach for an automated identification of relevant literature that could complement or support expert assessments as the one provided here (Callaghan et al., 2021).

16.2.3 Observed Impacts of changes in climate-related systems

In this section, we synthesise observed impacts of changes in climate-related systems across a range of ecosystems, sectors and regions. Figure 16.2 summarises the attribution of observed (regional) changes in natural, human or managed systems (orange symbols and confidence ratings), the quantification of weather sensitivity of those systems (blue symbols and confidence ratings) and the attribution of underlying changes in the climate-related systems to anthropogenic forcing (grey symbols and confidence ratings). The figure can be read as a summary and table of content for the underlying Tables SM16.21 on climate attribution, SM16.22 on impact attribution and SM16.23 on identification of weather sensitivity that provide the more detailed explanations behind each regional or global assessment, including all references. The synthesis was generated in collaboration with 'detection and attribution contact persons' from the individual chapters that each includes its own assessment of observed impacts, and contributing authors on individual topics. The synthesis of 'climate attribution' studies in Table SM16.21 was particularly informed by the WGI assessment.

If Figure 16.2 only provides an assessment of attributed impacts on a given system (e.g., phenology shifts in terrestrial ecosystems) but does not include an associated 'identification of weather sensitivity' that does not mean that the system is not sensitive to weather fluctuations. The focus of our assessment was on 'impact attribution', and we only provide an assessment of 'weather sensitivities' if the literature has turned out to provide only *limited evidence* on impacts of long-term changes in climate-related systems but rather addressed the responses of natural, human or managed systems to short-term weather fluctuations in the climate-related ones.

16.2.3.1 Ecosystems

The collapse or transformation of ecosystems is one of the most abrupt potential tipping points associated with climate change. Climate change has started to induce such tipping points, with the first examples including mass mortality in coral reef ecosystems (e.g., Donner et al., 2017; Hughes et al., 2018; Hughes et al., 2019) (*high confidence*), and changes in vegetation cover triggered by wildfires with climate change suppressing the recovery of the former cover (Tepley et al., 2017; Davis et al., 2019) (*low confidence* because of the still limited number of studies). Another example of an abrupt change in an ecosystem triggered by a climate extreme is the shift from kelp- to urchin-dominated communities along parts of the Western North America coast (Rogers-Bennett and Catton, 2019; McPherson et al., 2021, see 'Marine ecosystems—Kelp forest', Table SM16.22). The loss of kelp forests was induced by a marine heatwave where anthropogenic climate forcing has been shown to have increased the probability for an event of that duration by at least a factor of 33 (Laufkötter et al., 2020). Many terrestrial ecosystems on all continents show evidence of significant structural transformation, including woody thickening and 'greening' in more water-limited ecosystems, with a significant role played by rising atmospheric CO_2 fertilisation in these trends (*high confidence*) (Fang et al., 2017; Stevens et al., 2017; Burrell et al., 2020). Climate change is identified as a major driver of increases in burned areas in the Western USA (*high confidence*, see 'Terrestrial ecosystems—Burned areas', Table SM16.22).

There is also a clear footprint of climate change on species distribution, with appreciable proportions of tropical species expanding into the ranges of temperate species, and boreal species moving into Arctic regions (*high confidence*, see 'Marine ecosystems—Range reduction and shift' and 'Terrestrial ecosystems—Range reduction and shift', Table SM16.22). Climate change has also shifted the phenology of animals and plants on land and in the ocean (*high confidence*, see 'Marine ecosystems—Phenology shift' and 'Terrestrial ecosystems—Phenology shifts', Table SM16.22). Both processes have led to emerging hybridisation, competition, temporal or spatial mismatches in predator–prey, guest–host relationships, and the invasion of alien plant pests or pathogens (Edwards and Richardson, 2004; Bebber et al., 2013; Parmesan et al., 2013; Millon et al., 2014; Thackeray et al., 2016).

16.2.3.2 Water Distribution—River Flooding and Reduction in Water Availability

Observed trends in high river flows strongly vary across regions but also with the considered time period (Gudmundsson et al., 2019; Gudmundsson et al., 2021) as influenced by climate oscillations such as the El Niño-Southern Oscillation (Ward et al., 2014). On the global scale, the spatial pattern of observed trends is largely explained by observed changes in climate conditions as demonstrated by multi-model hydrological simulations forced by observed weather, while the considered direct human influences play only a minor role on global scale (Gudmundsson et al., 2021, see 'Water distribution—Flood induced economic damages', Table SM16.22). The annual total number of reported fatalities from flooding shows a positive trend (1.5% yr^{-1} from 1960 to 2013, Tanoue et al., 2016) which appears to be primarily driven by changes in exposure dampened by a reduction in vulnerability, while climate-induced increases in affected areas show only a weak positive trend on the global scale. However, the signal of climate change in flood-induced fatalities may be lost in the regional aggregation, where effects of increasing and decreasing hazards may cancel out. Thus, a climate-driven increase in flood-induced damages becomes detectable in continental subregions with increasing discharge, while the signal of climate change may not be detectable without disaggregation (Sauer et al., 2021, see 'Water distribution—Flood induced economic damages', Table SM16.22). Compared with river floods, the analysis of impacts of long-term changes in the climate-related systems on the reduction in water availability is much more fragmented and reduced to individual case studies regarding associated societal impacts (see 'Water distribution—Reductions in water availability + induced damages and fatalities', Table SM16.22). At the same time, weather fluctuations have led to reductions in water availability with severe societal consequences and high numbers of drought-induced fatalities and damages in particular in Africa and Asia (see 'Water distribution—Reductions in water availability + induced damages and fatalities', Table SM16.23) and impacts on malnutrition (see 'Food system—Malnutrition', Table SM16.23). Although anthropogenic climate forcing has increased droughts' intensity or probability in many regions of the world (*medium confidence*), (see 'Atmosphere—Droughts', Table SM16.21) the existing knowledge has not yet been systematically linked to attribute long-term trends in malnutrition, fatalities and damages induced by reduced water availability to anthropogenic climate forcing or long-term climate change. For impacts of individual attributable drought events, see Table 4.5 and 'Water distribution—Reductions in water availability + induced damages and fatalities', Table SM16.23.

16.2.3.3 Coastal systems

With their enormous destructive power, tropical cyclones represent a major risk for coastal systems (see 'Coastal systems—Damages', Table SM16.23). Despite its relevance, confidence in the influence of anthropogenic climate forcing on the strength and occurrence probability of tropical storms themselves is still low (see 'Coastal systems—Tropical cyclone activity', Table SM16.21). However, anthropogenic climate forcing has become the dominant driver of sea level rise (*high confidence*) (see 'Coastal systems—Mean and extreme sea levels', Table SM16.21) and has increased the risk of coastal flooding, including inundation induced by tropical cyclones. In addition, anthropogenic climate forcing has increased the amount of rainfall associated with tropical cyclones (*high confidence)* (Risser and Wehner, 2017; Van Oldenborgh et al., 2017; Wang et al., 2018, for Hurricane Harvey in 2017; Patricola and Wehner, 2018, for hurricane Katrina in 2005, Irma in 2017 and Maria in 2017, see 'Atmosphere—Heavy precipitation', Table SM16.21). Assuming that the extreme rainfall is a major driver of the total damages induced by the tropical cyclone, the contribution of anthropogenic climate forcing to the occurrence probability of the observed rainfall (fraction of attributable risk) can also be considered the fraction of attributable risk of the hurricane-induced damages or fatalities (Frame et al., 2020; Clarke et al., 2021, see 'Coastal systems—Damages', Table SM16.22). However, first studies do not only quantify the change in occurrence probabilities but translate the actual change in climate-related systems into the additional area affected by flooding in a process-based way (Strauss et al., 2021 for the contribution of anthropogenic sea level rise (SLR) to damages induced by Hurricane Sandy; Wehner and Sampson, 2021 for the contribution increased precipitation to damages induced by Hurricane Harvey) and attribute a considerable part of the observed damage to anthropogenic climate forcing. In addition, disruption of local economic activity in Annapolis, Maryland and loss of areas and settlements in Micronesia and Solomon Islands have been attributed to relative SLR (Nunn et al., 2017; Albert et al., 2018; Hino et al., 2019), while permafrost thawing and sea ice retreat are additional drivers of observed coastal damages in Alaska (Albert et al., 2016; Smith and Sattineni, 2016; Fang et al., 2017).

16.2.3.4 Food system

Crop yields respond to weather variations but also to increasing atmospheric CO_2, changes in management (e.g., fertilizer input, changes in varieties), diseases and pests. However, the weather signal is clearly detectable in national and subnational annual yield statistics in main production regions (see 'Food system—Crop yields', Table SM16.23). Over the last decades, crop yields have increased nearly everywhere mainly due to technological progress (e.g., Lobell and Field, 2007 [global]; Butler et al., 2018 [USA]; Hoffman et al., 2018 [Sub-Saharan Africa]; Agnolucci and De Lipsis, 2019 [Europe]), with only minor areas not experiencing improvements in maize, wheat, rice and soy yields. However, meanwhile, stagnation or decline in yields is also observed in parts of the harvested areas (*high confidence*) (~20–40% of harvested areas of maize, wheat, rice and soy with wheat being most affected) (Ray et al., 2012; Iizumi et al., 2018). Evidence on the contribution of climate change to recent trends is still limited (see 'Food system—Crop yields', Table SM16.22). Current global-scale process-based simulations forced by simulated historical and pre-industrial climate lack an evaluation to what degree simulations reproduce observed yields (Iizumi et al., 2018). Global-scale empirical approaches do not explicitly account for extreme weather events but growing season average temperatures and precipitation (e.g., Lobell et al., 2011; Ray et al., 2019). In addition, studies are constrained by only fragmented information about changes in agricultural management such as growing season adjustments. Some of these limitations have been overcome in regional studies indicating a climate-induced increase (28% of observed trend since 1981) in maize yields in the USA (Butler et al., 2018, based on a detailed accounting of impacts of extreme temperatures and growing season adjustments) and a climate-induced decrease in millet and sorghum yields (10–20% for millet and 5–15% for sorghum in 2000–2009 compared with pre-industrial conditions) in Africa and a negative effect of historical climate change on potential wheat yields (27% reduction from 1990 to 2015) in Australia (Hochman et al., 2017; Sultan et al., 2019 based on detailed process-based modelling including a dedicated evaluation against observed yield fluctuations). These findings need additional support by independent studies. Results are relatively convergent that climate change has been an important driver of the recent declines in wheat yields in Europe (*medium confidence*) (Moore and Lobell, 2015; Agnolucci and De Lipsis, 2019; Ray et al., 2019).

Due to complex interactions with socioeconomic conditions, climate-induced trends in crop yields and production do not directly transmit to crop prices, availability of food, or nutrition status. This complexity, in addition to the limited availability of long-term data, has so far impeded the detection and attribution of a long-term impact of climate change on associated food security indicators. However, in a few cases, observed crop prices (e.g., domestic grain price in Russia and Africa, Götz et al., 2016; Mawejje, 2016; Baffes et al., 2019) are shown to be sensitive to fluctuations in local weather through its impact on production (see 'Food system—Food prices', Table SM16.23). In addition, there is growing evidence that *climate extremes* (in particular, droughts) have led to malnutrition (in particular, stunting of children) in the historical period (*medium confidence*, see 'Food system—Malnutrition', Table SM16.23) but without an attribution of changes to long-term climate change.

16.2.3.5 Temperature-Related Mortality

There is nearly universal evidence that non-optimal ambient temperatures increase mortality (*high confidence*), with notable heterogeneity only in the shape of the temperature–mortality relationship across geographical regions but often sharply growing relative risks at the outer 5% of the local historical temperature distributions (Gasparrini et al., 2015; Guo et al., 2018; Carleton et al., 2020; Zhao et al., 2021; see 'Other societal impacts—Heat-related mortality', Table SM16.23). Significant advances have been made since AR5 regarding the analysis of temperature-related excess mortality in previously under-researched regions, such as developing countries and (sub)tropical climates (e.g South-East Asia: Dang et al., 2016; Ingole et al., 2017; Mazdiyasni et al., 2017; South Africa: Wichmann, 2017, Scovronick et al., 2018; the Middle East: Alahmad et al., 2019, Gholampour et al., 2019; and Latin America: Péres et al., 2020). Progress has also been made with regard to temporal changes in temperature-related excess mortality and underlying population vulnerability over time. Heat-attributable mortality fractions have declined over time in most countries owing to general improvements in health care systems, increasing prevalence of residential air conditioning, and behavioural changes. These factors, which determine the susceptibility of the population to heat, have predominated over the influence of temperature change (see 'Other societal impacts—Heat-related mortality', Table SM16.22, De'Donato et al., 2015; Arbuthnott et al., 2016; Vicedo-Cabrera et al., 2018a). Important exceptions exist, for example, where unprecedented heatwaves have occurred recently. No conclusive evidence emerges regarding recent temporal trends in excess mortality attributable to cold exposure (Vicedo-Cabrera et al., 2018b). Quantitative detection and attribution studies of temperature-related mortality are still rare. One study (Vicedo-Cabrera et al. 2021), using data from 43 countries, found that 37% (range 20.5–76.3%) of average warm-season heat-related mortality during recent decades can be attributed to anthropogenic climate change (*medium confidence*, see 'Other societal impacts—Heat-related mortality', Table SM16.22). Studying excess mortality associated with past heatwaves, such as the 2003 or 2018 events in Europe, even higher proportions of deaths attributable to anthropogenic climate change have been reported for France and the UK (Mitchell et al., 2016; Clarke et al., 2021). Formal attribution studies encompassing cold-related mortality are quasi non-existent. The very few studies from Europe and Australia (Christidis et al., 2010; Åström et al., 2013; Bennett et al., 2014) find weak impacts of climate change on cold-associated excess mortality, with contradictory outcomes both towards higher and lower risks (*low confidence*, see 'Other societal impacts—Heat-related mortality', Table SM16.22).

16.2.3.6 Waterborne Diseases

Infectious diseases with water-associated transmission pathways constitute a large burden of disease globally. Since the AR5, the evidence has strengthened that waterborne diseases, and especially gastrointestinal infections, are highly to moderately sensitive to weather variability (*medium confidence*, see 'Water distribution—Waterborne diseases', Table SM16.23). Increased temperature and high precipitation, with associated flooding events, have been shown to generally increase the risk of diarrhoeal diseases. There are, however, a number of studies that describe important exceptions and modifications to this general observation. While high temperatures favour bacterial diarrhoeal diseases, virally transmitted diarrhoea is on the contrary mostly associated with low temperatures (Carlton et al., 2016; Chua et al., 2021). Socioeconomic determinants, such as the existence of single-household water supplies (Herrador et al., 2015) or combined sewer overflows (Jagai et al., 2017), have been shown to critically increase the risk of gastrointestinal infections linked to heavy rainfall in high-income countries. Also, for both low- and high-income countries it has been found that gastrointestinal diseases increase following a heavy rainfall event only if preceded by a dry period (Carlton et al., 2014; Setty et al., 2018). Yet, so far there is no consistent evidence on the role of droughts in favouring waterborne disease transmission (Levy et al., 2016). As exemplified by the large cholera outbreak following the 2010 earthquake in Haiti, the existence of functioning sanitation systems is critical for preventing waterborne disease outbreaks, while climatic factors (especially rainfall) are important in driving the transmission dynamics once the outbreak has started (Rinaldo et al., 2012). Other socioeconomic factors, such as human mobility and water management projects (e.g., dam constructions), also modify the strength of the association between climatic factors and waterborne diseases, as shown by recent studies in Africa (Perez-Saez et al., 2015; Finger et al., 2016).

Whereas the weather sensitivity of waterborne diseases is well established for all world regions (see 'Water distribution—Water-borne diseases', Table SM16.23), studies attempting to attribute recent trends in waterborne disease to climate change are non-existent, except for investigations on the distribution of marine *Vibrio* bacteria and associated disease outbreaks in the coastal North Atlantic and the Baltic Sea regions (Baker-Austin et al., 2013; Baker-Austin et al., 2016; Vezzulli et al., 2016; Ebi et al., 2017). These investigations provide evidence that increases in sea surface temperatures over recent decades as well as during recent summer heatwaves are linked to increased concentrations of *Vibrio* bacteria in coastal waters and an associated rise in environmentally acquired *Vibrio* infections in humans.

16.2.3.7 Vector-Borne Diseases

Vector-borne diseases constitute a large burden of infectious diseases worldwide and are highly sensitive to fluctuations of weather conditions including extreme events. Thus, both extreme rainfall and droughts have increased infections (*high confidence*, see 'Other societal impacts—Vector-borne diseases', Table SM16.23). For example, in Sudan, anomalous high rainfall increased *Anopheles* mosquito breeding sites, leading to malaria outbreaks (Elsanousi et al., 2018), while in Barbados and Brazil, drought conditions in urban areas have enhanced dengue incidence due to changes in water storage behaviour creating breeding sites for *Aedes* mosquitoes around human dwellings (Lowe et al., 2018; Lowe et al., 2021) . In the Caribbean and Pacific Island nations, weather extremes, such as storms and flooding, have led to outbreaks of dengue due to disruption to water and sanitation services, leading to increased exposure to *Aedes* mosquito breeding sites (Descloux et al., 2012; Sharp et al., 2014; Uwishema et al., 2021). In South and Central America, and Asia, dengue incidence has been shown to be sensitive to variations in temperature and the monsoon season in addition to variations induced by urbanisation and population mobility (*high confidence* [South and Central America]*; medium confidence* [Asia]; see 'Other societal impacts—Vector-borne diseases', Table SM16.23).

The attribution of changes in disease incidence to long-term climate change is often limited by relatively short reporting periods often only covering 10–15 years. Most studies then attribute trends in the occurrence of vector-borne diseases to the trends in climate across the same observational period and do not refer to an early 'no climate change' baseline climate. This means that they also capture trends induced by longerterm climate oscillations. Nevertheless, we list them in Table SM16.22 on 'impact attribution' to clearly distinguish them from the analysis of interannual fluctuations. The overall consistency of their findings across regions and time windows indicates that climate change is an important driver of the observed latitudinal or altitudinal range expansions of vector-borne diseases into previously colder areas (*medium* to *high confidence*, see 'Other societal impacts—Vector-borne diseases', Table SM16.22). In highland areas of Africa and South America, epidemic outbreaks of malaria have become more frequent due to warming trends that allow *Anopheles* mosquitoes to persist at higher elevations (Pascual et al., 2006; Siraj et al., 2014). In the USA, ticks that transmit Lyme disease have expanded their range northwards because of warmer temperatures (*high confidence*; Kugeler et al., 2015; McPherson et al., 2017; Lin et al., 2019; Couper et al., 2020; see 'Other societal impacts—Vector-borne diseases', Table SM16.22). In Southern Europe, climate suitability for *Aedes* mosquitoes, which transmit dengue and chikungunya, and *Culex* mosquitoes, which transmit West Nile virus, has also increased and contributed to unprecedented outbreaks including the 2018 West Nile fever outbreak (*medium confidence*, Medlock et al., 2013; Paz et al., 2013; Roiz et al., 2015; ECDC, 2018, see 'Other societal impacts—Vector-borne diseases', Table SM16.22).

16.2.3.8 Economic Impacts

Since the AR5, there has been significant progress regarding the identification of economic responses to weather fluctuations: evidence has increased that *extreme weather events* such as tropical cyclones, droughts, and severe fluvial floods have not only caused substantial immediate direct economic damage (*high confidence*, see 'Coastal Systems—Damages, Table SM16.23, 'Water distribution—Reductions in water availability + induced damages and fatalities', Table SM16.23, and 'Water distribution—Flood-induced economic damages', Table SM16.22) but have also reduced economic growth in the short term (year of, and year after event) (Strobl, 2011; Strobl, 2012; Fomby et al., 2013; Felbermayr and Gröschl, 2014, Loyaza et al. 2012) (*high confidence*) as well as in the long term (up to 10–15 years after event) (*medium confidence*) (Hsiang and Jina, 2014; Berlemann and Wenzel, 2016; Berlemann and Wenzel, 2018; Krichene et al., 2020; Tanoue et al., 2020, see 'Other societal impacts—Macroeconomic output', Table SM16.23). Short- and long-term reductions of economic growth by *extreme weather events* affect both developing and industrialised countries, but have been shown to be more severe in developing than in industrialised economies, thereby increasing inequality between countries (*high confidence*, see 'Other societal impacts—Between-country inequality', Table SM16.23). Further, *extreme weather events* have increased within-country inequality since poorer people are more exposed and suffer relatively higher well-being losses than richer parts of the population (*medium confidence*, see 'Other societal impacts—Within-country inequality', Table SM16.23). Going beyond *extreme weather events*, economic production depends nonlinearly on temperature fluctuations: below a certain threshold temperature, economic production increases with temperature, whereas it decreases above a certain threshold temperature (*high confidence*) (Burke et al., 2015; Pretis et al., 2018; Kalkuhl and Wenz, 2020; Kotz et al., 2021).

So far, there are few individual studies attributing observed economic damages to long-term climate change except for damages induced by river flooding, droughts and tropical cyclones (see 'Coastal systems—Damages', 'Water distribution—Flood-induced damages', and 'Water distribution—Reduction in water availability + induced damages and fatalities', Table SM16.22). In addition, the empirical findings on the sensitivity of macroeconomic development to weather fluctuations and *extreme weather events* have been used to estimate the cumulative effect of historical warming on long-term economic development (see 'Other societal impacts—Macroeconomic output', Table SM16.22): anthropogenic climate change is estimated to have reduced gross domestic product (GDP) growth over the last 50 years, with substantially larger negative effects on developing countries and in some cases positive effects on colder industrialised countries (*low confidence*) (Diffenbaugh and Burke, 2019). Globally, between-country inequality has decreased over the last 50 years. Climate change is estimated to have substantially slowed down this trend, that is, increased inequality compared with a counterfactual no-climate-change baseline (*low confidence*) (Diffenbaugh and Burke, 2019). On a regional level, decreasing rainfall trends in Sub-Saharan Africa may have increased the GDP per capita gap between Sub-Saharan Africa and other developing countries (*low confidence*) (Barrios et al., 2010). Overall, more research is needed on the impact channels through which *extreme weather events* and weather variability can hinder economic development, especially in the long term.

16.2.3.9 Social Conflict

There are few studies directly attributing changes in conflict risk to climate change in the modern era (van Weezel, 2020), preventing a confident assessment of the effect of long-term changes in the climate-related systems on armed conflict (see 'Other societal impacts—Social conflict', Table SM16.22). However, a sizeable literature links the prevalence of armed conflict within countries to within- and between-year variations in rainfall, temperature or drought exposure, often via reduced-form econometric analysis or statistical models that control for important non-climatic factors, such as agricultural dependence, level of economic development, state capacity and ethnopolitical marginalisation (see 'Other societal impacts—Social conflict', Table SM16.23). Overall, there is more consistent evidence that climate variability has influenced low-intensity organised violence than major civil wars (Detges, 2017; Nordkvelle et al., 2017; Linke et al., 2018). Likewise, there is more consistent evidence that climate variability has affected dynamics of conflict, such as continuation, severity and frequency of violent conflict events, than the likelihood of initial conflict outbreak (Yeeles, 2015; Eastin, 2016; Von Uexkull et al., 2016, Section 7.2.7). Moreover, research suggests with *medium confidence* (*medium evidence*, *medium agreement*) that weather effects on armed conflict have been most prominent in contexts marked by a large population, low socioeconomic development, high political marginalisation and high agricultural dependence (Theisen, 2017; Koubi, 2019; Buhaug et al., 2020; Ide et al., 2020).

Some studies also seek to evaluate potential indirect links between climate and weather anomalies and prevalence of armed conflict via food price shocks or forced migration. While there is *robust evidence* that the likelihood of social unrest in the developing world generally increases in response to rapid growth in food prices (Bellemare, 2015; Rudolfsen, 2018), the magnitude of the climate effect on unrest via food prices is less well established (Martin-Shields and Stojetz, 2019). Similarly, research shows with *high confidence* that climate variability and extremes have affected human mobility (see 'Other societal impacts—Displacement and migration', Table SM16.23), but there is *low agreement* and *limited evidence* that weather-induced migration has increased the likelihood of armed conflict (Section 7.2.7, Brzoska and Fröhlich, 2016; Kelley et al., 2017; Selby et al., 2017; Abel, 2019). Research on weather-related effects on interstate security generally concludes that periods of transboundary water scarcity are more likely to facilitate increased international cooperation than conflict (Bernauer and Böhmelt, 2020).

In general, the historical influence of climate on conflict is judged to be small when compared with dominant conflict drivers (Mach et al., 2019). Much of this research is limited to (parts of) Sub-Saharan Africa, which raises some concerns about selection bias and generalisability of results (Adams et al., 2018).

16.2.3.10 Displacement and Migration

Given the complexity of human migration processes and decisions (e.g., Boas et al., 2019, Cattaneo et al., 2019) and the paucity of long-term, reliable and internally consistent observational data on displacement (IDMC, 2019; IDMC, 2020) and migration (Laczko, 2016), the contribution of long-term changes in climate-related systems to observed human displacement or migration patterns has not been quantified so far, except for individual examples of displacement induced by inland flooding where the heavy precipitation has been attributed to anthropogenic climate forcing and coastal flooding (see 'Other societal impacts—Displacement and migration', Table SM16.22; Section CCP2).

However, new evidence has emerged since the AR5 that further documents widespread effects of weather fluctuations and extreme events on migration (see 'Other societal impacts—Displacement and migration', Table SM16.23). Numerous studies find significant links between temperature or precipitation anomalies, or *extreme weather events* such as storms or floods, and internal as well as international migration (Coniglio and Pesce, 2015; Cattaneo and Peri, 2016; Nawrotzki and DeWaard, 2016; Beine and Parsons, 2017, for international migration; and IDMC, 2019, for internal displacement). Internal displacement of millions of people every year is triggered by natural hazards, mainly floods and storms (IDMC, 2019). The effects of weather fluctuations and extremes on migration are considered more important for temporary mobility and displacement than permanent migration, and more influential on short-distance movement, including urbanisation, than international migration (McLeman, 2014; Hauer et al., 2020; Hoffmann et al., 2020, Section 7.2.6). Importantly, these links are conditional on the socioeconomic situation in the origin; for example, poor populations may be 'trapped' and not able to migrate in the face of adverse climate or weather conditions (Black et al., 2013; Adams, 2016). Many studies have also explored the channels through which climate or weather influence migration, and have identified incomes in the agricultural sector as one of the main channels (Nawrotzki et al., 2015; Viswanathan and Kavi Kumar, 2015; Cai et al., 2016a). In particular, declines in agricultural incomes and employment due to changed weather variability may foster increased rural–urban movement, and the resulting pressures on urban wages in turn foster international migration (Marchiori et al., 2012; Maurel and Tuccio, 2016). Another possible but controversial channel is violent conflict, which may be fostered (though not exclusively caused) by adverse climate conditions such as drought, and in turn lead to people seeking refugee status, although evidence of such an indirect effect is weak (Brzoska and Fröhlich, 2016; Abel et al., 2019; Schutte et al., 2021).

16.3 Synthesis of Observed Adaptation-Related Responses

A new development since AR5 is that there is now growing evidence assessing progress on adaptation across sectors, geographies and spatial scales. Uncertainty persists around what defines adaptation and how to measure it (Cross-Chapter Box FEASIB in Chapter 18, UNEP, 2021). As a result, most literature synthesising responses is based on documented or reported adaptations only, and is thus subject to substantial reporting bias.

Box 16.1: Case Study on Climate Change and the Outbreak of the Syrian Civil War

Separating between climatic and non-climatic factors in impact attribution is often challenging, as highlighted by the debate surrounding the causes of the Syrian civil war. During the years 2006–2010, the Fertile Crescent region in Eastern Mediterranean and Western Asia was hit by the worst drought on meteorological record, compounding a consistent drying of the region over the past half century (Trigo et al., 2010; Hoerling et al., 2012; Mathbout et al., 2018, SR15 BOX 3.2 (Hoegh-Guldberg et al., 2018a)). The magnitude of the multi-year drought is estimated to have become two to three times more likely as a result of increased CO_2 forcing (Kelley et al., 2015). The drought had a devastating impact on agricultural production in the northeast of Syria. In 2007–2008 alone, average crop yields dropped by 32% in irrigated areas and as much as 79% in rain-fed areas (De Châtel, 2014), and herders in the northeast lost around 85% of their livestock (Werrell et al., 2015). Successive years with little or no income eventually forced people to leave their farms in great numbers and seek employment in less affected parts of the country, adding to existing pressures on housing, labour market and public goods provision (Gleick, 2014; Kelley et al., 2015). In March 2011, by which time the 'Arab Spring' uprisings had gained momentum and spread across much of the region, anti-regime protests broke out in Syria, first in the southern city of Dara'a and then in Damascus and throughout the country.

Yet, the attribution of the Syrian civil war to climate change has triggered a heated debate. A number of studies argue that the principal drivers of the drought-induced economic collapse were political rather than environmental in nature, shaped by adverse economic reforms and unsustainable agricultural policies, promoting water-intensive irrigation schemes for cotton cultivation and implementing abrupt subsidy cuts at the peak of the drought, implying that many poor farmers no longer could afford fertilis ers or fuel to power irrigation pumps (Barnes, 2009; De Châtel, 2014; Eklund and Thompson, 2017; Selby et al., 2017). Thus, the 2006–2010 drought did not precipitate similar devastating socioeconomic impacts on agrarian communities across the borders in Turkey, Iraq or Jordan, although environmental conditions were comparable (Trigo et al., 2010; Eklund and Thompson, 2017; Feitelson and Tubi, 2017).

However, the relevant attribution question is not whether the same drought would produce the same consequences under different political and socioeconomic conditions, but rather, given the same political and socioeconomic context, how would the outcomes have differed in the absence of climate change? Research still provides very limited insights into whether and how the escalation process would have evolved differently in a counterfactual no-climate-change world.

Thus, the role of the drought in augmenting pre-existing internal migration, and the role of the distress migration in accentuating demographic, economic and social pressures in receiving areas, remain contested. Estimates of the number of people who abandoned their farms in response to the drought range from less than 40,000–60,000 families (Selby et al., 2017) to more than 1.5 million displaced (Gleick, 2014). However, the numbers have to be seen in the context of prevailing population growth, significant rural–urban migration, and the preceding inflow of around 1.5 million refugees from neighbouring Iraq (De Châtel, 2014; Hoffmann, 2016). In addition, research suggests that the migrants played a peripheral role in the initial social mobilisation in March 2011 (Fröhlich, 2016).

While it is undisputed that the drought caused direct economic losses, its overall additional impact on the Syrian economy, relative to other prevalent drivers of economic misery, including rampant unemployment, increasing inequalities, declining rural productivity, and loss of oil revenues (Aïta, 2009; Landis, 2012; De Châtel, 2014; Selby, 2019), has not been quantified.

In addition, the protesters' demands centred around contentious political rather than economic issues, including release of political prisoners, ending of torture and indiscriminate violence by security forces, and abolishment of the near 50-year-old state of emergency (Selby et al., 2017; Ash and Obradovich, 2020). The mobilisation in Syria in the spring of 2011 also made explicit references to events across the Middle East and North African region. Analyses of regional and social media and networks show a high level of interaction across the Arab world, and the initial Syrian uprising adopted a mobilisation model and rhetorical frames similar to those developed in Tunisia and Egypt (Leenders, 2013; 2014). However, the Syrian uprising stands out in how it was met with overwhelming violent force by the police and security forces, which changed the character of the resistance and opened up for militarisation of non-state actors that further escalated the conflict (Heydemann, 2013; Leenders, 2013; Bramsen, 2020).

In summary, the drought itself is shown to be attributable to GHG emissions. The agricultural losses and internal migration from rural to urban areas can be directly linked to the drought and in this way are partly attributable to GHG emissions, although there are no studies comparing the observed losses and number of people displaced with a counterfactual situation of a weaker drought in a 'no climate change' situation. Current research does not provide enough evidence to attribute the civil war to climate change. In contrast, it is likely that social uprisings would have occurred even without the drought.

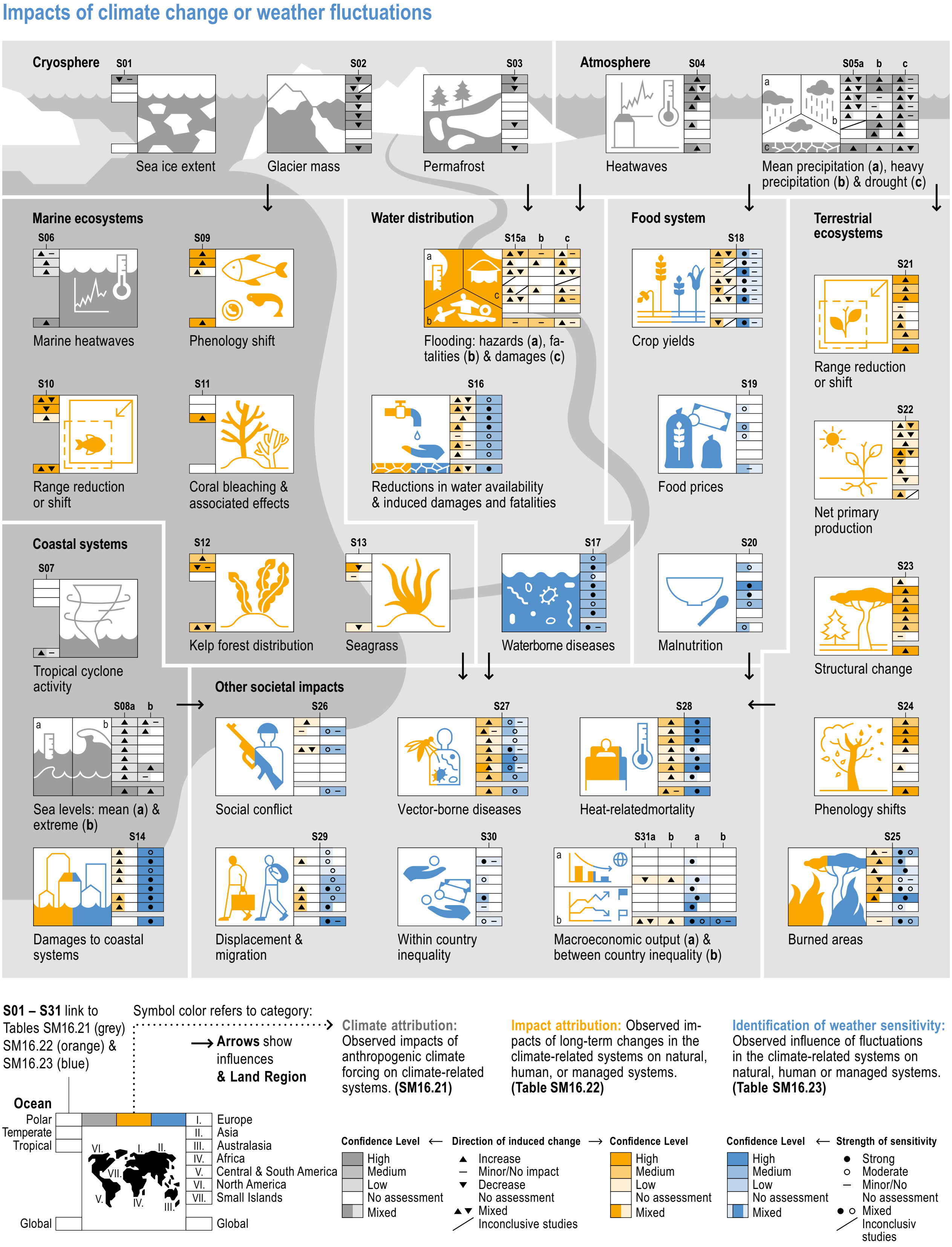


Figure 16.2 | Impact of climate change or weather fluctuations.

We document implemented adaptation-related responses that could directly reduce risk. Adaptation *as a process* is more broadly covered in Chapter 17 (Section 17.4.2), including risk management, decision making, planning, feasibility (see Cross-Chapter Box FEASIB in Chapter 18), legislation and learning. Here, we focus on a subset of adaptation activities: adaptation-related responses of species, ecosystems, and human societies that have been implemented, observed, and could directly reduce risk. We consider all adaptation-related responses to assumed, perceived or expected climate risk, regardless of whether or not impacts or risks have been formally attributed to climate change.

We use the term 'adaptation-related responses', recognising that not all responses reduce risk. While 'adaptation' implies risk reduction, we use the broader term 'responses' to reflect that responses may decrease risk, but in some cases may increase risk.

It is not currently possible to conduct a comprehensive global assessment of effectiveness, adequacy or the contribution of adaptation-related responses to changing risk owing to an absence of robust empirical literature. This constrains assessment of adaptation progress and gaps in the context of over-shoot scenarios. Given *limited evidence* to inform comprehensive global assessment of effectiveness and adequacy, we assess evidence that adaptation responses in human systems indicate transformational change. Chapter 17 considers adaptation planning and governance, including adaptation solutions, success, and feasibility assessment (Cross-Chapter Box FEASIB in Chapter 18), discussed further in Box 16.2 (also see Cross-Chapter Box PROGRESS in Chapter 17).

In natural ecosystems or species, detectable changes can be considered as 'impact' or 'response'. The distinction between 'observed impacts' (Section 16.2) and 'observed responses' (Section 16.3) is not always clear. For example, autonomous distributional shifts in wild species induced by increasing temperatures (an observed impact) may reduce risk to the species (an autonomous adaptation response), but this process can be enhanced or supported by human intervention such as intentional changes in land use. Observed autonomous changes in natural ecosystems or species unsupported by human intervention are treated as impacts (see Section 16.2).

Adaptation-related responses are frequently motivated by a combination of climatic and non-climatic drivers, and interact with other transitions to affect risk. For societal responses, it is difficult to say whether they are triggered by observed or anticipated changes in climate, by non-climatic drivers, or by a combination of all three. In the case of observed impacts, assessment typically focuses on detection and attribution *vis à vis* a counterfactual of no climate change. While there has been some effort to attribute reduced climate risk to adaptation-related responses (Toloo et al., 2013a; Toloo et al., 2013b; Hess et al., 2018; Weinberger et al., 2018), in many cases this has not been feasible given difficulties in defining adaptation and empirically disentangling the contribution of intersecting social transitions and changing risks. Literature on adaptation-related response frequently draws on theories of change to assess the likely contribution of adaptations to changes in risk, including maladaptation and co-benefits.

16.3.1 Adaptation-Related Responses by Natural Systems

There is growing evidence of shifts in species distributions and ecosystem structure and functioning in response to climate change (Chapter 2). While many species are increasingly responding to climate change, there is *limited evidence* that these responses will be fully adaptive, and for many species the rate of response appears insufficient to keep pace with the rate of climate change under mid- and high-range emissions scenarios (*medium confidence*). There is relatively limited, but growing, empirical data to document adaptation of natural systems in the absence of human interventions. For example, Scheffers et al. (2016) reviewed climate responses across diverse species, reporting widespread and extensive observed changes in organisms (genetics, physiology, morphology), populations (phenology, abundance and dynamics), species (distributions) and ecosystems. A systematic review by Franks et al. (2014) synthesised evidence from 38 empirical studies of changes in terrestrial plant populations, finding evidence to support a mix of plastic and evolutionary responses. Boutin and Lane (2014) similarly reviewed adaptive responses in mammals, finding most species' responses to be due to phenotypic plasticity. Charmantier and Gienapp (2014) reviewed responses to climate change among birds, finding emerging evidence that birds from a range of taxa show advancement in their timing of migration and breeding in response to warming. Aragão et al. (2018) reviewed adaptation responses in marine systems, including 12 studies of live marine mammals. They observed widespread evidence of shifting distributions and timing of biological events (Chapter 2, Chapter 3, and Cross-Chapter Paper 1).

Some ecosystems and species' responses may be insufficient to keep pace with rates of climate change. It is difficult to distinguish whether adaptations are due to genotypic change or to phenotypic plasticity. Long-term natural adaptations will require the former, but the latter may provide short-term coping mechanisms to 'buy time' to respond to climate changes or lay foundations for evolutionary adaptation. There is mixed evidence regarding evolutionary versus plastic responses, with relatively limited evidence of longer-term evolutionary responses of species that can be associated with climate change. Similarly, it is difficult to assess whether responses are indeed potentially adaptive (e.g., coping, shifting, migrating) or simply reflective of impacts (e.g., stress, damage). Among mammal responses reviewed by Boutin and Lane (2014), for example, only 4 of 12 studies found some evidence that responses were adaptive. Even where adaptive responses are occurring, they may not be sufficient to keep pace with the rate of climate change. found, for example, that, among the 12 studies in their review that directly assessed the sufficiency of responses to keep pace with the rate of climate change, 8 concluded that responses would be insufficient to avert extinction.

16.3.2 Adaptation-Related Responses by Human Systems

The literature that seeks to assess adaptation progress is growing at the global (Berrang-Ford et al., 2021a), regional (Bowen and Ebi, 2015; England et al., 2018; Robinson, 2018a; Wirehn, 2018; Olazabal et al., 2019; Thomas et al., 2019a; Biesbroek et al., 2020; Canosa et al., 2020; Robinson, 2020b), national (Hegger et al., 2017; Lesnikowski et al., 2019a; Lesnikowski et al., 2019b) and municipal (Araos et al., 2016; Reckien et al., 2018; Reckien et al., 2019; Lesnikowski et al., 2020; Singh et al., 2021) levels, using National Communications (Gagnon-Lebrun and Agrawala, 2007; Lesnikowski et al., 2015; Muchuru and Nhamo, 2017), local climate change action plans (Regmi et al., 2016b; Regmi et al., 2016a; Reckien et al., 2018; Reckien et al., 2019), adaptation project proposals, and reported adaptations in the peer-reviewed literature. There remains persistent publication bias in the evidence base on adaptation given the difficulty of integrating diverse knowledge sources (see Section 16.3.3). To better assess how adaptation is occurring in human systems, we draw on this literature base and characterise evidence of adaptation across regions and sectors in terms of five key questions (Table 16.4, Ford et al., 2013; Biagini et al., 2014; Ford et al., 2015a; Bednar and Henstra, 2018; Reckien et al., 2018; Tompkins et al., 2018): What types of hazards are motivating adaptation-related responses? Who is responding? What types of responses are being documented? What evidence is available on adaptation effectiveness, adequacy and risk reduction? To characterise evidence that adaptation responses indicate transformation, we use a typology based on four dimensions of climate adaptation: scope, depth, speed, and consideration of limits to adaptation (Section 16.4, Termeer et al., 2017; Berrang-Ford et al., 2021a).

Salience of different types of hazards in the scientific literature on adaptation-related responses

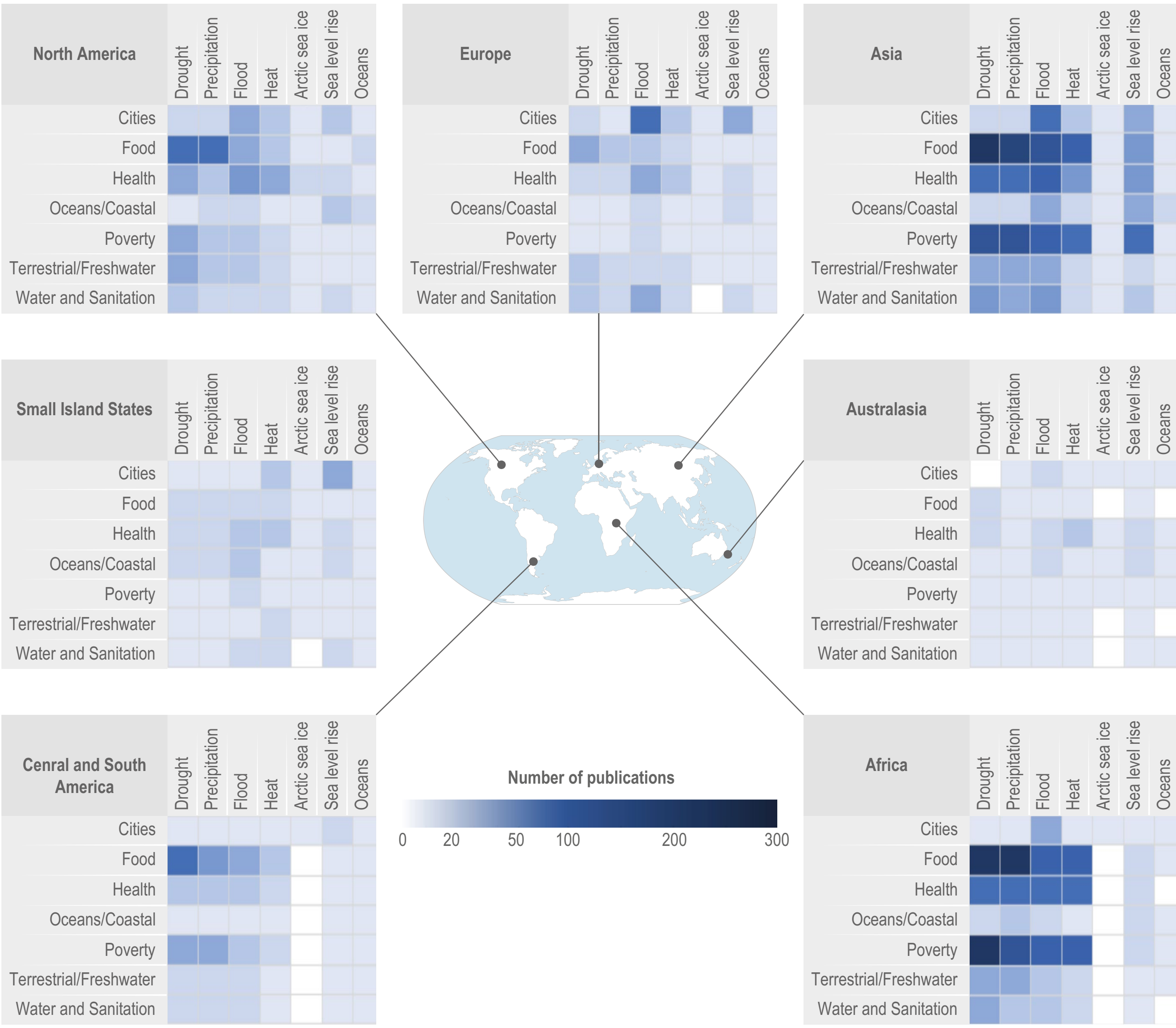


Figure 16.3 | Salience of different types of hazards in the scientific literature on adaptation-related responses (i.e., responses that people undertake to reduce risk from climate change and associated hazards). Updated from a systematic review of 1682 scientific publications (2013–2019) reporting on adaptation-related responses in human systems (Berrang-Ford et al., 2021a). Numbers in table reflect the number of publications reporting. Darker colours denote more extensive reporting on a hazard as a motivating factor for the response. Publications are counted in all relevant regions or sectors.

16.3.2.1 What Hazards Are Motivating Adaptation-Related Responses?

Drought and precipitation variability are the most prevalent hazards in the adaptation literature, particularly in the context of food and livelihood security. Adaptation frequently occurs in response to specific rapid or slow-onset physical events that can have adverse impacts on people. In some cases, people adapt in anticipation of climate change in general or to take advantage of new opportunities created by hazards (e.g., increased navigability due to melting sea ice). There is evidence that prior experience with hazards increases adaptation response (Barreca et al., 2015). Following drought and precipitation variability, the next specific hazards that are most frequently documented in the global adaptation literature are heat and flooding. Heat, while less salient, appears to be a driver of adaptation across all regions and sectors (Stone Jr et al., 2014; Hintz et al., 2018; Nunfam et al., 2018). Drought, extreme precipitation, and inland flooding are commonly reported in the context of water and sanitation (Bauer and Steurer, 2015; Lindsay, 2018; Kirchhoff and Watson, 2019; Hunter et al., 2020; Simpson et al., 2020). Flooding is frequently reported as a key hazard for adaptation in cities, followed by drought, precipitation variability, heat, and SLR (Broto and Bulkeley, 2013; Araos et al., 2016; Georgeson et al., 2016; Mees, 2017; Reckien et al., 2018; Hunter et al., 2020).

16.3.2.2 Who Is Responding?

Individuals and households play a central role in adaptation globally. The most frequently reported actors engaged in adaptation-related responses in the scientific literature are individuals and households, particularly in the Global South (Figure 16.4). Regionally, household- and individual-level adaptation is documented most extensively in Africa and Asia, and to a lesser but still substantial extent in North America (Figure 16.4).

National and local governments are also frequently engaged in reported adaptation across most regions. In Africa and Asia, reported adaptations have been primarily associated with individuals, households, national governments, non-governmental organisations (NGOs), and international institutions, with more limited reporting of involvement from sub-national governments or the private sector (Ford et al., 2015a; Ford and King, 2015; Hunter et al., 2020). Engagement by sub-national governments in adaptation is more frequently documented in Europe and North America (Craft and Howlett, 2013; Craft et al., 2013; Bauer and Steurer, 2014; Lesnikowski et al., 2015; Shi et al., 2015; Austin et al., 2016). Reporting of private sector engagement is generally low. Civil society participation in adaptations is reported across all regions. Consistent with this, local governments are also widely reported in documented adaptation responses, particularly where municipal jurisdiction is high, including cities, infrastructure, water and sanitation.

16.3.2.3 What Types of Responses Are Documented?

Behavioural change is the most common form of adaptation. The scientific literature presents extensive evidence of behavioural adaptation—change in the strategies, practices and actions that people, particularly individuals and households, undertake to reduce risk (Figure 16.5). This includes, for example, household measures to protect homes from flooding, protect crops from drought, relocation out of hazard zones, and shifting livelihood strategies (Porter et al., 2014). This is followed by adaptation via technological innovation and infrastructural development, nature-based adaptation (enhancing, protecting or promoting ecosystem services) and institutional adaptation (enhancing multi-level governance or institutional capabilities). Behavioural adaptation is most frequently documented in Asia, Africa and Small Island States, and in the agriculture, health and development sectors. In the agricultural sector, households are adopting or changing to crops and livestock that are more adapted to drought, heat, moisture,

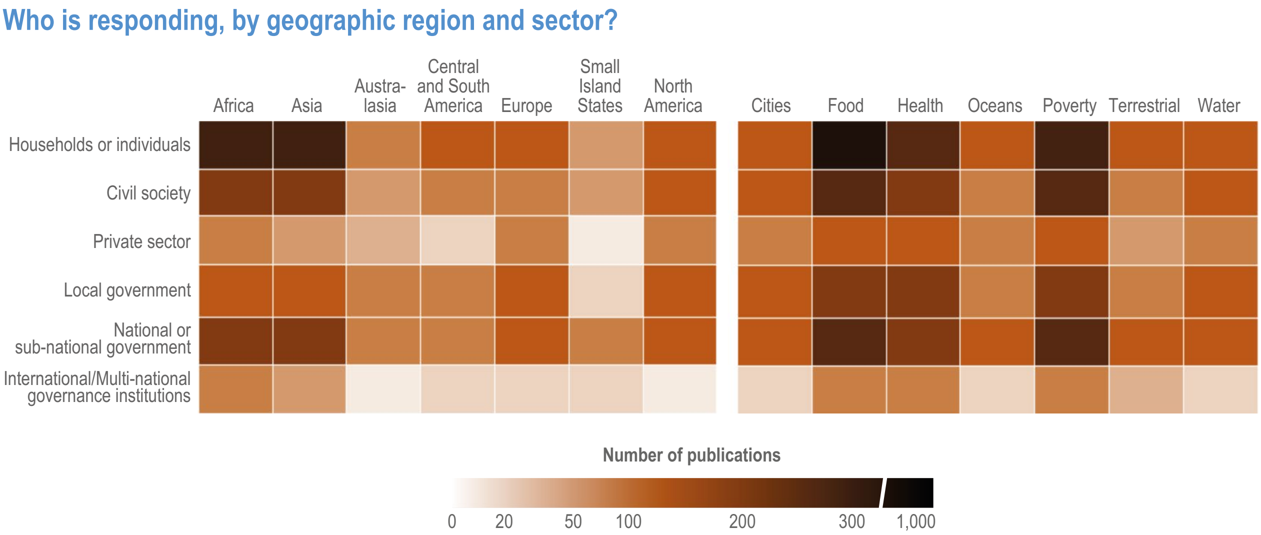


Figure 16.4 | Who is responding, by geographic region and sector? Cell contents indicate the number of publications reporting engagement of each actor in adaptation-related responses. Darker colours denote a high number of publications. Based on a systematic review of 1682 scientific publications (2013–2019) reporting on adaptation-related responses in human systems (Berrang-Ford et al., 2021a). SIS, Small Island States; Terr, terrestrial and freshwater ecosystems.

pests and salinity (Arku, 2013; Kattumuri et al., 2017; Wheeler and Marning, 2019). Studies in Africa and Asia have documented shifts in farming and animal husbandry practice (Arku, 2013; Garcia de Jalon et al., 2016; Gautier et al., 2016; Chengappa et al., 2017; Epule et al., 2017; Kattumuri et al., 2017; Abu and Reed, 2018; Asadu et al., 2018; Haeffner et al., 2018; Shaffril et al., 2018; Wiederkehr et al., 2018; Zinia and McShane, 2018; Currenti et al., 2019; Fischer, 2019a; Fischer, 2019b; Schofield and Gubbels, 2019; Sereenonchai and Arunrat, 2019; Wheeler and Marning, 2019; Mayanja et al., 2020). In Small Island Nations, studies have documented household flood protections measures such as raising elevation of homes and yards, creating flood barriers, improving drainage, moving belongings and, in some cases, relocating (Middelbeek et al., 2014; Currenti et al., 2019; Klock and Nunn, 2019).

The mix of adaptation response types differs across regions and sectors. Technological and infrastructural responses are widely reported in Europe, and globally in the context of cities and water and sanitation (Mees, 2017; Hintz et al., 2018). Responses to flood risk in Europe include the use of flood- and climate-resistant building materials, large-scale flood management, and water storage and irrigation systems (van Hooff et al., 2015; Mees, 2017). Technological and infrastructural responses are also documented to some extent in agriculture, including, for example, breeding more climate-resilient crops, precision farming and other high-tech solutions such as genetic modification (Makhado et al., 2014; Fisher et al., 2015; Costantini et al., 2020; Fraga et al., 2021; Grusson et al., 2021; Naulleau et al., 2021). While less common, institutional responses are more prominent in North America and Australasia as compared with other regions, and include zoning regulations, new building codes, new insurance schemes, and coordination mechanisms (Craft and Howlett, 2013; Craft et al., 2013; Parry, 2014; Ford et al., 2015b; Beiler et al., 2016; Lesnikowski et al., 2016; Labbe et al., 2017; Sterle and Singletary, 2017; Hu et al., 2018; Conevska et al., 2019). Institutional adaptations are more frequently reported in cites than other sectors. Institutional adaptation may be particularly subject to reporting bias, however, with many institutional responses likely to be reported in the grey literature (see Chapter 17). Nature-based solutions are less frequently reported, except in Africa, where they are relatively well documented, and in the content of terrestrial systems where reports included species regeneration projects, wind breaks, erosion control, reforestation and riparian zone management (Munji et al., 2014; Partey et al., 2017; Muthee et al., 2018).

Some but not all adaptation-related responses are engaging vulnerable populations in planning or implementation (*high confidence*) (Araos et al., 2021). Consideration of vulnerable populations is most frequently focused on low-income populations and women through the inclusion of informal or formal institutions or representatives in adaptation planning, or through targeted adaptations to reduce risk in these populations (*high confidence*). Consideration of vulnerable groups in adaptation responses is more frequently reported in the Global South (*medium confidence*). Engagement in adaptation planning of vulnerable elderly, migrants, and ethnic minorities remains low across all global regions (*medium confidence*). There is negligible literature on consideration of disabled peoples in planning and implementation of adaptation-related responses (*medium confidence*).

16.3.2.4 Adaptation Effectiveness, Adequacy and Risk Reduction

Despite a lack of systematic methods for assessing general adaptation effectiveness, there is some evidence of risk reduction for particular places and hazards, especially flood and heat vulnerability. There is some evidence of a reduction in global vulnerability, particularly for flood risk (Jongman et al., 2015; Tanoue et al., 2016; Miao, 2019) and extreme heat (Bobb et al., 2014; Boeckmann and Rohn, 2014; Gasparrini et al., 2015; Arbuthnott et al., 2016; Chung et al., 2017; Sheridan and Allen,

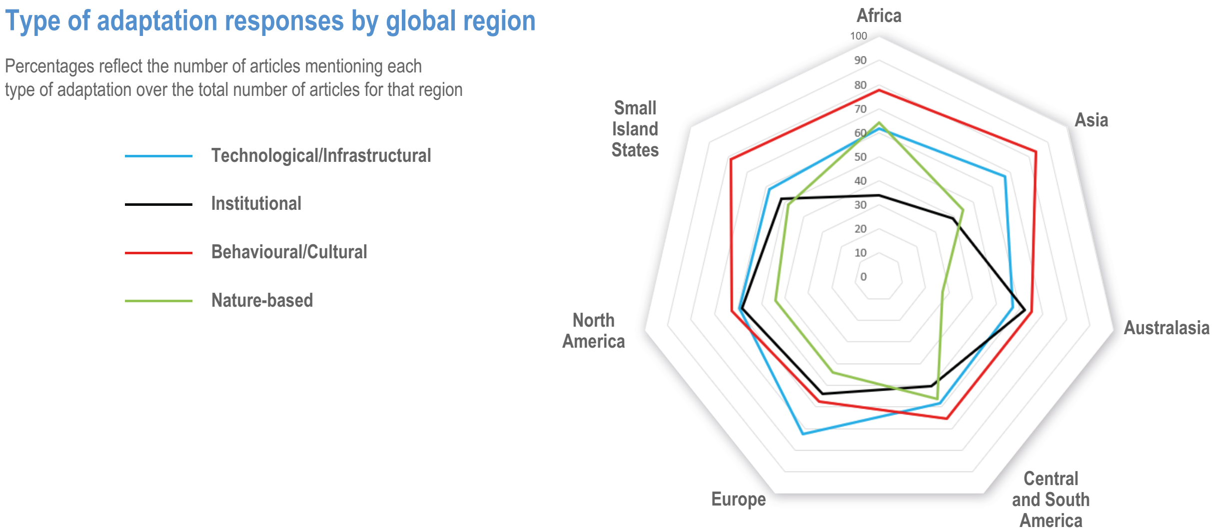


Figure 16.5 | Type of adaptation responses by global region. Percentages reflect the number of articles mentioning each type of adaptation over the total number of articles for that region. Radar values do not total 100% per region since publications frequently report multiple types of adaptation; for example, construction of drainage systems (infrastructural), changing food storage practices by households (behavioural), and planting of tree cover in flood-prone areas (nature-based) in response to flood risk to agricultural crops. Data updated and adapted from Berrang-Ford et al. (2021a), based on 1682 scientific publications reporting on adaptation-related responses in human systems.

2018; Folkerts et al., 2020). Investment in flood protection, including building design and monitoring and forecasting, have reduced flood-related mortality over time and are cost-effective (Bouwer and Jonkman 2018; Ward et al. 2017). Declining heat sensitivity, primarily reported in developed nations, has also been observed, and has been linked to air conditioning, reduced social vulnerability and improved population health (Boeckmann and Rohn, 2014; Chung et al., 2017; Kinney, 2018; Sheridan and Allen, 2018). Formetta and Feyen (2019) demonstrate declining global all-cause mortality and economic loss due to extreme weather events over the past four decades, with the greatest reductions in low-income countries, and with reductions correlated with wealth. Studies that correlate changes in mortality or economic losses with wealth indicators, to infer changes in vulnerability or exposure, lack direct empirical measures of vulnerability or exposure and are limited in their ability to assess how indirect effects of extreme events (e.g., morbidity, relocation, social disruption) may have changed or how changes may redistribute risk across populations.

There remain persistent difficulties in defining and measuring adaptation effectiveness and adequacy for many climate risks. No studies have systematically assessed the adequacy and effectiveness of adaptation at a global scale, across nations or sectors, or for different levels of warming. There has, however, been progress in operationalising assessment of adaptation feasibility (Cross-Chapter Box FEASIB in Chapter 18). Effectiveness of adaptation-related responses reflects whether a particular response actually reduces climate risk, typically through reductions in vulnerability and exposure (Figure 1.7 in Section 1.4). Some adaptation-related responses may increase risk or create new risks (maladaptation) or have no or negligible impact on risk. Adequacy of adaptation-related responses refers to the extent to which responses are collectively sufficient to reduce the risks or impacts of climate change (Figure 1.7 in Section 1.4). A set of adaptation-related responses may, for example, result in reduced climate risk (effectiveness), but these reductions may be insufficient to offset the level of risk and avoid loss and damages. Feasibility reflects the degree to which climate responses are possible or desirable, and integrates consideration of potential effectiveness. A feasibility assessment drawing on these methods is presented in Cross-Chapter Box FEASIB in Chapter 18.

Global adaptation is predominantly slow, siloed and incremental with little evidence of transformative adaptation (*high confidence*). In the absence of a general method to assess the adequacy of adaptation actions, we assessed evidence for transformational adaptation documented in peer-reviewed publications identified by a global stock-taking initiative (Berrang-Ford et al., 2021b) and in other AR6 chapters (2–15) (see Supplemental Material, SM16.1 for details). 'Transformational adaptation' refers to the degree to which adaptations have been implemented widely (scope), reflect major shifts (depth), occur rapidly (speed) and challenge limits to adaptation (limits, Pelling et al., 2015; Few et al., 2017; Termeer et al., 2017, Table 16.1).

Based on the literature, the overall transformative nature of adaptation across most global regions and sectors is low (*high confidence)* (Figure 16.6). Documented adaptations tend to involve minor modifications to usual practices taken to address extreme weather conditions (*high confidence*). For example, changing crop variety or timing of crop planting to address floods or droughts, new types of irrigation, pursuing supplementary livelihoods, and home elevations are widely reported but typically do not reflect radical or novel shifts in practice or values and are therefore considered low depth (*high confidence*) (see SM16.1 for more examples). Adaptations documented in the literature are also frequently focused on a single sector or small geographic area (*high confidence*). Actions taken by individuals or households are generally small in scope (Hintz et al., 2018; Hlahla and Hill, 2018) unless they are widely adopted (e.g., by farmers across a region) or address

Table 16.1 | Evidence of transformational adaptation assessed across four components (depth, scope, speed and limits). Transformational adaptation does not imply adequacy or effectiveness of adaptation (low transformation may be sufficient for some climate risks, and high transformation may be insufficient to offset others). Nevertheless, these components provide a systematic framework for tracking adaptation progress and assessing the state of adaptation-related responses. The 'high' categories across each component reflect more transformative scenarios. Methods are described in SM16.1.

	Transformative potential of adaptation		
Dimensions	**Low**	**Medium**	**High**
Overall	Adaptation is largely sporadic and consists of small adjustments to Business-As-Usual. Coordination and mainstreaming are limited and fragmented.	Adaptation is expanding and increasingly coordinated, including wider implementation and multi-level coordination.	Adaptation is widespread and implemented at or very near its full potential across multiple dimensions.
Depth	Adaptations are largely expansions of existing practices, with minimal change in underlying values, assumptions or norms.	Adaptations reflect a shift away from existing practices, norms or structures to some extent.	Adaptations reflect entirely new practices involving deep structural reform, complete change in mindset, major shifts in perceptions or values, and changing institutional or behavioural norms.
Scope	Adaptations are largely localised and fragmented, with *limited evidence* of coordination or mainstreaming across sectors, jurisdictions or levels of governance.	Adaptations affect wider geographic areas, multiple areas and sectors, or are mainstreamed and coordinated across multiple dimensions.	Adaptations are widespread and substantial, including most possible sectors, levels of governance, and actors.
Speed	Adaptations are implemented slowly.	Adaptations are implemented moderately quickly.	Change is considered rapid for a given context.
Limits	Adaptations may approach but do not exceed or substantively challenge soft limits.	Adaptations may overcome some soft limits but do not challenge or approach hard limits.	Adaptations exceed many soft limits and approach or challenge hard limits.

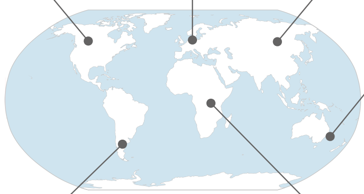
Evidence of transformative adaptation by sector and region

North America	Depth	Scope	Speed	Limits	Overall
Cities	**	**	**	**	**
Food	*	**	*	**	**
Health	*	**	*	**	**
Oceans/Coastal	*	**	**	**	**
Poverty	*	***	**	**	**
Terrestrial/Freshwater	*	**	**	**	**
Water and Sanitation	*	**	**	**	**

Europe	Depth	Scope	Speed	Limits	Overall
Cities	***	**	*	**	**
Food	***	**	*	***	**
Health	***	**	*	**	**
Oceans/Coastal	*	**	*	**	**
Poverty	**	**			*
Terrestrial/Freshwater	***	***	*	*	**
Water and Sanitation	**	*			*

Asia	Depth	Scope	Speed	Limits	Overall
Cities	***	**	*	***	**
Food	***	***	*	**	**
Health	**	**	*	**	**
Oceans/Coastal	*	*	*	**	*
Poverty	*	*		**	*
Terrestrial/Freshwater	***	**	**	**	**
Water and Sanitation	**	**	*	**	**

Small Island States	Depth	Scope	Speed	Limits	Overall
Cities	**	**	**	**	**
Food	**	**		**	**
Health	*	**	**	**	**
Oceans/Coastal	**	**	**	*	**
Poverty	**	**	*	**	**
Terrestrial/Freshwater	**	**		*	**
Water and Sanitation	**	**	*	*	**



Australasia	Depth	Scope	Speed	Limits	Overall
Cities	*	*			*
Food	**	**	**	**	**
Health	**	**	*	**	**
Oceans/Coastal	**	***	***	**	***
Poverty	**	*	**	**	**
Terrestrial/Freshwater					
Water and Sanitation	***	**	**	**	**

Cenral and South America	Depth	Scope	Speed	Limits	Overall
Cities	*	**	**	*	**
Food	*	***	**	**	**
Health	*	*	*	**	**
Oceans/Coastal	*	**	**	**	**
Poverty	*	*	*	**	*
Terrestrial/Freshwater	**	**	**	**	**
Water and Sanitation	**	**	**	**	**

Evidence of transformational adaptation
- High
- Medium
- Low

Confidence
- *** High
- ** Medium
- * Low

Insuficient information or very low confidence

Africa	Depth	Scope	Speed	Limits	Overall
Cities	***	**	**	**	**
Food	**	***	**	**	**
Health	**	***	**	**	**
Oceans/Coastal	**	***	**	**	**
Poverty	***	***	**	**	***
Terrestrial/Freshwater	**	**	**	**	**
Water and Sanitation	**	**	**	**	**

Figure 16.6 | Evidence of transformative adaptation by sector and region. Evidence of transformational adaptation does not imply effectiveness, equity or adequacy. Evidence of transformative adaptation is assessed based on the scope, speed, depth and ability to challenge limits of responses reported in the scientific literature (see Supplementary Material for methods). Studies relevant to multiple regions or sectors are included in assessment for each relevant sector/region.

numerous aspects of life. National policies are more likely to be broad in scope (Puthucherril et al., 2014), although they frequently focus on a single sector and are therefore still limited. The speed of adaptation is rarely noted explicitly, but the average speed documented in the literature is slow (*medium confidence*) (Cross-Chapter Box FEASIB in Chapter 18). Adaptation efforts frequently encounter either soft or hard limits (see Section 16.4), but there is *limited evidence* to suggest these limits are being challenged or overcome (*medium confidence*).

Few documented responses are simultaneously widespread, rapid and novel (*high confidence*). Some examples exist, such as village relocations or creation of new multi-stakeholder resource governance systems (Schwan and Yu, 2018; McMichael and Katonivualiku, 2020), but these are rare. In general, adaptations that are broad in scope tend to be slow (*medium confidence*), suggesting that achieving high transformation in all four categories (depth, scope, speed and limits) may be particularly challenging or even involve trade-offs.

16.3.2.5 Observed Maladaptation and Co-benefits

There is increasing reporting of maladaptation globally (Table 16.2, Section 17.5.1) (*high confidence*). Maladaptation has been particularly reported in the context of agricultural, forestry and fisheries practices, migration in the Global South, and some infrastructure-based interventions. Urban heat adaptations have been linked to maladaptation that increase health risks and/or energy consumption. Heat poses significant risks to the evolutionary tolerance levels of humans, animals and crops (Asseng et al., 2021), and current adaptation interventions for reducing urban heat like cool or evaporation roofs and street trees may be insufficient to reduce heat-related vulnerabilities in some urban areas at higher levels of warming (Krayenhoff et al., 2018) (see also Section 16.4 on adaptation limits). There is evidence that autonomous adaptation by individuals and households can shift risk to others, with net increases in vulnerability. Intensification of pasture use as a coping response to climate-induced drought has been observed to increase risks to livestock reproduction and human life expectancy due to overgrazing, suggesting responses to pastoral vulnerability can cross tolerance limits for animals, humans and food available for foraging (Suvdantsetseg et al., 2017).

Evidence on *realised* co-benefits of implemented adaptation responses with other priorities in the SDGs is emerging among the areas of poverty reduction, food security, health and well-being, terrestrial and freshwater ecosystem services, sustainable cities and communities, energy security, work and economic growth, and mitigation (Table 16.2) (*high confidence*). Evidence on co-benefits of adaptation for mitigation is particularly strong, and is observed in various agricultural, forestry and land use management practices like agroforestry, climate-smart agriculture and afforestation (Kremen and Miles, 2012; Christen and Dalgaard, 2013; Mbow et al., 2014; Locatelli et al., 2015; Suckall et al., 2015; Wichelns, 2016; Kongsager, 2018; Debray et al., 2019; Loboguerrero et al., 2019; Morecroft et al., 2019; Chausson et al., 2020) as well as in the urban built environment (Perrotti and Stremke, 2020; Sharifi, 2020). Evidence on co-benefits of implemented responses for other SDG priority areas is less developed, however, in the areas of education, gender inequality and reduced inequalities, clean water and sanitation, industry, innovation and infrastructure, consumption and production, marine and coastal ecosystem protection, and peace, justice, and strong institutions. This indicates a gap between some assumed likely co-benefits of adaptation and empirical evidence on the realisation of these co-benefits within the context of implemented adaptation responses (Berga, 2016; Froehlich et al., 2018; Gattuso et al., 2018; Morris et al., 2018; Chausson et al., 2020; Karlsson et al., 2020; Krauss and Osland, 2020).

16.3.3 Knowledge Gaps in Observed Responses

Many adaptation responses are not documented, and reporting bias is a key challenge for assessment of observed responses. Evidence of absence (i.e., where no adaptations are occurring) is different from absence of evidence (where responses are occurring but are not documented), with implications for understanding trends in global responses.

Table 16.2 | Observed examples of maladaptation and co-benefits from adaptation-related responses in human systems.

Implemented adaptations	Observed maladaptation	References
Agricultural and forestry practices		
Intensified cultivation of marginal lands: clearing of virgin forests for farmland; frequent weeding; poorly managed irrigation schemes; dependence on rainfed agriculture	Increased competition for resources such as water and nutrients; reduced soil fertility; invasive species; degraded environment; increased greenhouse gas emissions; reduced crops diversity and reduced harvest, thus increasing food insecurity in rural areas; accelerated illegal logging practices; increased vulnerability of herders, translated into poor health and working conditions (Mongolia)	Bele et al. (2014); D'haen et al. (2014); Chapman et al. (2016); Ifeanyi-obi et al. (2017); Suvdantsetseg et al. (2017); Villamayor-Tomas and Garcia-Lopez (2017); Afriyie et al. (2018); Ticehurst and Curtis (2018); Tran et al. (2018); Neset et al. (2019); Work et al. (2019); Yamba et al. (2019); Singh and Basu (2020)
Agroforestry systems	Higher water demand where trees were combined with crops and livestock; native trees replaced with non-indigenous trees; reduced resilience of certain plants (e.g., cocoa); degraded soil and water quality and accelerated environmental degradation in Africa and Asia (Pakistan, Nepal, India, China, Philippines)	Nordhagen and Pascual (2013); D'haen et al. (2014); Hoang et al. (2014); Ruiz-Mallen et al. (2015); Kibet et al. (2016); Chengappa et al. (2017); Haji and Legesse (2017); Abdulai et al. (2018); Antwi-Agyei et al. (2018); Mersha and van Laerhoven (2018); Ullah et al. (2018); Krishnamurthy et al. (2019)
Agricultural transitions: commercialisation of common property; market integration and sedentarisation of pastoralists; adoption and expansion of commercial crops	Soil degradation and high dependency on external inputs in South and Central America (El Salvador, Guatemala, Honduras, Nicaragua and Peru); dependency on foreign corporation seed systems; land enclosures; adaptation that forced local farmers in Costa Rica to switch crops to commercially viable products (e.g., from rice to sugar cane) impoverished the land by removing nutrients and affecting food security for smallholder farmers	Nordhagen and Pascual (2013); D'haen et al. (2014); Warner et al. (2015); Kibet et al. (2016); (Warner and Kuzdas, 2016); Haji and Legesse (2017); Antwi-Agyei et al. (2018); Mersha and van Laerhoven (2018); Krishnamurthy et al. (2019); Neset et al. (2019)
Proper, improper and increased use of agrochemicals, pesticides and fertilizers	Fertilizer and agrochemicals negatively affected soil quality and accelerated environmental degradation in several parts of Africa (Ghana, Nigeria) and Asia (Pakistan, Nepal, India, China, Philippines). In Europe (Sweden and Finland), there are concerns about the risk of pests and weeds developing immunity to pesticides, and drainage systems and rain transferred chemicals to other fields, thereby affecting arable land. In South and Central America (El Salvador, Guatemala, Honduras, Nicaragua and Peru), agrochemicals led to soil degradation, and high dependency on external input was reported. Loss of soil nutrients, increased GHG emissions (Sweden, Finland); high nitrate and phosphate concentration (Great Britain)	Postigo (2014); Rodriguez-Solorzano (2014); Fezzi et al. (2015); Sujakhu et al. (2016); Begum and Mahanta (2017); de Sousa et al. (2018); Tang et al. (2018); Yamba et al. (2019)

Implemented adaptations	Observed maladaptation	References
Tree planting	The lack of shaded trees increased vulnerability to landslides in areas where Robusta coffee was grown (Mexico); new tree species to cope with climate change increased sensitivity and displaced non-indigenous trees (India; Tanzania and Kenya); cocoa planted under shade trees had higher mortality rate and more stress (Ghana); eucalyptus trees planted to reduce soil erosion had high water demand (Pakistan); in certain urban areas, trees planted to provide shade damaged buildings during heavy storms	Benito-Garzon et al. (2013); Hoang et al. (2014); Ruiz Meza (2015); Chengappa et al. (2017); Abdulai et al. (2018); Ullah et al. (2018)
Fisheries and water management		
Increased fishing activity	Fishery depletion and exacerbated negative trends in the ecosystem that threatened fishermen's subsistence	Goulden et al. (2013); Mazur et al. (2013); Rodriguez-Solorzano (2014); Pershing et al. (2016); Kanda et al. (2017); Kihila (2018); Pinsky et al. (2018)
Shrimp farming	A driver of deforestation of mangroves in Bangladesh; imposes external cost on paddy farmers; salinity levels are relatively higher in paddy plots closer to shrimp ponds; coral mining increased vulnerability to flooding (in small islands in the Philippines)	Johnson et al. (2016); Jamero et al. (2017); Paprocki and Huq (2018); Sovacool (2018); Morshed et al. (2020)
Water irrigation infrastructure for agriculture; water desalination in response to water shortages	Increased land loss; redistributed risk among agrarian stakeholders; affected the rural poor (Cambodia; Costa Rica); uneven distribution of cost and benefits (USA–Mexico border); desalination plants to led disproportionately high cost for low-income water users	Barnett and O'Neill (2013); Olmstead (2014); Warner and Kuzdas (2016); Work et al. (2019)
Storage of large quantities of water in the home	Water rendered unsafe for drinking due contamination by faecal coliforms in Zimbabwe; drought-induced changes in water harvesting and storage increased breeding sites for mosquitoes (Australia); water storage facilities and tanks provided ideal breeding conditions for mosquitoes and flies, bringing both vectors and diseases closer to people (Ethiopia)	Boelee et al. (2013); Trewin et al. (2013); Kanda et al. (2017)
Increased number of farm dams for water storage; groundwater extraction and interbasin water transfers	Reduced river and ground water flow downstream; water grabs from shared surface or groundwater resources with poorly defined property rights shifted vulnerability to other groups and ecosystems (Cambodia; California): water extractions increased risks for the environment and food security, while transfers reduced hydropower generation and resulted in higher costs paid by electricity consumers and health impacts from air pollution caused by more electricity generation from natural gas (California); increase the concentration in the hands of the more powerful large farmers (Argentina)	Mazur et al. (2013); Christian-Smith et al. (2015); (Hurlbert and Mussetta, 2016); Work et al.)
Built environment		
Seawalls and infrastructural development along coastlines	Coastal erosion, beach losses, changes in water current, and destruction of natural ecosystems in Asia, Australasia, Europe and North America; increased or shifted erosion from protected to unprotected areas in Fiji, Marshall Islands, Nuie, Kiribati and Norway; failed or sped up flood waters and worsened conditions for riparian habitat and downstream residents; harmed nearby reefs and impeded autonomous adaptation practise that could be effective (Bangladesh)	Macintosh (2013); Maldonado et al. (2014); Porio (2014); Betzold (2015); Renaud et al. (2015); Gundersen et al. (2016); Sayers et al. (2018); Craig (2019); Javeline and Kijewski-Correa (2019); Loughran and Elliott (2019); Rahman and Hickey (2019); Piggott-McKellar et al. (2020); Simon et al. (2020) Dahl et al. (2017)
Smart or green luxury real estate development designed to reduce impacts from storm surges and erosion along coastal area; artificial islands	Redistributed risk and vulnerability; displaced and diminished adaptive capacity of vulnerable groups, created new population of landless peasants; negatively affected neighbouring coastal areas and local ecology (Lagos, Miami, Hanoi, Jakarta, Manila; Maldives)	Caprotti et al. (2015); Magnan et al. (2016); Atteridge and Remling (2018); Ajibade (2019); Salim et al. (2019); Thomas and Warner (2019)
Subsidised insurance premiums for properties located in flood-prone areas, levees, dykes	Rebuilding in risky areas	Shearer et al. (2014); O'Hare et al. (2016); Craig (2019); Loughran and Elliott (2019)
Autonomous flood strategies such as sandbags, digging channels and sand walls around homes	Sandbags used to reduce coastal erosion released plastics into the sea and led to loss of recreational value of beaches; sand walls shifted the flood impacts across space and time and were more detrimental to poor informal urban settlers (Dakar); caused erosion and degraded coastal lands (South Africa)	Schaer (2015); Wamsler and Brink (2015); (Chapman et al., 2016); Magnan et al. (2016); Mycoo (2018); Rahman and Hickey (2019)
Top-down technocratic adaptation with no consideration for ecosystem biodiversity, local adaptive capacity and gender issues	Ignored the complexities of the landscapes and socio-ecological systems; constrained autonomous adaptation due to time and labour demands of public work; increased gender vulnerability; hamper women's water rights (South Africa); altered local gender norms (Ethiopia); led to a mismatch that undermine local-level processes that are vital to local adaptive capacity (Rwanda)	Cartwright et al. (2013); Goulden et al. (2013); Nordhagen and Pascual (2013); Carr and Thompson (2014); Nyamadzawo et al. (2015); Ruiz-Mallen et al. (2015); Djoudi et al. (2016); Gautier et al. (2016); Gundersen et al. (2016); Barnett and McMichael (2018); Kihila (2018); Mersha and van Laerhoven (2018); Clay and King (2019); Currenti et al. (2019); Yang et al. (2019)

Implemented adaptations	Observed maladaptation	References
Migration and relocation		
Out-migration or rural-to-urban migration in response to food insecurity and agricultural livelihood depreciation	Migration mostly undertaken by poorer households weakened local subsistence production capacity; disrupted family structures; reduced labour available for agricultural work; increased burden of responsibilities on women; fostered loss of solidarity within communities; increased divorce rates; exacerbated conflicts among different groups; increased pressure on urban housing and social services; expanded slum settlements around riparian and coastal areas including flood plains and swamplands (Ethiopia, Namibia, Benin, Botswana, Nigeria, Ghana, Kenya, Niger, Mail, Tanzania, Zimbabwe, South Africa, Morocco, Nepal, Pakistan, Bangladesh China, India, Australia, Nicaragua); out-migration from small communities had devastating consequences on their fragile economies, thereby reducing community resilience in the long term (Australia)	Su et al. (2017);Aziz and Sadok (2015);Bhatta and Aggarwal (2016);Clay and King (2019); Elagib et al. (2017);Gao and Mills (2018); Kattumuri et al. (2017); Magnan et al. (2016); Ofoegbu et al. (2016); Rademacher-Schulz et al. (2014);Rademacher-Schulz et al. (2014);Wiederkehr et al. (2018); Yegbemey et al. (2017); Yila and Resurreccion (2013); Nizami et al. (2019); Mersha and Van Laerhoven (2016); Ojha et al. (2014); Radel et al. (2018); Gioli et al. (2014); Hooli (2016); Koubi et al. (2016)
Certain autonomous, forced and planned relocation Temporary resettlement (India)	Expansion of informal settlements in cities (Solomon Islands); relocation to areas prone to landslide and soil erosion or insufficient housing (Fiji); disproportionate burden on vulnerable communities (China); temporary relocation created gender inequality associated with minimal privacy; poor access to private toilets; sexual harassment; reduced sleep; insufficient or food rationing; exploitation and abuse of children (India); inadequate funding and governance mechanism for community-based relocation caused loss of culture, economic decline and health concerns (Alaska); relocation of supply chain to reduce exposure to climate change resulted in adverse outcomes for communities along the supply chain	Monnereau and Abraham (2013); Maldonado et al. (2014); Pritchard and Thielemans (2014); Averchenkova et al. (2016); Lei et al. (2017); Barnett and McMichael (2018); Currenti et al. (2019)
Agricultural practices		
Integrated agricultural practices (e.g., climate-smart agriculture, urban and peri-urban agriculture and forestry; agro-ecology; silvopasture; soil desalinisation; drainage improvement; integrated soil–crop system management; no tillage farming; rainwater harvesting; check dams)	Mitigation, especially carbon sequestration (but see Sommer et al., 2018); improved household equity regarding farming decisions, particularly inclusion of women; food security	Furman et al. (2014); Lwasa et al. (2014); Kibue et al. (2015); Nyasimi et al. (2017); Aryal et al. (2018); Han et al. (2018); Kakumanu et al. (2018); Sikka et al. (2018); Debray et al. (2019); Kerr et al. (2019); (Teklewold et al., 2019a); Teklewold et al. (2019b); Wang et al. (2020) Sommer et al. (2018)
Improved irrigation systems	Mitigation, especially avoided emissions; improved crop yields	Islam et al. (2020)
Conservation agriculture (e.g., crop diversification; soil conservation; cover cropping)	Mitigation, especially carbon sequestration; increased crop yields; food security; reduced heat and water stress; increased food security	Helling et al. (2015); Sapkota et al. (2015); Kimaro et al. (2016); Mainardi (2018); Asmare et al. (2019); Gonzalez-Sanchez et al. (2019)
Return to traditional farming practices	Mitigation, especially carbon sequestration	Pienkowski and Zbaraszewski (2019)
Place-specific practices and innovations: animal cross-breeding; direct crop seeding; site-specific nutrient management; irrigation innovations; use of riparian buffer strips; use of green winter land; rice–rice system	Mitigation, especially carbon sequestration; improved crop yields; food security	Sushant (2013); Balaji et al. (2015); Helling et al. (2015); Jorgensen and Termansen (2016); Sen and Bond (2017); Wilkes et al. (2017); Kakumanu et al. (2018); Mainardi (2018); Sikka et al. (2018) Yadav et al. (2020)
Land and water management		
Agroforestry	Mitigation, especially carbon sequestration; biodiversity and ecosystem conservation; improved food security; plant species diversification; diversification of household livelihoods; improved household incomes; improved access to forage material; energy access and reduced fuel wood gathering time and distance for women; soil and water conservation; aesthetic improvements in landscapes	Holler (2014); Suckall et al. (2015); Sharma et al. (2016); Nyasimi et al. (2017); Pandey et al. (2017); Schembergue et al. (2017); Ticktin et al. (2018); Debray et al. (2019); Jezeer et al. (2019); Krishnamurthy et al. (2019); Nyantakyi-Frimpong et al. (2019); Tschora and Cherubini (2020)
Afforestation and reforestation programs; forest management practices (e.g., tree thinning)	Mitigation, especially carbon sequestration; biodiversity and ecosystem conservation; new employment opportunities; diversification of household livelihoods; increased household incomes; improved access to fuel wood; harvesting opportunities from enclosures	Holler (2014); Etongo et al. (2015); Diederichs and Roberts (2016); Acevedo-Osorio et al. (2017); Nyasimi et al. (2017); Krishnamurthy et al. (2019); Rahman et al. (2019) Wolde et al. (2016)
Ecosystem-based adaptations such as mangrove restoration and natural coastal defences	Mitigation, especially carbon sequestration; habitat enhancement and protection for marine species; prevention of floor-related deaths, injuries and damage; improved nutrition and income generation for local communities, improved water quality	Fedele et al. (2018) Roberts et al. (2012); Morris et al. (2019); (Jones et al., 2020)

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Implemented adaptations	Observed maladaptation	References
Sustainable water management	Mitigation, especially avoided emissions; reduced water demand; increased awareness about impacts of water consumption; decreased incidence of faecal–oral disease transmission; decreased use of drinking water for irrigation; reduced soil loss; increased groundwater retention; increased vegetation cover; increased food security and health and well-being; increased forage for livestock and amount of cultivated area; enhanced recreational areas	Spencer et al. (2017); Siraw et al. (2018); Stanczuk-Galwiaczek et al. (2018)
Return to traditional land management practices (e.g., the Ngitili system)	Mitigation, especially carbon sequestration; increased water availability for household and livestock use; increase in presence of edible and medicinal plants; regional economic growth; reduced land management conflicts; increased household income and access to education for children; improved access to wood fuel and reduced collection time for women; improved wildlife habitat	Duguma et al. (2014)
REDD+ participation to maintain intact forest ecosystems	Mitigation, especially carbon sequestration; improved air quality; water and soil conservation; slowed rate of vector-borne disease; improved mental well-being associated with cultural continuity; clean water; nutritional and spiritual value of forest-derived foods; protection from violence related to natural resource extraction	McElwee et al. (2017); Spencer et al. (2017)
Urban planning and design		
Spatial planning—walkable neighbourhood design; strategic densification	Mitigation, particularly avoided emissions; public health—increases in physical activity, reductions in air pollution and urban heat island effect	Beiler et al. (2016); Belanger et al. (2016)
Urban greening (e.g., tree planting; construction of stormwater retention areas; construction of green roofs and cool roofs; provision of rainwater barrels; pervious pavement materials)	Mitigation, particularly avoided emissions; public health improvements—increases in physical activity, reductions in air and noise pollution, reduced urban heat island effect, improved mental health; urban flood risk management; water savings; energy savings	Samora-Arvela et al. (2017); Vahmani and Jones (2017); Newell et al. (2018); Alves et al. (2019); De la Sota et al. (2019)
Improved building efficiency standards	Mitigation, particularly avoided emissions; improved air quality; reduced urban heat island; improved natural indoor lighting	Barbosa et al. (2015); Koski and Siulagi (2016); Balaban and Puppim de Oliveira (2017); Landauer et al. (2019)
Use of local building materials	Mitigation, particularly avoided emissions	Lundgren-Kownacki et al. (2018)

Adaptation is being reported differently across different sources of knowledge. The peer-reviewed literature, for example, has been primarily reporting reactive adaptation at the individual, household and community levels, while the grey literature has been more mixed, reporting adaptation across governmental levels and civil society, with less focus on individuals and households (Ford et al., 2015a; Ford and King, 2015). Synthesis of impacts and responses within the private sector is particularly limited (Averchenkova et al., 2016; Minx et al., 2017), further suggesting that knowledge accumulation on climate responses has been particularly slow, and that more *robust evidence* synthesis is required to fill key knowledge gaps.

The potential for under-reporting is most acute in the context of minorities and remote and marginalised groups, who are often also the most affected by the impacts of climate change and least able to respond to, or benefit from, the responses to climate change (Araos et al., 2021). Deficits in reporting on impacts and responses are well recognised in the Global South, among vulnerable populations (e.g., women, socioeconomically disadvantaged, Indigenous, people living with disabilities) and within civil society (ibid.).

There is growing support for more comprehensive and systematic approaches to assess adaptation progress (Berrang-Ford et al., 2015; Ford et al., 2015a; Ford and King, 2015; Ford and Berrang-Ford, 2016; Biesbroek et al., 2018). Since the AR5, there is increased recognition of the value of integrating diverse knowledge sources to fill knowledge gaps in observation of impacts and responses (Chapter 17; Cross-Chapter Box PROGRESS in Chapter 17). Van Bavel, for example, found that the involvement of local and diverse knowledge can improve the detection (*medium confidence*) and attribution (*medium confidence*) of health impacts, and improve the action (*high confidence*) (Van Bavel et al., 2020).

A new development since AR5, there is now growing evidence assessing progress on adaptation across sectors, geographies and spatial scales. Uncertainty persists around what defines adaptation and how to measure it (Cross-Chapter Box FEASIB in Chapter 18, UNEP, 2021). As a result, most literature synthesising responses is based on documented or reported adaptations only, and is thus subject to substantial reporting bias.

We document implemented adaptation-related responses that could directly reduce risk. Adaptation *as a process* is more broadly covered in Chapter 17 (Section 17.4.2), including risk management, decision making, planning, feasibility (see Cross-Chapter Box FEASIB in Chapter 18), legislation and learning. Here, we focus on a subset of adaptation activities: adaptation-related responses of species, ecosystems, and human societies that have been implemented and observed, and could directly reduce risk. We consider all adaptation-related responses to assumed, perceived or expected climate risk, regardless of whether or not impacts or risks have been formally attributed to climate change.

We use the term 'adaptation-related responses', recognising that not all responses reduce risk. While 'adaptation' implies risk reduction, we use the broader term 'responses' to reflect that responses may decrease risk, but in some cases may increase risk.

Given *limited evidence* to inform comprehensive global assessment of effectiveness and adequacy, we assess evidence that adaptation responses in human systems indicate transformational change. Chapter 17 considers adaptation planning and governance, including adaptation solutions, success, and feasibility assessment (Cross-Chapter Box FEASIB in Chapter 18). It is not currently possible to conduct a comprehensive global assessment of effectiveness, adequacy or the contribution of adaptation-related responses to changing risk due to an absence of robust empirical literature (discussed further in Cross-Chapter Box PROGRESS in Chapter 17).

In natural ecosystems or species, detectable changes can be considered as 'impact' or 'response'. The distinction between 'observed impacts' (Section 16.2) and 'observed responses' (Section 16.3) is not always clear. For example, autonomous distributional shifts in wild species induced by increasing temperatures (an observed impact) may reduce risk to the species (an autonomous adaptation response), but this process can be enhanced or supported by human intervention such as intentional changes in land use. Observed autonomous changes in natural ecosystems or species unsupported by human intervention are treated as impacts (see Section 16.2).

Adaptation-related responses are frequently motivated by a combination of climatic and non-climatic drivers, and interact with other transitions to affect risk. For societal responses, it is difficult to say whether they are triggered by observed or anticipated changes in climate, by non-climatic drivers or, as is the case in many societal responses, by a combination of all three. In the case of impacts, assessment typically focuses on detection and attribution *vis à vis* a counterfactual of no climate change. While there has been some effort to attribute reduced climate risk to adaptation-related responses (Toloo et al., 2013a; Toloo et al., 2013b; Hess et al., 2018; Weinberger et al., 2018), in many cases this has not been feasible given difficulties in defining adaptation and empirically disentangling the contribution of intersecting social transitions and changing risks. Literature on adaptation-related response frequently draws on theories of change to assess the likely contribution of adaptations to changes in risk, including maladaptation and co-benefits.

Cross-Chapter Box INTEREG | Inter-regional Flows of Risks and Responses to Risk

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Introduction

Our world today is characterised by a high degree of interconnectedness and globalisation which establish pathways for the transmission of climate-related risks across sectors and borders (*high confidence*) (Challinor et al., 2018; Hedlund et al., 2018). While the IPCC 5th Assessment Report (AR5) has pointed to this connection of risks across regions as 'cross-regional phenomena' (Hewitson et al., 2014), only a few countries so far have integrated inter-regional aspects into their climate change risks assessments (Liverman, 2016; Surminski et al., 2016; Adams et al., 2020), and adaptation is still framed as a predominantly national or local issue (Dzebo and Stripple, 2015; Benzie and Persson, 2019).

Inter-regional risks from climate change—also called cross-border, transboundary, transnational or indirect risks—are risks that are transmitted across borders (e.g., transboundary water use) and/or via teleconnections (e.g., supply chains, global food markets) (Moser and Hart, 2015). The risks can result from impacts, including compound or concurrent impacts, that cascade across several tiers, in ways that either diminish or escalate risk within international systems (Carter et al., 2021). Risk transmission may occur through trade and finance networks, flows of people (Cross-Chapter Box MIGRATE in Chapter 7), biophysical flows (natural resources such as water) and ecosystem connections. However, not only risks are transmitted across borders and systems; the adaptation response may also reduce risks at the origin of the risk, along the transmission channel or at the recipient of the risk (Carter et al., 2021). This cross-chapter box discusses four inter-regional risk channels (trade, finance, food and ecosystems) and how adaptation can govern these risks.

Trade

Most commodities are traded on global markets, and supply chains have become increasingly globalised. For instance, specialised industrial commodities such as semiconductors are geographically concentrated in a few countries (Challinor et al., 2017; Liverman, 2016). When climatic events like flooding or heat affect the location of these extraction and production activities, economies are not only disrupted locally but also across borders and in distant countries (*high confidence*), as exemplified by the Thailand flood 2011 that led to a shortage of key inputs to the automotive and electronics industry not only in Thailand but also in Japan, Europe and the USA (Figure Cross-Chapter Box INTEREG.1). For many industrialised countries like the UK, Japan, the USA and the European Union, there is increasing evidence that the trade impacts of climate change are significant and can have substantial domestic impacts (*medium confidence*) (Nakano, 2017; Willner et al., 2018, Section 13.9.1; Benzie and Persson, 2019; Knittel et al., 2020). Enhanced trade can transmit risks across borders and thereby amplify damages (Wenz and Levermann, 2016), but it can also increase resilience (Lim-Camacho et al., 2017; Willner et al., 2018).

Cross-Chapter Box INTEREG (continued)

Figure Cross-Chapter Box INTEREG.1 | Inter-regional climate risks: the example of the trade transmission channel, illustrated for the Thailand flood 2011 (Abe and Ye, 2013; Haraguchi and Lall, 2015; Carter et al., 2021).

Finance

Climate risks can also spread through global financial markets (Mandel et al., 2021). For the case of coastal and riverine flooding with low adaptation 2080 (RCP 8.5-SSP5), the financial system is projected to amplify direct losses by a factor of 2 (global average), but reach up to a factor of 10 for countries that are central financial hubs (Mandel et al., 2021, Figure 13.28). Indirect impacts may also arise through indirect effects on foreign direct investment, remittance flows and official development assistance (Hedlund et al., 2018).

Cross-Chapter Box INTEREG (continued)

Food

The global supply of agricultural products is concentrated to a few main breadbaskets (Bren d'Amour et al., 2016; Gaupp et al., 2020, Chapter 5). For instance, Central and South America is one of the regions with the highest potential to increase food supplies to more densely populated regions in Asia, the Middle East and Europe (Chapter 12). The exports of agricultural commodities (coffee, bananas, sugar, soybean, corn, sugarcane, beef livestock) have gained importance in the past two decades as international trade and globalisation of markets have shaped the global agri-food system (Chapter 5).

The export of major food crops like wheat, maize and soybeans from many of the world's water-scarce area—the Middle East, North Africa, parts of South Asia, North China Plains, southwest USA, Australia—to relatively water-abundant parts of the world carries a high virtual water content (the net volume of water embedded in trade) (*high confidence*) (Hoekstra and Mekonnen, 2012; Dalin et al., 2017; Zhao et al., 2019, Chapter 4). Both importing and exporting countries are exposed to transboundary risk transmission through climate change impacts on distant water resources (Sartori et al., 2017; Zhao et al., 2019; Ercin et al., 2021). Climate change is projected to exacerbate risk and add new vulnerabilities for risk transmission (*medium confidence*). Rising atmospheric CO_2 concentration is projected to decrease water efficiency of growing maize and temperate cereal crops in parts of the USA, East and Mediterranean Europe, South Africa, Argentina, Australia and Southeast Asia, with important implications for future trade in food grains (Fader et al., 2010). By 2050 (SRES B2 scenario), virtual water importing countries in Africa and the Middle East may be exposed to imported water stress as they rely on imports of food grains from countries which have unsustainable water use (Sartori et al., 2017). Until 2100, virtual trade in irrigation water is projected to almost triple (for SSP2-RCP6.5 scenarios) and the direction of virtual water flows is projected to reverse, with the currently exporting regions like South Asia becoming importers of virtual water (Graham et al., 2020). An additional 10–120% trade flow from water-abundant regions to water-scarce regions will be needed to sustain environmental flow requirements on a global scale by the end of the century (Pastor et al., 2019). Exports of agricultural commodities contribute to deforestation, over-exploitation of natural resources and pollution, affecting the natural capital base and ecosystem services (Agarwala and Coyle, 2020; Rabin et al., 2020, Section 12.5.4).

Species and ecosystems

The spatial distributions of species on land and in the oceans are shifting due to climate change, with these changes projected to accelerate at higher levels of global warming (Pecl et al., 2017). These 'species on the move' have large effects on ecosystems and human well-being, and present challenges for governance (Pecl et al., 2017). For example, the number of transboundary fish stocks is projected to increase as key fisheries species are displaced by ocean warming (Pinsky et al., 2018). Conflict over shifting mackerel fisheries has already occurred between European countries (Spijkers and Boonstra, 2017), because few regulatory bodies have clear policies on shifting stocks; this leaves species open to unsustainable exploitation in new waters in the absence of regularly updated catch allocations to reflect changing stock distributions (Caddell, 2018).

Human health will also be affected as vector-borne diseases such as malaria and dengue shift geographic distributions (Caminade et al., 2014). There is also evidence that many warm-adapted invasive species, such as invasive freshwater cyanobacterium, have spread to higher latitudes because of climate change (Chapter 2).

Adaptation to inter-regional climate risks

Adaptation responses to reduce inter-regional risks can be implemented at a range of scales: at the point of the initial climate change impact (e.g., assistance for recovery after an extreme event, development of resilient infrastructure, climate-smart technologies for agriculture); at or along the pathway via which impacts are transmitted to the eventual recipient (e.g., trade diversification, re-routing of transport); in the recipient country (e.g., increasing storage to buffer supply disruptions), or by third parties (e.g., adaptation finance, technology transfer) (Bren d'Amour et al., 2016; Carter et al., 2021; Talebian et al., 2021). A knowledge gap exits on the need for, effectiveness of, and limits to adaptation under different socioeconomic and land use futures.

Due to regional and global interdependencies, climate resilience has a global, multi-level public good character (Banda, 2018). The benefits of adaptation are therefore shared beyond the places where adaptation is initially implemented. Conversely, adaptation may be successful at a local level while redistributing vulnerability elsewhere or even driving or exacerbating risks in other places (Atteridge and Remling, 2018). International cooperation is therefore needed to ensure that inter-regional effects are considered in adaptation and that adaptation efforts are coordinated to avoid maladaptation. However, regional- and global-scale governance of adaptation is only just beginning to emerge (Persson, 2019).

The United Nations Framework Convention on Climate Change (UNFCCC) Paris Agreement frames adaptation as a 'global challenge' (Article 7.2) and establishes the global goal on adaptation (Article 7.1), which provides space for dialogue between parties on the

Cross-Chapter Box INTEREG (continued)

global-scale challenge of adaptation and the need for renewed political and financial investment in adaptation, including to address inter-regional effects (Benzie et al., 2018).

National Adaptation Plans (NAPs) can evolve to consider inter-regional effects as well as domestic ones (Liverman, 2016; Surminski et al., 2016; European Environment, 2020). Regional and international coordination of NAPs, coupled with building capacities and addressing existing knowledge gaps at the country level, can help to ensure that resources are oriented towards reducing inter-regional risks and building systemic resilience to climate change globally (Booth et al., 2020; Wijenayake et al., 2020).

Given the important role of private actors in managing inter-regional climate risks (Goldstein et al., 2019; Tenggren et al., 2019), efforts will be needed to align public and private strategies for managing inter-regional climate risks to avoid maladaptation and ensure just and equitable adaptation at different scales (Talebian et al., 2021).

16.4 Synthesis of Limits to Adaptation across Natural and Human Systems

This section builds on previous IPCC Reports (i.e., AR5, SR15, SROCC, SRCCL) to advance concepts and emphasise remaining gaps in understanding about limits to adaptation. We provide case studies to illustrate these concepts and synthesise regional and sectoral limits to adaptation across natural and human systems that informs key risks (Section 16.5) and RFCs (Section 16.6). We also identify residual risks—risks that remain after efforts to reduce hazards, vulnerability and/or exposure—associated with limits to adaptation.

16.4.1 Definitions and Conceptual Advances since AR5

16.4.1.1 Limits to Adaptation since AR5

AR5 introduced the concept of limits to adaptation and provided a functional definition that has been used in subsequent Special Reports (SR15, SROCC, SRCCL) and is also used for AR6 (see also Chapter 1).

A limit is defined as the point at which an actor's objectives or system's needs cannot be secured from intolerable risks through adaptive actions (Klein et al., 2014). Tolerable risks are those where adaptation needed to keep risk within reasonable levels is possible, while intolerable risks are those where practicable or affordable adaptation options to avoid unreasonable risks are unavailable. This highlights that limits to adaptation are socially constructed and based on values that determine levels of reasonable or unreasonable risk as well as on available adaptation options, which vary greatly across and within societies.

Limits are categorised as being either 'soft' or 'hard'. Soft limits may change over time as additional adaptation options that are practicable or affordable become available. Hard limits will not change over time as no additional adaptive actions are possible. When a limit is exceeded, then intolerable risk may materialise and the actor's objectives or system's needs may be either abandoned or transformed (Box 16.2).

For human systems, soft and hard limits are largely distinguished by whether or not constraints to adaptation are able to be overcome. Constraints to adaptation (also called barriers) are factors that make it harder to plan and implement adaptation actions, such as limited financial resources, ineffective institutional arrangements or insufficient human capacity. Soft limits are mostly associated with human systems, due in part to the role of human agency in addressing constraints. For natural systems, the magnitude and rate of climate change and capacity of adaptation to such change largely determine the type of limit. Hard limits are largely associated with natural systems and are mostly due to inability to adapt to biophysical changes.

Using this understanding of limits, subsequent Special Reports have assessed relevant literature (Mechler et al., 2020). SR15 identifies several regions, sectors and ecosystems—including coral reefs, biodiversity, human health, coastal livelihoods, Small Island Developing States, and the Arctic—that are projected to experience limits at either 1.5°C or 2°C. SRCCL states that land degradation due to climate change may result in limits to adaptation being reached in coastal regions and areas affected by thawing permafrost. SROCC details that risks of climate-related changes in the ocean and cryosphere may result in limits for ecosystems and vulnerable communities in coral reef environments, urban atoll islands and low-lying Arctic locations before the end of this century in case of high-emissions scenarios.

A key area of advancement since AR5 is how incremental adaptation and transformational adaptation relate to limits to adaptation. Incremental adaptation maintains 'the essence and integrity of a system or process at a given scale', while transformational adaptation 'changes the fundamental attributes of a social-ecological system' (IPCC, 2018b). Both incremental and transformational adaptation may expand the adaptive possibilities for a system, providing additional adaptation options after a system reaches a soft limit (Felgenhauer, 2015; Pelling et al., 2015; Termeer et al., 2017, see also Chapters 1 and 17; Alston et al., 2018; Panda, 2018; Mechler and Deubelli, 2021). However, it is critical to note that adaptation, whether incremental or transformational, must support securing an actor's objectives or system's needs from intolerable risks. Once objectives or needs have been abandoned or transformed, a limit to adaptation has occurred. However, objectives or needs may change over time as values of a society change (Taebi et al., 2020), thus adding further complexity to assessing limits to adaptation.

16.4.1.2 Residual Risk since AR5

The term 'residual risk' was not assessed in detail in AR5 and was used interchangeably with other terms, including 'residual impacts', 'residual loss and damage' and 'residual damage'. SR15 includes discussion of residual risks without an explicit definition and relates these to L oss and D amage and limits to adaptation, concluding that residual risks rise as global temperatures increase from 1.5°C to 2°C. SRCCL refers to residual risks arising from limits to adaptation related to land management. Such residual risk can emerge from irreversible forms of land degradation, such as coastal erosion when land completely disappears, collapse of infrastructure due to thawing of permafrost, and extreme forms of soil erosion. SROCC advanced the conceptualisation of residual risk and integrated it within the risk framework, defining residual risk as the risk that remains after actions have been taken to reduce hazards, exposure and/or vulnerability. Residual risk is therefore generally higher where adaptation failure, insufficient adaptation or limits to adaptation occur. We use the SROCC definition of residual risk for our assessment in the following sections and identify residual risks that are associated with limits to adaptation.

16.4.2 Insights from Regions and Sectors about Limits to Adaptation

Here we provide example case studies to highlight constraints that may lead to soft limits, potential incremental and transformational adaptation options that may overcome soft limits, evidence of hard limits, and residual risks.

16.4.2.1 Small Island Developing States

An expanding volume of empirical research highlights existing adaptation constraints that may lead to soft limits in Small Island Developing States (SIDS). Investigation of national communications among 19 SIDS found that financial constraints, institutional challenges and poor resource endowments were the most frequently reported as inhibiting adaptation for a range of climate impacts (Robinson, 2018b). Governance, financial and information constraints such as unclear property rights and lack of donor flexibility have led to hasty implementation of adaptation projects in Kiribati, whereas in Vanuatu and the Solomon Islands, limited awareness of rural adaptation needs and weak linkages between central governance and local communities have resulted in an urban bias in resource allocation (Kuruppu and Willie, 2015). Limited availability and use of information and technology also present constraints to adaptation; many SIDS suffer from lack of data and established routines to identify losses and damages, and the combination of poor monitoring of slow-onset changes and influence of non-climatic determinants of observed impacts challenges attribution (Thomas and Benjamin, 2018). The fact that climate information is often available only in the English language represents another common constraint for island communities (Betzold, 2015). Although Indigenous and local knowledge systems can provide important experience-based input to adaptation policies (Miyan et al., 2017), socio-cultural values and traditions such as attachment to place, religious beliefs and traditions can also constrain adaptation in island communities, particularly for more transformational forms of adaptation (Ha'apio et al., 2018; Oakes, 2019).

Box 16.2 | Linking Adaptation Constraints, Soft and Hard Limits

McNamara et al. (2017) provides an example of community-scaled adaptation that highlights how constraints affect limits, the relationship between soft and hard limits, and the potential need to abandon or transform objectives. Community members of Boigu Island, Australia, are already adapting to perceived climate change hazards—including sea level rise and coastal erosion—to secure their objective of sustaining livelihoods and way of life in their current location. Existing seawall and drainage systems provide inadequate protection from flooding during high tides, leading residents to elevate their houses to prevent damages. However, these adaptation measures have proved to be insufficient. Standing saltwater for extended periods of time after floods has resulted in losses and damages, including erosion of infrastructure, increased soil salinity, and heightened public health concerns. Additional adaptation efforts are constrained by scarcity of elevated land, which inhibits movement of infrastructure within the community, and lack of financial, technical and human assets to improve coastal protection measures.

These constraints are leading to a soft limit to adaptation, where risks would become unreasonable as sea levels continue to rise and practicable and affordable adaptation options are limited to currently available approaches. This soft limit could be overcome through addressing constraints and allowing further adaptation to take place, such as providing financial, technical and human resources for more effective coastal protection and drainage systems that would reduce flooding. However, if the effectiveness of these new adaptation measures decreases as sea levels rise further and if constraints are not able to be overcome, another soft limit may be reached. Eventually, if constraints are not addressed, no further adaptation measures are implemented, and climate hazards intensify, the area could become uninhabitable. This would then be a hard limit for adaptation; there would be no adaptation options available that would allow the community to sustain livelihoods and way of life in its present location. This hard limit to adaptation may necessitate abandoning the objective of remaining in the community. The objective of the community may then transform to sustaining their livelihoods in a less vulnerable location, which would necessitate relocation. However, such transformation of the community's objectives may be hindered by the expressed resistance of residents to migrate, due to their strong sense of place.

Soft limits to adaptation for coastal flooding and erosion are already being experienced in Samoa owing largely to financial, physical and technological constraints (Crichton and Esteban, 2018). While sea walls have been erected to minimise coastal erosion, these defences need regular upgrading and replacement as high swells, tropical cyclones and constant wave action erode their effectiveness. The high costs of installing, upgrading and enlarging such infrastructure has led to sea walls only being used in specific locations, leaving communities that are beyond the extent of these measures exposed to inundation and erosion. Native tree replanting has also been implemented, but coastal flooding and erosion persist as large swells lead to high failure rates of replanting efforts. Across SIDS, adaptation to coastal flooding and erosion in particular is increasingly facing soft limits due to high costs, unavailability of technological options and limited physical space or environmental suitability for hard engineering or ecosystem-based approaches (Mackey and Ware, 2018; Nalau et al., 2018).

Retreat and relocation constitute transformative adaptation options, although evidence of permanent community-scale relocation in response to climate change remains limited at present (Kelman, 2015; McNamara and Des Combes, 2015). Material and emotional cost of emigration as well as loss of homeland, nationhood, and other intangible assets and values imply that relocation is generally considered a last resort (Jamero et al., 2017) and may mean abandoning objectives of remaining in existing locations, hence exceeding adaptation limits.

Hard limits in SIDS are mostly due to adaptation being unable to prevent intolerable risks from escalating climate hazards such as SLR and related risks of flooding and surges, severe tropical cyclones, and contamination of groundwater. Emerging evidence suggests that shortage of water and land degradation have already contributed to migration of multiple island communities in the Pacific (Handmer and Nalau, 2019).

Residual risks for SIDS include loss of marine and terrestrial biodiversity and ecosystem services, increased food and water insecurity, destruction of settlements and infrastructure, loss of cultural resources and heritage, collapse of economies and livelihoods, and reduced habitability of islands (Section 3.5.1, Section 15.3).

16.4.2.2 Agriculture in Asia

Lack of financial resources is found to be a significant constraint that contributes to soft limits to adaptation in agriculture across Asia. Although smallholder farmers are currently adapting to climate impacts, lack of finance and access to credit prevents upscaling of adaptive responses and has led to losses (Bauer, 2013; Patnaik and Narayanan, 2015; Bhatta and Aggarwal, 2016; Loria, 2016). Other constraints further contribute to soft limits, including governance and associated institutional factors such as ineffective agricultural policies and organisational capacities (Tun Oo et al., 2017), information and technology challenges such as limited availability and access to technologies on the ground (Singh et al., 2018), socio-cultural factors such as the social acceptability of adaptation measures that are affected by gender (Huyer, 2016; Ravera et al., 2016), and limited human capacity (Masud et al., 2017). A wide range of pests and pathogens are predicted to become problematic to regional food crop production as average global temperatures rise (Deutsch et al., 2018), increasing crop loss across Asia for which farmers are already experiencing a variety of adaptation constraints, including financial, economic and technological challenges (Sada et al., 2014; Tun Oo et al., 2017; Fahad and Wang, 2018). Extreme heatwaves are projected in the densely populated agricultural regions of South Asia, leading to increased risk of heat stress for farmers and resultant constraints on their ability to implement adaptive actions (Im et al., 2017). However, socioeconomic constraints appear to have a higher influence on soft limits to adaptation in agriculture than biophysical constraints (Thomas et al., 2021). For example, an examination of farmers' adaptation to climate change in Turkey found that constraints related to access to climate information and access to credit will likely limit the yield benefits of incremental adaptation (Karapinar and Özertan, 2020). In Nepal, conservation policies restrict traditional grazing inside national parks, which promotes intensive agriculture and limits other cropping systems that have been implemented as climate change adaptation (Aryal et al., 2014).

In Bangladesh, small and landless farm households are already approaching soft limits in adapting to riverbank erosion (Alam et al., 2018). While wealthier farming households can implement a range of adaptation responses, including changing planting times and cultivating different crops, poorer households have limited access to financial institutions and credit to implement such measures. Their adaptation responses of shifting to homestead gardening and animal rearing are insufficient to maintain their livelihoods, and these households are more likely to engage in off-farm work or migrate.

Palao et al.. (2019) identify the possible need for transformational adaptation in Asian-Pacific agricultural practices due to changes in biophysical parameters as global average temperatures rise. In this context, transformational adaptation would consist of changing farming locations to different provinces or different elevations for the production of specific crops or introducing new farming systems. Nearly 50% of maize in the region along with 18% of potato and 8% of rice crops would need to either be shifted in location or use new cropping systems, with the most significant transformation being needed in China, India, Myanmar and the Philippines. For maize suitability by 2030, seven provinces in the east and northeast of China are projected to experience over 50% reduction in suitability, and two northern states in India may experience 70% reduction in suitability. Cassava and sweet potato may play a critical role in food resilience in these areas, as these crops are more resilient to climate change (Prain and Naziri, 2019).

In terms of hard limits, the rate and extent of climate change is critical as agriculture is climate-dependent and sensitive to changes in climate parameters. Poudel and Duex (2017) document that over 70% of the springs used as water sources in Nepalese mountain agricultural communities had a decreased flow, and approximately 12% had dried up over the past decade. While there are some adaptation measures to address reduced water availability—such as the introduction of water-saving irrigation technology among Beijing farmers to alleviate water scarcity in metropolitan suburbs (Zhang et al., 2019)—these actions still depend on some level of water availability. If climate hazards intensify to the point where water supply cannot meet agricultural demands, hard limits to adaptation will occur.

Residual risks associated with agriculture in Asia include declines in fisheries, aquaculture and crop production, particularly in South and Southeast Asia (Section 10.3.5), increased food insecurity (Section 10.4.5), reductions of farmers' incomes by up to 25% (Section 10.4.5), loss of production areas (Section 10.4.5) and reduced physical work capacity for farmers—between 5% and 15% decline in south-southwest Asia and China under RCP8.5 (Section 5.12.4).

16.4.2.3 Livelihoods in Africa

For livelihoods dependent on small-scale rain-fed agriculture in Africa, climate hazards include floods and droughts. However, governance, financial and information/awareness/technology challenges are identified as the most significant constraints leading to soft limits, followed by social and human capacity constraints (Thomas et al., 2021). Finance and land tenure constraints restrict Ghanaian farmers when considering adaptation responses due to climate variability (Guodaar et al., 2017). Similarly, in East Africa, farmers with small pieces of land have limited economic profitability, making it difficult to invest in drought and/or flood management measures (Gbegbelegbe et al., 2018).

Increasing droughts and floods require costlier adaptation responses to reduce risks, such as using drought-tolerant species (Berhanu and Beyene, 2015) and coping strategies for flood-prone households (Schaer, 2015; Musyoki et al., 2016), resulting in soft limits for poorer households who cannot afford these responses. In Namibia, weak governance and poor integration of information, such as disregarding knowledge of urban and rural residents in flood management strategies, has resulted in soft limits to adaptation, leading to temporary or permanent relocation of communities (Hooli, 2016). Shortage of land—namely high population pressure and small per capita land holding—leads to continuous cultivation and results in poor soil fertility. This low productivity is further aggravated by erratic rainfall causing soft limits as farmers cannot produce enough and must depend on food aid (Asfaw et al., 2019).

Relocation due to flooding is discussed as a transformation adaptation action taken in Botswana where the government decided to permanently relocate hundreds of residents to a nearby dryland area (Shinn et al., 2014). Some residents permanently relocated, whereas others only temporarily relocated against the government's instructions. Such relocation processes must attend to micro-politics and risks of existing systemic issues of inequality and vulnerability.

In terms of hard limits, land scarcity poses a hard limit when implementing organic cotton production, an adaptation response supporting sustainable livelihoods (Kloos and Renaud, 2014).

Residual risks associated with livelihoods in Africa include poorer households becoming trapped in cycles of poverty (Section 9.9.3), increased rates of rural–urban migration (Section 9.8.4), decline of traditional livelihoods such as in agriculture (Sections 9.9.3, 9.11.3.1) and fisheries (Section 9.11.1.2), and loss of traditional practices and cultural heritage (Section 9.9.2).

16.4.3 Regional and Sectoral Synthesis of Limits to Adaptation

16.4.3.1 Evidence on Limits to Adaptation

There is *high agreement* and *medium evidence* that there are limits to adaptation across regions and sectors. However, much of the available evidence focuses on constraints that may lead to limits at some point with little detailed information on how limits may be related to different levels of socioeconomic or environmental change (*high confidence*). Figure 16.7 assesses evidence on constraints and limits for broad categories of region and sector. Small islands and Central and South America show most evidence of constraints being linked to adaptation limits across sectors, while ocean and coastal ecosystems and health, well-being and communities show most evidence of constraints being linked to limits across regions (*medium confidence*).

There are clusters of evidence with additional details on limits to adaptation, as detailed in Table 16.3. Evidence on limits to adaptation is largely focused on terrestrial and aquatic species and ecosystems, coastal communities, water security, agricultural production, and human health and heat (*high confidence*).

Beginning at 1.5°C, autonomous and evolutionary adaptation responses by terrestrial and aquatic species and ecosystems face hard limits, resulting in biodiversity decline, species extinction and loss of related livelihoods (*high confidence*). Interventionist adaptation strategies to reduce risks for species and ecosystems face soft limits due to governance, financial and knowledge constraints (*medium confidence*).

As sea levels rise and extreme events intensify, coastal communities face soft limits due to financial, institutional and socioeconomic constraints reducing the efficacy of coastal protection and accommodation approaches and resulting in loss of life and economic damages (*medium confidence*). Hard limits for coastal communities reliant on nature-based coastal protection will be experienced beginning at 1.5°C (*medium confidence*).

Beginning at 3°C, hard limits are projected for water management measures, leading to decreased water quality and availability, negative impacts on health and well-being, economic losses in water and energy dependent sectors and potential migration of communities (*medium confidence*).

Soft and hard limits for agricultural production are related to water availability and the uptake and effectiveness of climate-resilient crops, which is constrained by socioeconomic and political challenges (*medium confidence*).

Adaptation measures to address risks of heat stress, heat mortality and reduced capacities for outdoor work for humans face soft and hard limits across regions beginning at 1.5°C and are particularly relevant for regions with warm climates (*high confidence*).

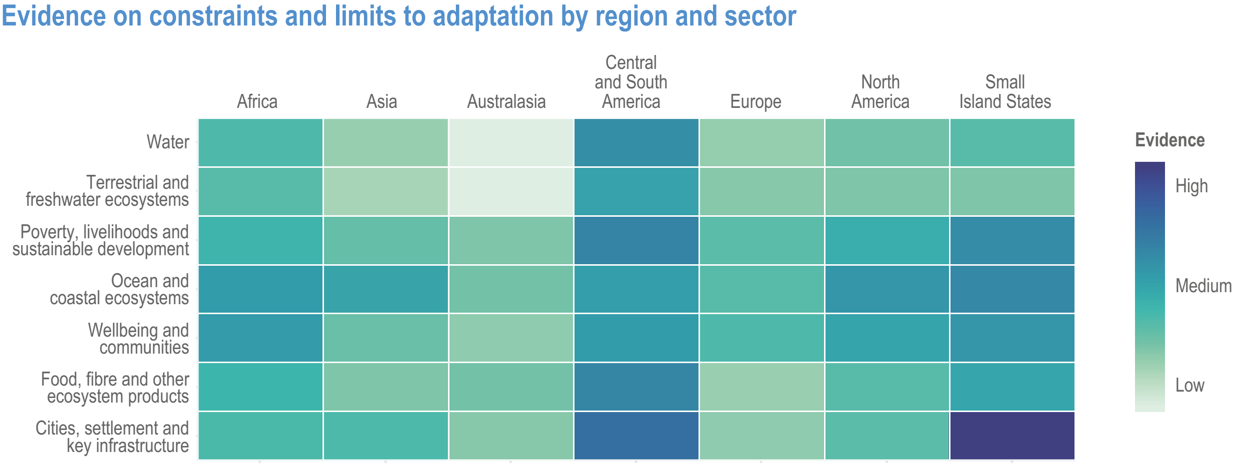

Figure 16.7 | Evidence on constraints and limits to adaptation by region and sector. Data from Thomas et al. (2021), based on 1682 scientific publications reporting on adaptation-related responses in human systems. See SM16.1 for methods. **Low evidence:** <20% of assessed literature has information on limits; literature mostly focuses on constraints to adaptation. **Medium evidence:** between 20% and 40% of assessed literature has information on limits; literature provides some evidence of constraints being linked to limits. **High evidence:** >40% of assessed literature has information on limits; literature provides broad evidence of constraints being linked to limits.

16.4.3.2 Constraints Leading to Limits to Adaptation

Across regions and sectors, a range of constraints (Figure 16.8) are identified as leading to limits to adaptation, particularly financial constraints and constraints related to governance, institutions and policy (*high confidence*). While individual constraints may appear straightforward to address, the combination of constraints interacting with each other leads to soft limits that are difficult to overcome (*high confidence*). The interplay of many different constraints that lead to limits makes it difficult to categorise limits beyond being either soft or hard.

16.4.3.3 Climate Change Impacts, Financial Constraints and Limits to Adaptation

Across regions and sectors, financial constraints are identified as significant and contributing to limits to adaptation, particularly in low-to-middle-income countries (*high confidence*) (Sections 3.6.3, 4.7.2, 5.14.3, 6.4.5, 7.4.2, 8.4.5, 12.5.1, 12.5.2, 15.6.1, 15.6.3, Figure 16.8, Table 16.4, Section CCP2.4.2). Impacts of climate change may increase financial constraints (*high confidence*) and contribute to soft limits to adaptation being reached (*medium confidence*). Table 16.5 details climate impact observations that point to potentially substantial negative impacts on the availability of financial resources for different regions.

At the national level, negative macroeconomic responses to climate change may limit the availability of financial resources, impede access to financial markets and stunt economic growth (*high confidence*). Economic growth has been shown to decline under higher temperatures (Burke et al., 2015; Kahn et al., 2019, Section 16.5.2.3.4) and following extreme events (Hsiang and Jina, 2014; IMF, 2017), particularly for medium- and low-income developing countries (Section 18.1). The most severe impacts of climate-related disasters on economic growth per capita have been observed in developing countries, although authors note a publication bias in the reporting of negative effects

Table 16.3 | Adaptation limits and residual risks for select actors and systems. Asterisks indicate confidence level

Actor/system at risk	Adaptation limits	Residual risks
Terrestrial species in islands at risk to loss of habitat	Hard: autonomous adaptation unable to overcome loss of habitat and lack of physical space ([c]) (Box CCP1.1)	Biodiversity decline, local extinctions, half of all species currently considered to be at risk of extinction occur on islands (Box CCP 1.1)
Terrestrial species across Africa at risk to habitat changes	Hard: beyond 2°C, many species will lack suitable climate conditions by 2100 despite migration and dispersal ([c]) (Section 9.6.4.1)	9% of species face complete range loss ([a]), mountaintop endemics and species at poleward boundaries of African continent at risk of range loss due to disappearing cold climates ([c]) (Section 9.6.4.1)
African aquatic organisms at risk to habitat changes	Hard: thermal changes above optimal physiological limits will reduce available habitats (Section 9.6.2.4)	Greater risks of loss of endemic fish species than generalist fish species (Section 9.6.2.4)
African coastal and marine ecosystems at risk to habitat changes	Hard: at 2°C, bleaching of east African coral reefs ([c]) (Section 9.6.2.3)	Over 90% of east African coral reefs destroyed at 2°C ([c]) (Section 9.6.2.3)
Coral reefs at risk to oceanic changes	Hard: coral restoration and management no longer effective after 2°C ([c]), enhanced coal and reef shading no longer effective after 3°C ([b]) (Figure 3.23)	Loss of more than 80% of healthy coral cover, loss of livelihoods dependent on coral reefs ([c]) (Figure 3.23, Table 8.7)
Cold-adapted species whose habitats are restricted to polar and high mountaintop areas at risk to loss of climate space	Hard: evolutionary responses unable to keep pace with the rate of climate change and degraded state of ecosystems (Sections 2.6.1, CCP1.2.4.2)	Species extinctions in the case of species losing their climate space entirely on a regional or global scale (Sections 2.6.1, CCP1.2.4.2)

Actor/system at risk	Adaptation limits	Residual risks
Ecosystems in North America at risk to multiple climate hazards	Soft: governance constraints hinder implementation of adaptation strategies Hard: some species unable to adapt (Table 14.8)	
Ecosystems and species at risk to multiple climate hazards	Soft: financial and knowledge constraints lead to limits for interventionist approaches such as translocation of species or ecosystem restoration Hard: some habitats unable to be effectively restored (Section 2.6.6)	Species extinctions and changes, irreversible major biome shifts (Section 2.6.6)
Coastal settlements in Australia and New Zealand at risk to sea level rise	Soft and hard: limits in the efficacy of coastal protection and accommodation approaches as sea levels rise and extreme events intensify (Box 11.5)	With 1–1.1 m of sea level rise, value of coastal urban infrastructure at risk in Australia is AUD 164 to >226 billion, while in NZ it is NZD 43 billion. Sea level rise will also result in significant cultural and archaeological sites disturbed and increasing flood risk and water insecurity with health and well-being impacts on Australia's small northern islands (Box 11.5)
Human settlements in coastal areas in the 1-in-100-year floodplain at risk to coastal flooding	Soft: socioeconomic, institutional and financial constraints may lead to soft limits well in advance of technical limits of hard engineering measures (Sections CCP 2.3.2, CCP2.3.4) Hard: Nature-based measures (e.g., restoration of coral reefs, mangroves, marshes) reach hard limits beginning at 1.5°C of global warming. Retreat strategies reach hard limits as availability and affordability of land decreases (CCPs 2.3.2.3, 2.3.5)	At 3°C, globally up to 510 million people and up to USD 12,739 billion in assets at risk by 2100 (Section CCP 2.2.1)
Communities in small islands at risk to freshwater shortages	Hard: domestic freshwater resources unable to recover from increased drought, sea level rise and decreased precipitation by 2030 (RCP8.5+ ice sheet collapse), 2040 (RCP8.5) or 2060 (RCP4.5) (Box 4.2, Section 4.7.2)	Migration of communities due to water shortages with impacts on well-being, community cohesion, livelihoods and people–land relationships (Box 4.2)
Communities in North America at risk to poor water quality	Soft: financial and technological constraints lead to limits in ability to treat water for harmful algal blooms (Table 14.8)	
Communities in Western and Central Europe at risk to water shortages	Hard: at 3°C, geophysical and technological limits reached in Southern Europe (Section 13.10.3.3)	At 3°C, two-thirds of the population of Southern Europe at risk to water security with significant economic losses in water- and energy-dependent sectors (b) (Sections 13.2.2, 13.6, 13.10.2.3)
Communities in Central and South America at risk to water shortages	Soft: improved water management as an adaptation strategy unable to overcome lack of trust and stakeholder flexibility, unequal power relations and reduced social learning (Section 12.5.3.4)	Increasing competition and conflict associated with high economic losses (b); glacier shrinkage leading to loss of related livelihoods and cultural values (Section 12.5.3.1, Table 8.7)
Agricultural production in Europe at risk to heat and drought	Soft: above 3°C, unavailability of water will limit irrigation as an adaptation response (c) (Sections 13.5.1, 13.10.2.2)	At 3–4°C, yield losses for maize may reach up to 50% (b) (Sections 13.5.1, 13.10.2.2)
Crops at risk to temperature increase	Soft: socioeconomic and political constraints limit uptake of climate-resilient crops (Section 5.4.4.3) Hard: after 2°C, cultivar changes unable to offset global production losses (Section 5.4.4.1)	Costs of adaptation and residual damages are USD 63 billion at 1.5°C. USD 80 billion at 2°C and USD 128 billion at 3°C, with greater risks and damages in tropical and arid regions (Section 5.4.4.1)
Human health in Europe at risk to heat	Soft: many adaptation measures will not be able to fully mitigate overheating in buildings with high levels of global warming (c) (Section 13.6.2.3) Hard: above 3°C, people and health systems unable to adapt (c) (Sections 13.6.2.3, 13.7.2, 13.7.4, 13.10.2.1, 13.8)	At 1.5°C, 30,000 annual deaths due to extreme heat with up to 90,000 annual deaths at 3°C in 2100 (c) (Section 13.7.1); at 3°C, thermal comfort hours during summer will decrease by as much as 74% in locations in southern Europe (c) (Section 13.6.1.5)
Human health at risk to heat	Soft: socioeconomic constraints limit adaptation responses to extreme heat (Section 7.4.2.6, Table 8.7)	Globally, the impact of projected climate change on temperature-related mortality is expected to be a net increase under RCP4.5 to RCP8.5, even with adaptation, particularly for regions with warm climates (d) (Section 7.3.1, Table 8.7)
South Asian settlements at risk to coastal flooding, drought, sea level rise and heatwaves	Soft and hard: at 4.5°C, maximum temperature is expected to exceed survivability threshGold across most of South Asia, particularly relevant for outdoor work (a) (Table 10.6)	At RCP4.5, 25–50% of population affected; at RCP8.5, more than 50% of population affected; at 4.5°C of warming, increase in heat-related deaths of 12.7% in South Asia (a) (Table 10.6)
Tourism in Europe reliant on snow at risk to higher levels of warming	Soft: at 3°C, snowmaking as an adaptation measure limited by biophysical and financial constraints (c) (Sections 13.6.1.4, 13.6.2.3)	Damages in European tourism with larger losses in Southern Europe (c) (Section 13.6.1.4)
Rapidly growing towns/cities and smaller cities at risk to range of climate hazards	Soft: governance and financial constraints lead to limits in ability to adapt (Sections 6.3, 6.4)	

Notes:
(a) *low confidence*
(b) *medium confidence*
(c) *high confidence*
(d) *very high confidence.*

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(Klomp and Valckx, 2014). Substantial immediate output losses and reduced economic growth due to extreme events have been observed in both the short and long term (Section 16.2.3). Estimates of the duration of negative effects of climate-related disasters differ, with some analyses suggesting that, on average, economies recover after 2 years (Klomp, 2016) and others finding negative effects of cyclones to persist 15–20 years following an event (Hsiang and Jina, 2014; IMF, 2017). Rising climate vulnerability has also been shown to increase the cost of debt (Kling et al., 2018). Rising climatic risks negatively affect developing countries' ability to access financial markets (Cevik and Jalles, 2020), and their disclosure may result in capital flight (Cross-Chapter Box FINANCE in Chapter 17). Overall, the direct and indirect economic effects of climate change represent a major risk to financial system stability (Section 11.5.2). These risks and effects may further limit the availability of financial resources needed to overcome constraints, in particular for developing countries.

Sectoral studies indicate that climate impacts will result in higher levels of losses and damages and decreases in income, thereby increasing financial constraints (*medium confidence*). Yield losses for major agricultural crops are expected in nearly all world regions (Figure 5.7). Decreases in estimated marine fish catch potential and large economic impacts from ocean acidification are expected globally, leading to the risk of revenue loss (Section 5.8.3). Losses of primary productivity and farmed species of shellfish are expected in tropical and subtropical regions (Section 5.9.3.2.2). Economic losses have been observed in the power generation sector and transport infrastructure (Section 10.4.6.3.8), including economic losses from floods in urban areas (Section 4.2.4.5). However, some positive sectoral climate change impacts have been identified for the timber and forestry sector (Section 5.6.2), for primary productivity and farmed species of shellfish in high-latitude regions (Section 5.9.3.2.2) and for agriculture in high-latitude regions (Section 5.4.1.1).

At the household or community level, climate impacts may increase financial constraints (*high confidence*). Impacts on agriculture and food prices could force between 3 and 16 million people into extreme poverty (Hallegatte and Rozenberg, 2017). Within-country inequality is expected to increase following extreme weather events (Section 16.2.3.6 and Chapter 8). Households affected by climate-related extreme events may be faced with continuous reconstruction efforts following extreme events (Adelekan and Fregene, 2015) or declines in critical livelihood resources in the agriculture, fisheries and tourism sectors (Forster et al., 2014, Section 3.5.1). Further erosion of livelihood security of vulnerable households creates the risk of poverty traps, particularly for rural and urban landless (Sections 8.2.1, 8.3.3.1), for example in Malawi and Ethiopia (Section 9.9.3). Levels of labour productivity and economic outputs are projected to decrease as temperatures rise particularly in urban areas (Section 6.2.3.1). At the same time, higher utilities demand under higher urban temperatures exerts additional economic stresses on urban residents and households. Substantial, negative impacts on the livelihoods of over 180 million people are expected from changes to African grassland productivity (Section 5.5.3.1). In Western Uzbekistan, farmers' incomes are at risk of declining (Section 10.4.5.3). For SIDS, loss of livelihoods is expected due to negative climatic impacts on coastal environments and resources (Section 3.5.1). Negative effects on households from extreme events can also persist in the long term and in multiple dimensions. Exposure to disasters during the first year of life significantly reduces the number of years of schooling and increases the chances of being unemployed as an adult and living in a multidimensionally poor household (González et al., 2021).

16.5 Key Risks across Sectors and Regions

This section builds on the analogous chapter in AR5 (Oppenheimer et al., 2014) to refine the definition of climate-related key risks (KRs) and criteria for identifying them (Section 16.5.1), and describe a broad range of key risks by sector and region as identified by the authors of WGII AR6 (Section 16.5.2, SM16.4). Based on this, eight clusters of key risks (i.e., Representative Key Risks, RKRs) are identified and assessed in terms of the conditions under which they would become severe. In addition, the section assesses variation in KRs and RKRs by the level of global average warming, socioeconomic development pathways, and levels of adaptation, and illustrates the implications from resulting dynamics in all risk dimensions (hazard, exposure, vulnerability) along a case study of densely populated river deltas (Section 16.5.3). Last, interactions among RKRs are discussed (Section 16.5.4).

16.5.1 Defining Key Risks

A key risk is defined as a potentially severe risk and therefore especially relevant to the interpretation of dangerous anthropogenic interference (DAI) with the climate system, the prevention of which is the ultimate objective of the UNFCCC as stated in its Article 2 (Oppenheimer et al., 2014). Key risks are therefore a relevant lens for the interpretation of this policy framing. The severity of a risk is a context-specific judgement based on a number of criteria discussed below. KRs are 'potentially' severe because, while some could already reflect dangerous interference now, more typically they may become severe over time due to changes in the nature of hazards (or, more broadly, climatic impact drivers; IPCC, 2021) and/or of the exposure/vulnerability of societies or ecosystems to those hazards. They also may become severe due to the adverse consequences of adaptation or mitigation responses to the risk (on the former, see Section 17.5.1; the latter is not assessed separately here, except as it contributes to risks from climate hazards). Dangerous interferences in this chapter are considered over the course of the 21st century.

KRs may be defined for a wide variety of systems at a range of scales. The broadest definition is for the global human system or planetary ecological system, but KRs may also apply to regions, specific sectors or communities, or to parts of a system rather than to the system as a whole. For example, the population at the lower end of the wealth distribution is often impacted by climate change much more severely than the rest of the population (Leichenko and Silva, 2014; Hallegatte and Rozenberg, 2017; Hallegatte et al., 2017; Pelling and Garschagen, 2019).

KRs are determined not just by the nature of hazards, exposure, vulnerability and response options, but also by values, which determine the importance of a risk. Importance is understood here as the degree of relevance to interpreting DAI at a given system's level or scale, and was

Constraints associated with limits by region and sector

Figure 16.8 | Constraints associated with limits by region and sector. Data from Thomas et al. (2021), based on 1682 scientific publications reporting on adaptation-related responses in human systems. See SM16.1 for methods. Constraints are categorised as: (1) economic: existing livelihoods, economic structures, and economic mobility; (2) social/cultural: social norms, identity, place attachment, beliefs, worldviews, values, awareness, education, social justice, and social support; (3) human capacity: individual, organisational, and societal capabilities to set and achieve adaptation objectives over time including training, education, and skill development; (4) governance, institutions and policy: existing laws, regulations, procedural requirements, governance scope, effectiveness, institutional arrangements, adaptive capacity, and absorption capacity; (5) financial: lack of financial resources; (6) information/awareness/technology: lack of awareness or access to information or technology; (7) physical: presence of physical barriers; and (8) biologic/climatic: temperature, precipitation, salinity, acidity, and intensity and frequency of extreme events including storms, drought, and wind. **Insufficient data:** there is not enough literature to support an assessment (fewer than five studies available); **Minor constraint:** <20% of assessed literature identifies this constraint; **Secondary constraint:** 20–50% of assessed literature identifies this constraint; **Primary constraint:** >50% of assessed literature identifies this constraint.

Table 16.4 | Key constraints associated with limits to adaptation for regions

Region	Key constraints associated with limits to adaptation
Africa	Financial constraints inhibit implementation of a variety of adaptation strategies including ecosystem-based adaptation (Section 9.11.4.2) and adoption of drought-tolerant crops by farmers (Section 9.12.3). Information constraints (including limited climate science information), governance constraints (such as communication disconnects between national, district and community levels) and human capacity constraints (limited capacities to analyse threats and impacts) are identified as negatively affecting the implementation of adaptation policies (Section 9.13.1). Social/cultural constraints (social status, caste and gender) also affect adaptation in contexts with deep-rooted traditions (Section 9.12.4).
Asia	Governance, human capacity, financial and informational constraints commonly present barriers to urban adaptation (Section 10.4.6.5). Economic, governance, financial and informational constraints are related to both soft and hard limits to adaptation against a range of hazards in South Asia (Box 10.7), while in West Asia, physical constraints to heatwaves and drought have been associated with limits to adaptation (Box 10.7).
Australasia	A range of constraints, including governance, information and awareness, social/cultural, human capacity and financial, have been identified as impeding adaptation action in the region (Section 11.7.2, Box 11.1). Evidence of limits to adaptation are primarily for ecosystems (Sections 11.7.2, 11.6), although individuals and communities are also approaching soft limits owing to social constraints (Section 11.7.2).
Central and South America	Financial, governance, knowledge, biophysical and social/cultural constraints identified as most significant for adaptation (Section 12.5, Table 12.3). Soft limits are largely related to governance constraints, while evidence of hard limits is related to biophysical constraints, such as glacier shrinking leading to loss of livelihoods and cultural values (Section 12.5.3.4).
Europe	Key constraints are identified as technical, biophysical, economic and social (Section 13.6.2.4). For cities, settlements and key infrastructure, technical socioeconomic and environmental and regulatory constraints may lead to limits at a range of spatial scales (Figure 13.12). Biophysical constraints may lead to limits to the ability of water saving and water efficiency measures to prevent water insecurity under high warming scenarios (Section 13.2.2.2).
North America	Social/cultural, governance, financial, knowledge and biophysical constraints are identified as most significant for adaptation and leading to both soft and hard limits (Sections 14.5.2.1, 14.6, 14.6.2.1, Table 14.8).
Small islands	Financial, governance, information/awareness, technological, cultural and human capacity constraints are identified as affecting adaptation and leading to soft limits (Sections 15.5.3, 15.5.4, 15.6.1, 15.6.3, 15.6.4). Differences between constraints and soft limits in the small island context is marginal, with policymakers in the Caribbean and Indian Oceans seeing these as synonymous (Section 15.6.1).

Table 16.5 | Evidence of climate change impacts affecting availability of financial resources.

Region	Evidence of climate change impacts affecting availability of financial resources
Africa	Negative consequences for economic growth and GDP growth rate from higher average temperatures and lower rainfall (c) (Sections 9.9.1.1, 9.9.2, 9.9.3) Economic losses from damage to infrastructure in the energy, transport, water supply, communication services, housing, health and education sectors (observed) (Sections 9.7.2.2, 9.8.2)
Asia	High coastal damages due to sea level rise (China, India, Korea, Japan, Russia) (c) (Section 10.4.6.3.4) Decline in aquaculture production (Section 10.4.5.2.1) Loss of coastal ecosystem services (Bangladesh) (Section 5.9.3.2.4)
Australasia	Loss of wealth and negative impacts on GDP (Sections 11.5.1.2, 11.5.2.2) High disaster costs (observed in Australia, New Zealand) (Section 11.5.2.1)
Central and South America	High costs of extreme events relative to GDP (observed in Guatemala, Belize) (Section 12.3.1.4) Decrease in growth of total GDP per capita and total income and labour income from one standard deviation in the intensity of a hurricane windstorm (Section 12.3.1.4)
Europe	Negative combined effect of multiple risks on economy for Europe in total (b) (Sections 13.9.1, 13.10.2) Negative combined effect of multiple risks on economy for Southern Europe (c) (Sections 13.9.1, 13.10.2) High economic costs in agriculture and construction following heatwaves and flooding (Sections 6.2.3.2, 7.4.2.2.1)
North America	Small but persistent negative economy wide effect on GDP (observed in the USA and Mexico) (b) (Box 14.5) Economic risks associated with high-temperature scenarios (c) (Box 14.5) Small but persistent positive economy wide effect on GDP (observed in Canada) (b) (Box 14.5) Significant economic costs for urban, natural and ecosystem infrastructure (USA) (Section 6.2.5.9) High economic damages for a subset of sectors from high warming (southern and southeastern USA) (Box 14.5) Adverse effects on municipal budgets due to costly liabilities, and disruption of financial markets (Box 14.5)
Small islands	High economic costs relative to GDP from extreme events, particularly tropical cyclones (observed) (Section 15.3.4.1) Negative long-term implications of extreme events for state budgets (Section 8.2.1.4) Inundation of almost all port and harbour facilities (Caribbean) (Section 15.3.4.1)

Notes:
(a) *low confidence*
(b) *medium confidence*
(c) *high confidence*

an explicit criterion for identifying key vulnerabilities and risks in AR5 (Oppenheimer et al., 2014). Because values can vary across individuals, communities or cultures, as well as over time, what constitutes a KR can vary widely from the perspective of each of these groups, or across individuals. For example, ecosystems providing indirect services and cultural assets such as historic buildings and archaeological sites may be considered very important to preserve by some people but not by others; and some types of infrastructure, such as a commuter rail, may be important to the well-being of some households but less so to others. Therefore, Chapter 16 authors do not make their own judgements about the importance of particular risks. Instead, we highlight importance as an overarching factor but identify and evaluate KRs based on four other criteria for what may be considered potentially severe.

Magnitude of adverse consequences. Magnitude measures the degree to which particular dimensions of a system are affected, should the risk materialise. Magnitude can include the size or extent of the system, the *pervasiveness of the consequences* across the system (geographically or in terms of affected population), as well as the *degree of consequences*. Consequences can be measured by a wide range of characteristics. For example, risks to food security can be measured as uncertain consequences for food consumption, access or prices. The magnitude of these consequences would be the degree of change in these measures induced by climate change and accounting for the interaction with exposure and vulnerability. In addition to *pervasiveness* and *degree of change*, several other aspects can contribute to a judgement of magnitude, although they refer to concepts that are difficult to capture and highly context-specific:

Irreversibility of consequences. Consequences that are irreversible, at least over long time scales, would be considered a higher risk than those that are temporary. For example, changes to the prevailing ecosystem in a given location may not be reversible on the decade to century scale.

Potential for impact thresholds or tipping points. Higher risks are posed by the potential for exceeding a threshold beyond which the magnitude or rate of an impact substantially increases.

Potential for cascading effects beyond system boundaries. Higher risks are posed by those with the potential to generate downstream cascading effects to other ecosystems, sectors or population groups within the affected system and/or to another system, whether neighbouring or distant (Cross-Chapter Box INTEREG in this Chapter).

Likelihood of adverse consequences. A higher probability of high-magnitude consequences poses a larger risk *a priori*, whatever the scale considered. This probability may not be quantifiable, and it may be conditional on assumptions about the hazard, exposure or vulnerability associated with the risk.

Temporal characteristics of the risk. Risks that occur sooner, or that increase more rapidly over time, present greater challenges to natural and societal adaptation. A persistent risk (due to the persistence of the hazard, exposure and vulnerability) may also pose a higher threat than a temporary risk due, for example, to a short-term increase in the vulnerability of a population (e.g., due to conflict or an economic downturn).

Ability to respond to the risk. Risks are more severe if the affected ecosystems or societies have limited ability to reduce hazards (e.g., for human systems, through mitigation, ecosystem management and possibly solar radiation management); to reduce exposure or vulnerability through various human or ecological adaptation options; or to cope with or respond to the consequences, should they occur.

The relative influence of these different criteria is case-specific and left to author judgement in the identification of KRs (groups of authors in regional and sectoral chapters) and the assessment of representative key risks (author teams, see SM16.4). But in general, the more criteria are met, the higher is the risk.

16.5.2 Identification and Assessment of Key Risks and Representative Key Risks

16.5.2.1 Identification of Key Risks

The authors of the sectoral and regional chapters and cross chapter papers of the WGII AR6 Report identified more than 120 key risks (SM16.7.4). Authors were asked to rely on the above definition and criteria to identify risks that could potentially become severe according to changes in the associated hazards, the study systems' exposure and/or vulnerability, and important adaptation strategies that could reduce these risks (see SM16.3 for methodology). Wherever possible, identification is based on literature that includes projected future conditions for all three components of risk and adaptation. Where literature was insufficient, potential severity is based on current vulnerability and exposure to climate hazards and the expectation that hazards will increase in frequency and/or intensity in the future. This approach is more limited in that it does not consider future changes in exposure and vulnerability nor in adaptation, but has the benefit of being grounded in observed experience.

Table SM16.24 indicates that climate change presents a wide range of risks across scales, sectors and regions that could become severe under particular conditions of hazards, exposure and vulnerability, which may or may not occur. Some illustrations of the extent and diversity of KRs are provided here, and more detailed assessment can be found in the Chapters referenced in the table.

Global-scale KRs include threats to biodiversity in oceans, coastal regions and on land, particularly in biodiversity hotspots, as well as other ecological risks such as geographic shifts in vegetation, tree mortality, reduction in populations and reduction in growth (such as for shellfish). These ecological risks include cascading impacts on livelihoods and food security. Global-scale risks also include risks to people, property and infrastructure from river flooding and extreme heat (particularly in urban areas), risks to fisheries (with implications for living standards and food security) and some health risks from food-borne diseases as well as psychopathologies.

Many KRs are especially prominent in particular regions or systems, or for particular subgroups of the population. For example, coastal systems and small islands are a nexus of many KRs, including those to ecosystems and their services, especially coral reefs; people (health, livelihoods); and assets, including infrastructure. Risks to socio-ecological systems in polar regions are also identified as KRs, as are ecological risks to the Amazon Forest in South America and savannahs in Africa. For some regions, risks from wildfire are of particular concern, including in Australasia and North America. Vector-borne diseases are a particular concern in Africa and Asia. Loss of cultural heritage is identified as a KR in small islands, mountain regions, Africa, Australasia and North America.

For many risks, low-income populations are particularly vulnerable to KRs. Climate-related impacts on malnutrition and other forms of food insecurity will be larger for this group, along with small-holder farming households and Indigenous communities reliant on agriculture, and for women, children, the elderly and the socially isolated (Section 5.12). KRs in coastal communities are expected to affect low-income populations more strongly, including through risks to livelihoods of those reliant on coastal fisheries. KRs related to health are generally higher for low-income populations less likely to have adequate housing or access to infrastructure.

16.5.2.2 Identification of Representative Key Risks

As in AR5 Oppenheimer et al. (2014), major clusters of KRs are further analysed, and here referred to as 'representative key risks' (RKRs). RKRs were defined in a three-step process (SM16.3.1). First, half of Chapter 16 authors independently mapped the KRs (SM16.7.4) to a set of candidate RKRs. Second, all Chapter 16 authors discussed the set of independent results and proposed a list of RKRs, considering scope and overlap. Third, this proposal was discussed with a consultative group of about 20 WGII AR6 authors from other chapters closely involved in the KR identification process, and a final list of eight RKRs was identified (Table 16.6).

The RKRs are intended to capture the widest variety of KRs to human or ecological systems with a small number of categories that are easier to communicate and provide a manageable structure for further assessment. They expand the scope of some AR5 KR clusters (e.g., on coasts, health, food and water) and add new ones (e.g., on peace and human mobility). The RKRs encompass a diversity of types of systems, including an example of a geographically defined system (RKR-A on coastal regions), ecosystem well-being and integrity (RKR-B), a cross-cutting issue relevant to several outcomes of concern (RKR-C on critical infrastructure) and several topics focused directly on aspects of human well-being and security (RKR-D to RKR-H). This set of RKRs manages but does not eliminate overlap, instead providing alternative perspectives on underlying key risks that sometimes include complementary views on common risks. For example, the water security RKR highlights the many key risks mediated by water quantity or quality, which are sometimes manifested as risk to food security (RKR-F) or health (RKR-E).

16.5.2.3 Assessment of Representative Key Risks

Each RKR was assessed by a team of four to nine members drawn from Chapter 16, other WGII AR6 chapters, and external contributing authors (SM16.4). The following subsections describe the scope of the category of risk (underlying KR considered) and the approach to defining 'severe' risks for each particular RKR. They also assess the conditions in terms of warming (more broadly, climatic impact drivers; (Ranasinghe et al., 2021), exposure/vulnerability and adaptation under which the RKR would become severe. For each of these dimensions, RKR teams considered generic levels ranging from High to Medium and Low. For warming levels, in line with WGI framing, High refers to climate outcomes consistent with RCP8.5 or higher, Low refers to climate outcomes consistent with RCP2.6 or lower, and Medium refers to outcomes for scenarios between RCPs 2.6 and 8.5. For reference, the full range of warming levels (across all climate models) associated with RCP8.5 for the 2081–2100 period is 3.0–6.2°C; for RCP2.6 it is 0.9–2.3°C; and for intermediate RCPs it is 1.8–3.6°C (Cross-Chapter Box CLIMATE in Chapter 1). For Exposure-Vulnerability, levels are determined by the RKR teams relative to the range of future conditions considered in the literature, for example based on the Shared Socioeconomic Pathways (SSPs) in which future conditions based on SSPs 1 or 5 represent Low exposure or vulnerability and those based on SSPs 3 or 4 represent High exposure or vulnerability (O'Neill et al., 2014; van Vuuren and Carter, 2014). For Adaptation, two main levels have been considered: High refers to near maximum potential, and Low refers to the continuation of today's trends. Despite being intertwined in reality, Exposure-Vulnerability and Adaptation conditions are distinguished to help understand their respective contributions to risk severity. Importantly, this assessment does not consider all risks, but only those that can be considered severe given the definition and criteria presented in Section 16.5.1. The assessment does not exclude the possibility that severe risks are already observed in some contexts, and considers projected risks through the end of this century.

Each RKR assessment followed a common set of guidelines (SM16.3) that included broad criteria for defining severity (Section 16.5.1), consideration of complex risks and interactions within and across RKRs, and consideration of risks across a range of scales, regions, and ecological and human development contexts. The specific definition of severity within each RKR was determined by the author teams of that assessment, applying different combinations of key risk criteria and metrics as judged appropriate in each case. Definitions are transparent and use common criteria, but are nonetheless based on the respective author team's judgement. Conclusions about severity and associated confidence statements are therefore conditional on those definitions.

Assessments are based on different types of evidence depending on the nature of the literature. In some cases, quantitative projections of potential impacts are available. In others and as for KR identification, the potential for severe risk is inferred from high levels of current vulnerability and the expectation that the relevant climate hazards (climatic impact drivers, CIDs) will increase in frequency or intensity in the future.

16.5.2.3.1 Risk to the integrity of low-lying coastal socio-ecological systems (RKR-A)

RKR-A considers climate-change-related risks to low-lying coasts including their physical, ecological and human components. Low-lying systems are those occupying land below 10 m of elevation that is contiguous and hydrologically connected to the sea (McGranahan et al., 2007). The assessment builds on Key Risks identified in Chapters

Table 16.6 | Climate-related representative key risks (RKRs). The scope of each RKR is further described in the assessments in Section 16.5.2.3. Relation to categories of overarching key risks identified in AR5 is provided for continuity.

Code	Representative key risk	Scope	Relation to AR5 overarching key risks; for definitions, refer to Oppenheimer et al. (2014)	Subsection assessment
RKR-A	Risk to low-lying coastal socio-ecological systems	Risks to ecosystem services, people, livelihoods and key infrastructure in low-lying coastal areas, and associated with a wide range of hazards, including sea level changes, ocean warming and acidification, weather extremes (storms, cyclones), sea ice loss, etc.	Contains key risk (i), overlaps with key risks (iii) and (vii)	16.5.2.3.1
RKR-B	Risk to terrestrial and ocean ecosystems	Transformation of terrestrial and ocean/coastal ecosystems, including change in structure and/or functioning, and/or loss of biodiversity.	Contained in key risks (vii) and (viii)	16.5.2.3.2
RKR-C	Risks associated with critical physical infrastructure, networks and services	Systemic risks due to extreme events leading to the breakdown of physical infrastructure and networks providing critical goods and services.	Overlaps with key risk (iii)	16.5.2.3.3
RKR-D	Risk to living standards	Economic impacts across scales, including impacts on gross domestic product (GDP), poverty and livelihoods, as well as the exacerbating effects of impacts on socioeconomic inequality between and within countries.	Broader version of key risk (ii)	16.5.2.3.4
RKR-E	Risk to human health	Human mortality and morbidity, including heat-related impacts and vector-borne and waterborne diseases.	Broader version of key risk (iv)	16.5.2.3.5
RKR-F	Risk to food security	Food insecurity and the breakdown of food systems due to climate change effects on land or ocean resources.	Overlaps with key risk (v)	16.5.2.3.6
RKR-G	Risk to water security	Risk from water-related hazards (floods and droughts) and water quality deterioration. Focus on water scarcity, water-related disasters and risk to indigenous and traditional cultures and ways of life.	Overlaps with key risk (iv)	16.5.2.3.7
RKR-H	Risks to peace and to human mobility	Risks to peace within and among societies from armed conflict as well as risks to low-agency human mobility within and across state borders, including the potential for involuntarily immobile populations.	New	16.5.2.3.8

3 and 15, Cross Chapter Paper 2 as well as in the SROCC (Magnan et al., 2019; Oppenheimer et al., 2019). It highlights risks to (i) natural coastal protection and habitats; (ii) lives, livelihoods, culture and well-being; and (iii) critical physical infrastructure; it therefore overlaps with several other RKRs (Figures 16.10, 16.11) but within a coastal focus. It encompasses all latitudes and considers multiple sources of climate hazards, including SLR, ocean warming and acidification, permafrost thaw, and sea ice loss and changes in weather extremes.

Severe risks to low-lying coasts involve irreversible long-term loss of land, critical ecosystem services, livelihoods, well-being or culture in relation to increasing combined drivers, including climate hazards and exposure and vulnerability conditions. The definition depends on the local context because of variation in the perception of tolerable risks and the limits to adaptation (Handmer and Nalau, 2019). Accordingly, a qualitative range of consequences is presented here, in place of a quantitative global severe risk threshold.

The literature suggests that severe risks generally occur at the nexus of high levels and rates of anthropogenic-driven change in climate hazards (Section 16.2.3.2), concentrations of people and tangible and intangible assets, non-climate hazards such as sediment mining and ecosystem degradation (Section 3.4.2.1), and the reaching of adaptation limits (Section 16.4) (*medium evidence*, *high agreement*). In some Arctic communities and in communities reliant on warm-water coral reefs, even 1.5–2°C warming will lead to severe risks from loss of ecosystem services (Section 3.4.2.2; Cross-Chapter Paper 6) (*high confidence*). Loss of land is already underway globally due to accelerating coastal erosion and will be amplified by increased sea level extremes and permanent flooding (*high confidence*; Oppenheimer et al. 2019, Ranasinghe et al. 2021). Observed impacts of and projected increases in high-intensity extreme events (Ranasinghe et al. 2021) also provide evidence for severe risk to occur on livelihoods, infrastructure and well-being (Section 16.5.2.3.3) by mid-century (*high confidence*). Consequently, the combination of high warming, continued coastal development and low adaptation levels will challenge the habitability of many low-lying coastal communities in both developing and developed countries over the course of this century (*limited evidence*, *high agreement*) (Duvat et al., 2021; Horton et al., 2021). In some contexts, climate risks are already considered severe (*medium evidence*, *medium agreement*), and in others, even lower warming will induce severe risks to habitability, which will not necessarily be offset by ambitious adaptation (*limited evidence*, *medium agreement*).

i) Natural coastal protection and habitats—severe risks from the loss of shoreline protection from reductions in wave attenuation (Beck et al., 2018, Sections 3.5.5.1, 3.5.4.5) and sediment delivery (Sections 3.4.2.5, 15.3.3) are already observed in some coastal systems (Section 16.2.3.1) and occur broadly even with 1.5°C of global warming (Hoegh-Guldberg et al., 2018a; Bindoff et al., 2019, Section 3.4.2). These impacts are the consequence of warming and SLR on coastal ecosystems.

Warm-water coral reefs are at risk of widespread loss of structural complexity and reef accretion by 2050 under 1.5°C global warming (Section 3.4.2.1) (*high confidence*). Kelp forests may experience shifts in community structure (Arafeh-Dalmau et al., 2019; Rogers-Bennett and Catton, 2019; Smale, 2020; Smith et al., 2021) with >2°C of global warming especially at lower latitudes (Section 3.4.2.2) (*high confidence*). In addition, depending on the local tide and sediment conditions, SLR associated with >1.5°C of global warming (SSP1–2.6; 3.4.2.5) is sufficient to initiate shifts to alternate states in some seagrass and coastal wetland systems (van Belzen et al., 2017; El-Hacen et al., 2018, Section 3.4.2.5, Cross-Chapter Box SLR in Chapter 3), and submergence of some mangrove forests (Section 3.4.2.5). A striking example of risks becoming severe at higher levels of warming is the one of coral islands with low elevation (Section 15.3.4, Box 15.1): the risk of loss of habitability transitions from Moderate-to-High under RCP2.6 for most island types (urban and rural) to High-to-Very High under RCP8.5 (Duvat et al., 2021), even under a high adaptation scenario (Oppenheimer et al., 2019), partly due to declining sediment supply (Perry et al., 2018) and increased annual flooding (Giardino et al., 2018; Storlazzi et al., 2018).

More broadly, about 28,000 km^2 of land have been lost globally since the 1980s due to anthropogenic factors (e.g., coastal structures, disruption of sediment fluxes) and coastal hazards (Mentaschi et al., 2018), and an additional loss of 6000–17,000 km^2 is estimated by the end of the century due to coastal erosion alone associated with SLR in combination with other drivers (Hinkel et al., 2013).

ii) Impacts to lives, livelihoods, culture and well-being—in the absence of effective adaptation, changing extreme and slow-onset hazards combined with anthropogenic drivers (e.g., increased population pressure at the coast between +5% and +13.6% by 2100 compared with today, Jones and O'Neill, 2016) will lead to loss of lives, livelihoods, health, well-being and/or culture (McGregor et al., 2016; Pinnegar et al., 2019; Pugatch, 2019; Schneider and Asch, 2020; Thomas and Benjamin, 2020; McNamara et al., 2021) (*high confidence*). Catastrophic examples that may foreshadow the future include Hurricane Sandy in 2012 (Strauss et al., 2021) and Super Typhoon Haiyan in 2013 (>6,000 deaths and inequities in access to safe housing; Trenberth et al. 2015) (Sections 6.2.2, 6.3.5.1). Although there is no unique definition of 'intolerable' loss, risks are generally expected to become severe over this century (Tschakert et al., 2017; Dannenberg et al., 2019; Tschakert et al., 2019). Globally, with High warming, 90–380 million more people will be exposed to annual flood levels by the mid- and end-century, respectively, compared with 250 million people today (Kulp and Strauss, 2019; Kirezci et al., 2020), with potential implications on forced displacement or migration (Oppenheimer et al., 2019; Wrathall et al., 2019; Hauer et al., 2020; Lincke and Hinkel, 2021, Section 16.5.2.3.8). Some of the largest fish-producing and fish-dependent ecoregions have already experienced losses of up to 35% in marine fisheries productivity due to warming (Free et al., 2019), and about 11% of the global population will face increasing nutritional risks if current trajectories continue (Golden et al., 2016). While difficult to measure, current climate-driven losses to (Indigenous) knowledge, traditions (Tschakert et al., 2019; Pearson et al., 2021) and well-being (Ebi et al., 2017; Cunsolo and Ellis, 2018; Jaakkola et al., 2018) indicate such risk as already severe in some regions (*limited evidence*, *medium agreement*), jeopardising communities' realisation of their rights to food, health and culture. In the Arctic, climate-driven changes to ice and weather regimes have substantially affected traditional coastal-based hunting and fishing activities (Fawcett et al., 2018; Galappaththi et al., 2019; Huntington et al., 2020; Nuttall, 2020, Cross-Chapter Paper 6), and where permafrost thaw, SLR and coastal erosion are contributing to threatening cultural sites (Hollesen et al., 2018; Fenger-Nielsen et al., 2020).

iii) Critical physical infrastructure—severe risks are also illustrated through damages that lead to possibly long-lasting disruption of key services like transportation as well as energy generation and distribution in coastal areas (Section 16.5.2.3.3) under all RCPs (Section CCP2.2.3) and if no additional adaptation (*medium confidence*). Critical transport infrastructure is already suffering from structural failures in polar regions, for instance, due to permafrost thaw and increased erosion associated with ocean warming, storm surge flooding and loss of sea ice (Melvin et al., 2017; Fang et al., 2018, Sections 14.5.2.8, 16.2.3.2, Cross-Chapter Paper 6). One hundred airports are projected to be below mean sea level in 2100 with 2°C of warming (i.e., 0.62 m SLR, Yesudian and Dawson, 2021), including in small islands (Monioudi et al., 2018; Storlazzi et al., 2018) and megacities. Projections show San Francisco International Airport, for instance, to be inundated by 2100 under the upper likely range of SLR in RCP8.5 (also considering subsidence trends, Shirzaei and Bürgmann, 2018). On the energy side, it is estimated that with 1.8 m SLR, for example, 4 out of 13 US nuclear power plant facilities will become exposed to storm surges and 3 others will be surrounded or submerged by seawater (Jordaan et al., 2019; Jenkins et al., 2020).

16.5.2.3.2 Risk to terrestrial and ocean ecosystems (RKR-B)

This risk refers to transformations of terrestrial and ocean/coastal ecosystems that would include significant changes in structure and/or functioning, and/or loss of a substantial fraction of species richness (commonly used to indicate loss of biodiversity). These are sourced mainly from Chapters 2 and 3, Cross-Chapter Paper 1, and reference the 1.5C report, Chapter 4 from WGII AR5, and Chapter 4 from WGII AR4 Reports.

Severe adverse impacts on biodiversity include significant risk of species extinction (e.g., loss of a substantial fraction (one-tenth or more) of species from a local to global scale), mass population mortality (>50% of individuals or colonies killed), ecological disruption (order-of-magnitude increases or abrupt reductions of population numbers or biomass), shifts in ecosystem structure and function (order-of magnitude increases or abrupt decreases in cover and/or biomass of novel growth forms or functional types) and/or a socioeconomically material increase in environmental risk (e.g., destruction by wildfire) or socioeconomically material decline in goods and services (e.g., carbon stock losses, loss of grazing, loss of pollination). Metrics relevant to SDGs are also germane.

A substantial proportion of biodiversity is at risk of being lost below 2°C of global warming (Chapter 2), due to range reductions and loss globally, with this risk amplified roughly three times in insular ecosystems and biodiversity hotspots, due to the increased vulnerability of endemic species (Manes et al., 2021). High-latitude, high-altitude, insular, freshwater, and coral reef ecosystems and biodiversity hotspots (Chapter 2, Cross-Chapter Paper 1) are at appreciable risk of substantial biodiversity loss due to climate change even under Low warming (*high confidence*). These systems comprise a large fraction of unique and endemic biodiversity, with species impacts often exacerbated by multiple drivers of global change (Chapter 2, Chapter 3). Roughly one-third of all known plant species are extremely rare, vulnerable to climate impacts, and clustered in areas of higher projected rates of anthropogenic climate change (Enquist et al., 2019). Much evidence shows increased risk of the loss of 10% or more of terrestrial biodiversity with increasing anthropogenic climate change (Urban, 2015; Smith et al., 2018) (*medium confidence*), *likely* with 2°C warming above pre-industrial level (Chapter 2), with consequent degradation of terrestrial, freshwater and ocean ecosystems (Oliver et al., 2015) and adverse impacts on ecosystem services (Pecl et al., 2017) and dependent human livelihoods (Dube et al., 2016). Adverse impacts on biodiversity may show lagged responses (Essl et al., 2015), and loss of a substantial fraction of species could occur abruptly, simultaneously across multiple taxa, below 4°C of global warming (Trisos et al., 2020).

Mass population-level mortality (>50% of individuals or colonies killed) and resulting abrupt ecological changes can be caused by simple or compound climate extreme events, such as exceedance of upper thermal limits by vulnerable terrestrial species (Fey et al., 2015), who also note reduced mass mortality trends due to extreme low thermal events; marine heatwaves that can cause mortality, enhance invasive alien species establishment, and damage coastal ecological communities and small-scale fisheries (*high confidence*) (Section 3.4.2.7); and increased frequency and extent of wildfires that threaten populations dependent on habitat availability (like Koala Bears, Lam et al., 2020). Abrupt ecological changes are widespread and increasing in frequency (Turner et al., 2020), and include tree mortality due to insect infestation exacerbated by drought, and ecosystem transformation due to wildfire (Vogt et al., 2020). Freshwater ecosystems and their biodiversity are at high risk of biodiversity loss and turnover due to climate change (precipitation change and warming, including warming of water bodies), due to high sensitivity of processes and life histories to thermal conditions and water quality (Chapter 2) (*high confidence*). In marine systems, heatwaves cause damages in coastal systems, including extensive coral bleaching and mortality (*very high confidence*) (Section 3.4.2.1), mass mortality of invertebrate species (*low* to *high confidence*, depending on system) (Sections 3.4.2.2, Section 3.4.2.5, Section 3.4.4.1), and abrupt mortality of kelp-forest (*high confidence*) (Section 3.4.2.3) and seagrass-meadow habitat (*high confidence*) (Section 3.4.4.2). The biodiversity of polar seas shows strong impacts of climate change on phenological timing of plankton activity, Arctic fish species range contractions and species community change (Table SM16.22) (*high confidence*). Extreme weather events and storm surges exacerbated by climate change have severe and sudden adverse impacts on coastal systems, including loss of seagrass meadows and mangrove forests (*high confidence*) (see Section 3.4.2.7, Section 3.4.2.8, Cross-Chapter Box EXTREMES in Chapter 2).

Ecological disruption (order-of-magnitude increases or abrupt reductions of population numbers or biomass) can occur due to unprecedented inter-species interactions with unpredictable outcomes in 'novel ecosystems' (Chapter 2) as species shift geographic ranges idiosyncratically in response to climatic drivers (Table SM16.22). Idiosyncratic geographic shifts are now observed in an appreciable fraction of species studied (Chapter 2, Table 16.2). Commensal or parasitic diseases may infect immunologically naive hosts (e.g., chytrid fungus in amphibians). Atypical disturbance regimes may be enhanced, for example, with the spread of flammable plant species (e.g., du Toit et al., 2015), exacerbated by introduced species (e.g., Martin et al., 2015), thus significantly increasing risk of losses and damages to infrastructure and livelihoods, as well as ecological degradation, and challenging existing management approaches.

Landscape- and larger-scale shifts in ecosystem structure and function (order-of-magnitude increases or abrupt decreases in cover and/or biomass of novel growth forms or functional types) are occurring in non-equilibrium ecosystems (systems which exist in multiple states, often disturbance-controlled) in response to changing disturbance regime, climate and rising CO_2 (*high confidence*) Woody plant encroachment has been occurring in multiple ecosystems, including subtropical and tropical fire driven grassland and savanna systems, upland grassland systems, arid grasslands and shrublands (*high confidence*), leading to large-scale biodiversity changes, albedo changes, and impacts on water delivery, grazing services and human livelihoods (*medium confidence*). Expansion of grasses (alien and native) into xeric shrublands is occurring, causing increasing fire prevalence in previous fire-free vegetation (Cross-Chapter Paper 3). In tropical forests, repeated droughts and recurrence of large-scale anthropogenic fires increase forest degradation, loss of biodiversity and ecosystem functioning (*high confidence*) (Anderson et al., 2018b; Longo et al., 2020). Accelerated growth rates and mortality of tropical trees is also adversely affecting tropical ecosystem functioning (McDowell et al., 2018; Aleixo et al., 2019). Projected changes in ecosystem functioning, such as via wildfire (Section 2.5.5.2), tree mortality (Section 2.5.5.3) and woody encroachment under climate change (Chapter 2) would alter hydrological processes, with adverse implications for water yields and water supplies (Sankey et al., 2017; Robinne et al., 2018; Rodrigues et al., 2019; Uzun et al., 2020).

The loss of a substantial fraction of biodiversity globally, abrupt impacts such as significant local biodiversity loss and mass population mortality events, and ecological disruption due to novel species interactions have been observed or are projected at global warming levels below 2°C (Chapter 2 Table SM2.5, Cross Chapter Box: EXTREMES in Chapter 2, Section 2.4.4.3.1, Section 2.4.2.3.3) (*medium confidence*). Simple and compound impacts of extreme climate events are already causing significant losses and damages in vulnerable ecosystems, including through the facilitation of important global change drivers of ecological disruption and homogenisation like invasive species (*high confidence*). Severe impacts on human livelihoods and infrastructure, and valuable ecosystem services, are all projected to accompany these changes. Adaptation potential for many of these risks is low due to the projected rate and magnitude of change, and to the requirement of significant amounts of land for terrestrial ecosystems (Hannah et al., 2020). Biodiversity conservation efforts may be hampered due to climate change impacts on the effectiveness of protected areas, with high sensitivity of effectiveness to forcing scenario (*medium confidence*). In addition, climate-related risks to ecosystems pose challenges to ecosystem-based adaptation responses ('nature-based solutions') (Section 2.1.3) (*medium confidence*).

16.5.2.3.3 Risk to critical physical infrastructure and networks (RKR-C)

RKR-C includes risks associated with the breakdown of physical infrastructure and networks which provide goods and services considered critical to the functioning of societies. It encompasses infrastructure systems for energy, water, transportation, telecommunications, health care and emergency response, as well as compound, cascading and cross-boundary risks resulting from infrastructure interdependencies (Birkmann et al., 2016; Fekete, 2019). Critical infrastructures such as transport or energy supply also play a central role in coping with climate risks, especially in acute disaster situations in which the services of transport infrastructure, communication technologies or electricity are particularly needed, despite the fact that these very systems are themselves exposed to disaster impacts (Garschagen et al., 2016; Pescaroli et al., 2018). The major hazards driving such risks are acute extreme events such as cyclones, floods, droughts or fires (*high confidence*), but cumulative and chronic hazards such as SLR are also considered.

RKR-C is considered severe when the functioning of critical infrastructure cannot be secured and maintained against climate change impacts, resulting in the frequent and widespread breakdown of service delivery and eventually a significant rise of detrimental impacts on people (lives, livelihoods and well-being), the economy (including averted growth) or the environment (disruption and loss of ecosystems) above historically observed levels. Severity in this RKR is assessed on two levels for (i) direct impacts of climate change on infrastructure assets and networks (e.g., amount of port infrastructure damaged or destroyed by SLR, flooding and storms) on which most of the literature focuses, as well as (ii) indirect and cascading downstream impacts to people, economy and environment (Markolf et al., 2019; Pyatkova et al., 2019; Chester et al., 2020), for which attribution is more difficult and uncertainties tend to be much higher. Overall, the literature with quantified assessments of climate change infrastructure risks remains to be less extensive than for many other risks, particularly with regard to assessments focusing on the Global South. While climate-related changes in hazards are widely considered in the literature, changes in future exposure and vulnerability conditions are often not treated explicitly. In addition, the severity of infrastructure risks also depends on future trends in the capacity to maintain, repair and rebuild infrastructure and adapt it to new hazard intensities (*medium evidence*, *high agreement*). These are mostly not quantified in a forward-looking manner in the literature; however, damage projections (see below) indicate a rapidly rising demand for investment, straining the financial capacity of countries (*medium evidence*, *high agreement*).

i) Risks related to direct impacts on critical infrastructure would become severe with high warming, current infrastructure development regimes and minimal adaptation (*high confidence*), and in some contexts even with low warming, current vulnerability and no additional adaptation (*medium confidence*), with severity defined as infrastructure damage and required maintenance costs exceeding multiple times the current levels. Transport and energy infrastructure in coasts and polar systems and along rivers are projected to face a particularly steep rise in risk, resulting in severe risk even under medium warming (*high confidence*). Risk in relation to the increasing intensity and frequency of extreme events might become severe before the middle of the century (*medium confidence*). Damages from multiple climate hazards to transport, energy, industry and social infrastructure in Europe could increase 10-fold by the 2080s, from 3.4 € billion annually to date, and 15-fold for transport infrastructure, under Medium warming (A1B, ~3°C by 2100) and with current adaptation levels, even if no further extension of the infrastructure in exposed areas is considered (Forzieri et al., 2018). Under High warming (RCP8.5) in 2100, the percent of roads in the USA that require rehabilitation due to high temperatures and precipitation is expected to increase to 23–33%, relative to 14% in 2100 when no climate change is considered (Mallick et al., 2018). Projections of climate-induced changes in exposure are an incomplete measure of risk but in the absence of other metrics can serve as a proxy for the potential for severe impacts. In the circumpolar Arctic, 14.8% of critical infrastructure assets would be affected by climate change under RCP8.5 by 2050, with lifecycle replacement costs projected to increase by 27.7% if infrastructure is to be preserved at current adaptation levels (Suter et al., 2019). Under RCP8.5, the number of ports under high risk will increase from 3.8% in the present day to 14.4% by 2100, as a result of increased coastal flooding and overtopping due to SLR, as well as the heat stress impacts of higher temperatures (Izaguirre et al., 2021). In the UK under High warming (4°C), the number of clean and wastewater treatment sites located in the 1-in-75-year floodplain will increase by a third relative to today by the 2080s under current vulnerability and adaptation levels (Dawson et al., 2018). A global assessment of changing climate and water resources for electricity generation finds considerable reductions in usable hydropower and thermoelectric capacity by 2050 for a range of warming scenarios from Low to High, with absolute declines on average for most (61–74%) of the world's hydropower resources and monthly maximum reductions above 30% of usable capacity for over two-thirds of 1427 thermoelectric power plants worldwide (Van Vliet et al., 2016). Many studies find large technical potential for coordinated adaptation–mitigation policies in the electricity sector to avoid a significant portion of projected climate change impacts (e.g., a two-thirds reduction, and in some cases fully offset) (Ciscar and Dowling, 2014; Van Vliet et al., 2016; Gerlak et al., 2018; Allen-Dumas et al., 2019).

ii) Studies quantifying the indirect impacts of infrastructure failure on lives, livelihoods and economies are still rare but emerging, suggesting that risks would become severe in many contexts globally with high warming, current vulnerability and no additional adaptation (*medium confidence*). Severity in this context is defined as the potential to disrupt the lives, livelihoods and well-being of a significantly increased proportion of the population and to significantly forestall economic growth and development potential. Global risks to air travel from SLR, expressed in terms of expected annual route disruptions, could increase by a factor of between 17 and 69 by 2100 under the 1.5°C and the 95th percentile value of the RCP8.5 SLR scenario, respectively (Yesudian and Dawson, 2021). By 2050, up to 185,000 airline passengers per year may be grounded due to extreme heat (48°C) if no additional adaptation is taken, roughly 23 times more than today (McKinsey Global Institute, 2020). In Africa, under RCP8.5 and without additional adaptation, a 250% increase in disruption time of the transport network is expected by 2050 due to extreme temperatures, a 76% increase due to precipitation, and 1400% increase due to flooding

(Cervigni et al., 2015). On the Dawlish railway section (UK), the number of days with line restrictions is set to increase by up to 1170%, to as high as 84–120 yr^{-1} by 2100 due to 0.8 m SLR with High warming (Dawson et al., 2016). Next to the limited number of projections or scenarios of indirect impacts, additional inferences from studies focusing on past and current impacts can be drawn. Already today, climate-related impacts on transport and energy infrastructure reach far beyond the direct impacts on physical infrastructure, triggering indirect impacts on, for example, health and income (*medium confidence*). A case study of future flood hazard in Europe found that the indirect impact of a power outage on the local economy is six to eight times greater than the direct flood damage and asset repair costs, due to the interruption of daily economic activity (Karagiannis et al., 2019). In low- and middle-income countries, the annual costs from infrastructure disruptions reach up to 300 billion USD for firms and 90 billion USD for private households, with natural hazards such as floods being responsible for 10–70% of these disruptions, depending on the sectors and regions (Hallegatte et al., 2019). Power outages triggered by floods or droughts have also been found to have substantial health implications, particularly among low-income populations (Klinger et al., 2014), and shown to impede disaster recovery efforts and severely disrupt local economies (Karagiannis et al., 2019; Nicolas et al., 2019). In addition, risks associated with infrastructure have the potential to become particularly severe when hazard-driven infrastructure disruptions undermine the capacity of emergency response in disaster situations (*limited evidence*, *high agreement*). A study on the UK shows, for example, that even a small increase in minor road flooding leads to a disproportionately high disruption of the efficacy of emergency services (Yu et al., 2020). Similar risks have been found for rural areas, particularly in developing countries (Alegre et al., 2020).

16.5.2.3.4 Risk to living standards (RKR-D)

This RKR includes risks to (i) aggregate economic output at the global and national levels, (ii) poverty and (iii) livelihoods, and their implications for economic inequality. It is informed by key risks identified by regional and sectoral chapters. Risks are potentially severe as measured by the magnitude of impacts in comparison with historical events or as inferred from the number of people currently vulnerable.

i) Risks to aggregate economic output would become severe at the global scale with high warming and minimal adaptation (*medium confidence*), with severity defined as the potential for persistent annual economic losses due to climate change to match or exceed losses during the world's worst historical economic recessions. With historically observed levels of adaptation, warming of ~4°C may cause a 10–23% decline in annual global GDP by 2100 relative to global GDP without warming, due to temperature impacts alone (Burke et al., 2015; Kahn et al., 2019; Kalkuhl and Wenz, 2020). These magnitudes exceed economic losses during the Great Recession (2008–2009, ~5% decline in global GDP, up to 15–18% in some countries) and the COVID-19 pandemic (2020, ~3% decline globally, up to 10% in some countries) (IMF, 2020; IMF, 2021). Unlike past recessions, climate change impacts would occur continuously every year. However, smaller effects (1–8%) are found when using alternative methodologies (Diaz and Moore, 2017; Nordhaus and Moffat, 2017; Kompas et al., 2018; Kalkuhl and Wenz, 2020), assuming less warming (Kahn et al., 2019; Takakura et al., 2019), and assuming lower vulnerability and/or more adaptation (Diaz and Moore, 2017); this literature is comprehensively summarised in Cross-Working Group Chapter Box ECONOMIC. Impacts at high levels of warming are particularly uncertain, as all methodologies require extrapolation and insufficiently incorporate possible tipping elements in the climate system (Kopp et al., 2016).

Annual economic output losses in developing countries could exceed the worst country-level losses during historical economic recessions (*medium confidence*). Assuming global warming of ~4°C by 2100, historical adaptation levels and high vulnerability, losses across Sub-Saharan Africa may reach 12% of GDP by 2050 (Baarsch et al., 2020) and 80% by 2100 (Burke et al., 2015), and ~9% on average across developing countries by 2100 (Acevedo et al., 2017). The largest estimates are debated and depend on assumptions about development trends, adaptive capacity, and whether temperature impacts the level or growth rate of economic activity (Kalkuhl and Wenz, 2020). Severe risks are more likely in (typically hotter) developing countries because of nonlinearities in the relationship between economic damages and temperature (Burke et al., 2015; Acevedo et al., 2017). These risks are highest in scenarios and countries with: a large portion of the workforce employed in highly exposed industries (Acevedo et al., 2017); a high concentration of population and economic activity on coastlines (Hsiang and Jina, 2014; Acevedo et al., 2017); and an increase in the frequency or intensity of disasters triggered by natural hazards (Berlemann and Wenzel, 2018; Botzen et al., 2019). Whether baseline economic growth may help avoid severe future risks is highly uncertain (Dell et al., 2012; Burke et al., 2015; Acevedo et al., 2017; Deryugina and Hsiang, 2017).

ii) Under medium warming pathways, climate change risks to poverty would become severe if vulnerability is high and adaptation is low (*limited evidence*, *high agreement*). We define poverty in terms of absolute consumption levels and define severity as tens to hundreds of millions of additional people in poverty relative to the number without climate change (globally) or an absolute increase in the number of people living in poverty compared with today (nationally or locally). This global impact is comparable to the effect of the 2007 food price shock (De Hoyos and Medvedev, 2009) and the 2020 COVID-19 pandemic (World Bank, 2020) and can be compared to about 700 million in poverty in 2017, down from 1.9 billion in 1990 (World Bank, 2020).

In a high-vulnerability development pathway, climate change in 2030 could push 35–132 million people into extreme poverty, in addition to the people already in poverty assuming climate is unchanged (disregarding impacts from natural variability; Hallegatte and Rozenberg, 2017; Jafino et al., 2020). In a low-warming pathway, risks from mitigation costs could also be severe if no progressive redistribution from carbon pricing revenues is applied (Soergel et al., 2021). At the national level, there is *limited evidence* of climate change causing an absolute increase in poverty (e.g., absolute increase of ~1–2% yr^{-1} through 2040, Montaud et al., 2017). Potentially severe risks to poverty are also supported by (1) the observed impacts of past disasters (Winsemius et al., 2018; Hallegatte et al., 2020; Rentschler and Melda, 2020) and previous crises

16

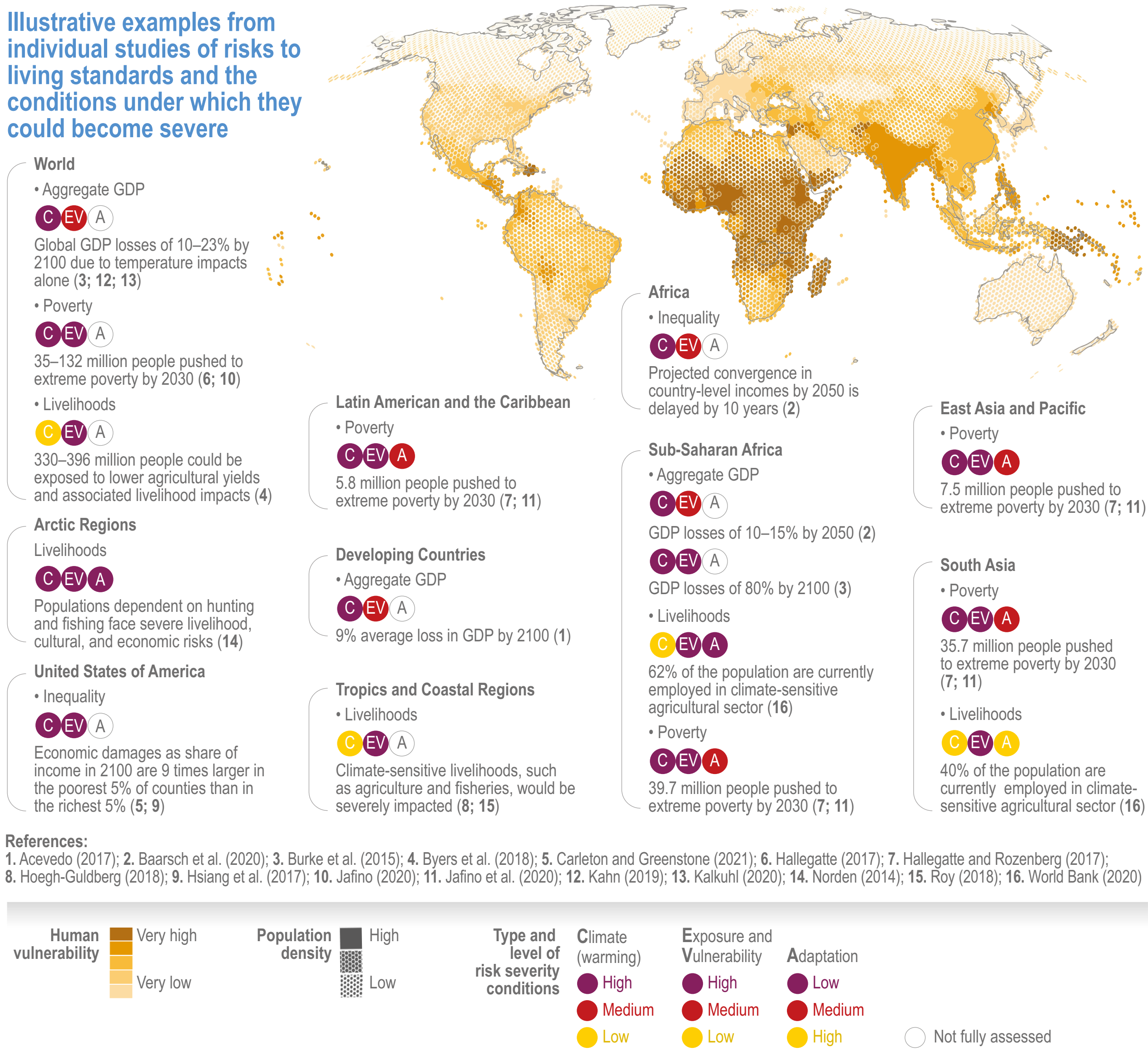

Figure 16.9 | Illustrative examples from individual studies of risks to living standards and the conditions under which they could become severe. Selected studies are not representative of the literature, but provide examples of potentially severe risks to aggregate economic output, poverty and livelihoods. High, medium and low levels of warming, exposure/vulnerability and adaptation are defined as in Figure 16.10.

such as food price shocks (Ivanic and Martin, 2008) or current diseases (WHO, 2018) on poor people and on poverty; (2) the expectation that these events will become more intense or frequent in some regions (WGI Chapter 12, Ranasinghe et al., 2021); and (3) population growth and the low adaptive and coping capacities of the poor (Leichenko and Silva, 2014; Huynh and Stringer, 2018; Thomas et al., 2020). This literature provides indirect evidence that climate change will keep many people poor and may cause more than tens of millions to fall into poverty (*limited evidence*, *high agreement*).

iii) Climate change poses severe risks to livelihoods at low levels of warming, high exposure/vulnerability and low adaptation in climate-sensitive regions, ecosystems and economic sectors (*high confidence*), where severity refers to the disruption of livelihoods for tens to hundreds of millions of additional people (Arnell and Lloyd-Hughes, 2014; Liu et al., 2018). More widespread severe risks would occur at high levels of warming (with high exposure/vulnerability and low adaptation) where there is additional potential for one or more social or ecological tipping points to be triggered (Cai et al., 2015; Cai et al., 2016b; Kopp et al., 2016; Steffen et al., 2018; Lenton et al., 2019), and for severe impacts on livelihoods to cascade from relatively more climate-sensitive to relatively less climate-sensitive sectors and regions (*medium confidence*) (Lawrence et al., 2020). Severity assessment is based on the current magnitude of exposure and vulnerability across multiple social and ecological systems, projected future exposure and vulnerability, and the rate at which hazard frequency or intensity is expected to increase (Otto et al., 2017; Roy et al., 2018; Li et al., 2019, Section 8.5). Without effective adaptation measures, regions with high dependence on climate-sensitive livelihoods—particularly agriculture and fisheries in the tropics and coastal regions—would be severely impacted even at low levels of warming (*high confidence*) (Hoegh-Guldberg et al., 2018b; Roy et al., 2018). For example, it is estimated that 330–396 million people could be exposed to lower agricultural yields and associated livelihood impacts at warming between 1.5°C and 2°C (Byers et al., 2018). Risks to the 200 million people with livelihoods derived from small-scale fisheries would also be severe, given sensitivity to ocean warming, acidification and coral reef loss occurring beyond 1.5°C (Cheung et al., 2018b; Froehlich et al., 2018; Free et al., 2019; Barnard et al., 2021). Livelihoods in highly exposed locations, such as Small Island Developing States, low-lying coastal areas, arid or semiarid regions, the Arctic, and urban informal settlements or slums, are particularly vulnerable (Ford et al., 2015c; Hagenlocher et al., 2018; Ahmadalipour et al., 2019; Tamura et al., 2019). Within populations, the poor, women, children, the elderly and Indigenous populations are especially vulnerable due to a combination of factors, including gendered divisions of paid and/or unpaid labour, as well as barriers in access to information, skills, services or resources (Bose, 2017; Thomas et al., 2019b; Anderson and Singh, 2020; Adzawla and Baumüller, 2021) (*high confidence*). Future structural transformation could moderate risk severity by improving adaptive capacity, creating livelihoods in less climate-sensitive sectors, or by enabling sustainable migration to less climate-sensitive locations (Henderson et al., 2017; Roy et al., 2018). However, successful risk moderation would depend upon simultaneous avoidance of both climate-change-related and mitigation-related (Doelman et al., 2019; Fujimori et al., 2019; Doelman et al., 2020) or maladaptation-related risks (Magnan et al., 2016; Benveniste et al., 2020; Schipper, 2020).

Climate change also could increase income inequality between countries (*high confidence*) as well as within them (*medium evidence*, *high agreement*) resulting from and exacerbating impacts on aggregate economic activity, poverty and livelihoods. Increasing inequality implies larger impacts on the least well-off, threatens their ability to respond to climate hazards, compromises basic principles of fairness and established global development goals, and potentially threatens the functioning of society and long-term progress (Roe and Siegel, 2011; Cingano, 2014; van der Weide and Milanovic, 2018). There is evidence that warming has slowed down the convergence in between-country income in recent decades (Diffenbaugh and Burke, 2019). Future impacts may halt or even reverse this trend during this century owing to high sensitivity of developing economies (Burke et al., 2015; Pretis et al., 2018; Baarsch et al., 2020), although projections depend as much or more on future socioeconomic development pathways and mitigation policies as on warming levels (Takakura et al., 2019; Harding et al., 2020; Taconet et al., 2020). Within countries, studies that find adverse impacts on low-income groups imply an increase in inequality (Hallegatte and Rozenberg, 2017; Hsiang et al., 2017), although evidence for long-term climate impacts on within-country inequality at global scale remains limited.

16.5.2.3.5 Risk to human health (RKR-E)

This RKR includes (i) mortality from heat, and morbidity and mortality from (ii) vector-borne diseases and (iii) waterborne diseases. It builds on KRs identified primarily in Chapter 7 and health risks in regional chapters.

A severe risk to health is the potential for a widespread, substantial worsening of health conditions due to climate change. We measure severity in terms of the magnitude of mortality and morbidity. We consider a severe mortality impact to be a sustained increase in the crude mortality rate (CMR) of more than about 2–4 deaths per 10,000 people yr^{-1}. This range of increase is consistent with current mortality impacts with substantial global effects, including traffic fatalities (CMR of 1.6/10,000 yr^{-1}; IHME, 2019) and the COVID-19 pandemic (CMR of 4/10,000 yr^{-1}, as of April 2021, expressed as an annualised rate; Ritchie et al., 2021). We use these global rates as thresholds in all cases, recognising that they reflect substantial variation across regions and sub-populations (for other points of comparison, see IHME, 2019). Morbidity impacts are measured in numbers of disease cases or hospital admissions. We find that severe health impacts are projected to occur for particular sub-populations and regions where vulnerability is currently high and is assumed to persist into the future; we focus our assessment on these cases. In other cases, literature is either inadequate or does not support severe outcomes.

i) Risks of heat-related mortality would become severe at global and regional scales with high levels of warming and vulnerability (*medium confidence*). Under these conditions (SSP3–8.5), accounting for adaptation, heat mortality would increase the global CMR by up to 7/10,000 yr^{-1} by 2100 (Carleton et al., 2020). For example, the USA would experience a CMR increase of 2–4/10,000 yr^{-1} by the end of the century (medium vulnerability without adaptation, and recent vulnerability with adaptation, respectively) (Weinberger et al., 2017; Shindell et al., 2020). Also assuming no adaptation and recent vulnerability, most populations of the world would experience an increase of 2–10 percentage points in the percentage of deaths attributable to heat by the end of the century (RCP8.5) (Vicedo-Cabrera, 2018a; Gasparrini, 2017). Harmful conditions for health are expected to increase in frequency and intensity over all land areas along with the rising temperatures in the coming decades (Pal and Eltahir, 2016; Russo et al., 2017; Ranasinghe et al., 2021; Saeed et al., 2021; Schwingshackl et al., 2021). Projections of exposure are an incomplete measure of risk but suggest the potential for severe impacts. For example, the percent of global population exposed to deadly heat stress would increase from today's 30% to 48–74% by the end of the century depending on level of warming and population distribution (Mora et al., 2017). Projected impacts are larger if exposure and/or vulnerability increases due to ageing of the population or increased inequality (Weinberger et al., 2017; Chen et al., 2020a; IPCC, 2021) and with limited adaptation capacity (e.g., poor infrastructure, limited air conditioning, few medical and public health resources) (SM16.7.4) (Carleton et al., 2020). Higher risks are also expected in urban areas owing to hazard amplification (i.e., urban heat island effect) and in highly dense settlements with other environmental hazards such as air pollution (Zhao et al., 2018; Sera et al., 2019).

ii) Risks of vector-borne disease would become severe with high warming and current vulnerability, concentrated in children and in sensitive regions (*medium confidence*). Severity is defined by regionally substantial numbers of additional malaria deaths, disease cases and episodic hospitalisation demands (for dengue).

With high warming, the CMR for malaria among children under the age of 1 year could increase by 5.2–10.1/10,000 yr^{-1} in Africa under current vulnerability levels. This estimate assumes a net increase of 70–130 million more people exposed to potential disease transmission due to climate change in a high-warming scenario (RCP8.5, end of century) (Caminade et al., 2014; Colón-González et al., 2021; Ryan et al., 2020), representing a 14–27% increase in the current population at risk (Ryan et al., 2020), and assumes children under 1 year of age are facing the same crude mortality in the future as for the African region today (IHME, 2019). The largest increase is observed in Eastern Africa, where the population exposed could nearly double by 2080 (Ryan et al., 2020) without accounting for population growth, driven mainly by changes among previously unexposed populations at higher altitude areas (Colón-González et al., 2021). Actual future disease burden of malaria will be highly sensitive to regional socioeconomic development and the effectiveness of malaria intervention programs.

For dengue, with high warming and current levels of vulnerability there could be as much as a doubling of cases and hospital admissions per year globally, relative to today, driven by both warming and population growth. These estimates are derived by assuming similar relative incidence rates as today (Shepard et al., 2016) combined with projections of a more than doubling of the population exposed to potential disease transmission by the end of the century in a high-warming scenario (RCP8.5), although much of this increase is driven by population growth (Colón-González et al., 2018; Monaghan et al., 2018; Messina et al., 2019). There are around 3 billion people exposed to dengue today.

iii) Climate change would lead to severe risks of morbidity and mortality caused by waterborne diseases, particularly for diarrhoea in children in many lower- and middle-income countries (LMICs) and where vulnerability remains high (*medium confidence*). The global CMR for diarrhoea is 1.98 for all ages, but varies by region and age group, reaching as high as 53 for <1-year-olds in Africa (IHME, 2019). In these vulnerable populations, even a small percentage increase can lead to substantial additional morbidity and mortality. For example, assuming no change in vulnerability or population, an increase in diarrhoea mortality of only 5% over 2019 baseline rates would create a severe risk (CMR of 2.0) for children under the age of 1 in the World Health Organization (WHO) Africa (AFRO) region. This percent increase due to climate change is plausible since diarrhoea incidence increases of 7% (95% confidence interval 3–10%) are associated with a 1°C increase in ambient temperature (WHO, 2014; Carlton et al., 2016), and diarrhoea is positively associated with heavy rainfall and flooding events (Levy et al., 2016), expected in some regions (WGI). Assuming vulnerability remains the same as today, mortality and morbidity rates would increase equivalently.

However, risks will be highly dependent on development trajectories, given that waterborne disease transmission is exacerbated by lack of clean drinking water and sanitation systems, inadequate food safety and hygiene conditions, lack of flood and drought protections, and interactions with other risks such as cholera outbreaks, food insecurity and infrastructure damage. Climate change threatens the progress that has been made towards reducing the burden of diarrhoea. For example, in Sub-Saharan Africa, while overall diarrhoea rates are expected to continue to decline (GBD 2016 Diarrhoeal Disease Collaborators, 2018), warming in 2030 (relative to the late 20th century) is projected to lead to diarrhoeal deaths in children under 15 equivalent to a CMR increase of 0.56/10,000 yr^{-1} (based on population projections for the region and age group; UN, 2020; WHO, 2014). In China, by 2030, climate change could delay progress towards reducing waterborne disease burden by 8–85 months (Hodges et al., 2014).

16.5.2.3.6 Risk to food security (RKR-F)

Climate change affects food security primarily through impacts on food production, including crops, livestock and fisheries, as well as disruptions in food supply chains, linked to global warming, drought, flooding, precipitation variability and weather extremes (Myers et al., 2017; FAO et al., 2018; Mbow et al., 2019). This RKR builds on Key Risks identified primarily in the Food, Fibre and Other Ecosystem Products Chapter, some sectoral (Health), and regional (Africa, Australasia, Central and South America, North America) chapters, as well as SR15, SRCCL and SROCC.

The severity of the risk to food security is defined here using a combination of criteria including the magnitude and likelihood of adverse consequences, affecting tens to hundreds of millions of people, timing of the risk and ability to respond to the risk. In this assessment, we use the number of undernourished people as a proxy outcome of these dimensions and their multiple interactions.

Climate change will pose severe risks in terms of increasing the number of undernourished people, affecting tens to hundreds of million people under High vulnerability and High warming, particularly among low-income populations in developing countries (*high confidence*). Extreme weather events will increase risks of undernutrition even on a regional scale, via spikes in food price and reduced income (*high confidence*) (FAO et al., 2018, Hickey and Unwin, 2020; Mbow et al., 2019). The timing of these impacts and our ability to respond to them vary based on the level of GHG emissions and Shared Socioeconomic Pathways (SSP).. Under a low vulnerability development pathway (SSP1), climate change starts posing a moderate risk to food security above 1°C of global warming (i.e., impacts become detectable and attributable to climate-related factors), while beyond 2.5°C the risk becomes high (widespread impacts on larger numbers or proportion of population or area, but with the potential to adapt or recover) (Hurlbert et al., 2019). Under high vulnerability–high warming scenario (i.e., SSP3-RCP6.0), up to 183 million additional people are projected to become undernourished in low-income countries owing to climate change by 2050 (Mbow et al., 2019). Climate-related changes in food availability and diet quality are estimated to result in a crude mortality rate of about 54 deaths per million people with about 2°C warming by 2050 (SSP2, RCP8.5), most of them projected to occur in South and East Asia (67–231 deaths per million depending on the country) (Springmann et al., 2016). In a medium vulnerability–high warming scenario

(SSP2, RCP6.0), Hasegawa et al. (2018) project that the number of undernourished people increases by 24 million in 2050, compared with outcomes without climate change and accounting for the CO_2 fertilisation effect. This number increases by around 78 million in a low-warming scenario (RCP2.6) accounting for the impacts of both climate change and mitigation policies. Caveats to these modelling studies are that most models (crop models in particular) are designed for long-term change in climate but not suited to project the impacts of short-term extreme events. The inclusion of adaptation measures into modelling estimates remains selective and partial.

Climate change risks of micronutrient deficiency will become severe in high-vulnerability development pathways and in the absence of societal adaptation, leading to hundreds of millions of additional people lacking key nutrients for atmospheric CO_2 levels above 500 ppm (*high confidence*) (Myers et al., 2017; Nelson et al., 2018; Mbow et al., 2019). For example, concentration of many micronutrients (e.g., phosphorus, potassium, calcium, sulphur, magnesium, iron, zinc, copper and manganese) can decrease by 5–10% under atmospheric CO_2 concentrations of 690 ppm (3.5°C warming). The decline in zinc content is projected to lead to an additional 150–220 million people affected by zinc deficiency with increases in existing deficiencies in more than 1 billion people (Myers et al., 2017). Similarly, decrease in protein and micronutrient content in rice due to a higher CO_2 concentration (568–590 ppm) can lead to 600 million people with rice as a staple at risk of micronutrient deficiency by 2050 (Zhu et al., 2018). Additionally, the impact on protein content of increased CO_2 concentration (>500 ppm) can lead an additional 150 million people with protein deficiency by 2050 (within the total of 1.4 billion people with protein deficiency) in comparison with the scenario without increased CO_2 concentration (Medek et al., 2017).

16.5.2.3.7 Risk to water security (RKR-G)

Water security encompasses multiple dimensions: water for sanitation and hygiene, food production, economic activities, ecosystems, water-induced disasters, and use of water for cultural purposes (Chapter 4; Box 4.1; Section 4.6.1). Water security risks are a combination of water-related hazards such as floods, droughts and water quality deterioration, and exposure of vulnerable groups exposed to too little, too much or contaminated water. Reasons for these can include both environmental conditions and issues of safety and access influenced by effectiveness of water governance (Sadoff et al., 2020). These are manifest through loss of lives, property, livelihoods and culture, and impacts on human health and nutrition, ecosystems and water-related conflicts which in turn can drive forced human displacement.

This RKR focuses on three types of risks with the potential to become severe: those associated with water scarcity, those driven by water-related disasters, and those impacting indigenous and traditional cultures and ways of life. Risk to water security constitutes a potentially severe risk because climate change could impact the hydrologic cycle in ways that would lead to substantial consequences for the health, livelihoods, property and cultures of large numbers of people. For those associated with water scarcity, 'severe' refers to magnitude (number of people in areas where water scarcity falls below recognised thresholds for adequate water supply per capita), along with the likelihood of unforeseen increases in water scarcity that outpace the ability to prepare for the increased risk by putting in place new large-scale infrastructure within the required time scale. For those associated with extreme events, 'severe' refers to magnitude (numbers of people affected, including deaths, physical health impacts including disease, mental health impacts, loss of livelihoods, loss of or damage to property) and timing (e.g., events coinciding with other stresses, e.g., a pandemic occurring at a time when local infrastructures are weakened by an extreme weather event). Important water-related extreme events include river flooding caused by heavy and/or prolonged rainfall, glacial lake outburst floods, and droughts. For those impacting cultures, 'severe' refers to the loss of key aspects of traditional ways of life. This includes consequences of the above two KRs.

Risks associated with water scarcity have the potential to become severe based on projections of large numbers of people becoming exposed to low levels of water availability per person, where 'water availability' includes fresh water in the landscape, including soil moisture and streamflows, available for all uses including agriculture as a dominant sector. Approximately 1.6 billion people currently experience 'chronic' water scarcity, defined as the availability of less than 1000 m^3 of renewable sources of fresh water per person per year (Gosling and Arnell, 2016). In this context, we define a severe outcome as an additional 1 billion people experiencing 'chronic' water scarcity, relating to all uses of water, representing an increase of a magnitude comparable to current levels. The global number of people experiencing chronic water scarcity is projected to increase by approximately 800 million to 3 billion for 2°C global warming, and up to approximately 4 billion for 4°C global warming, considering the effects of climate change alone, with a 9 billion population (Gosling and Arnell, 2016). Severe outcomes are projected to occur even with no changes in exposure: present-day exposure is defined here as 'medium' since either an increase or decrease in exposure could be possible. Vulnerability is not quantified in the literature assessed here, so in this assessment it is considered that severe outcomes could occur with present-day levels of vulnerability, again defined here as 'medium'. Particularly severe outcomes (i.e., the high end of these ranges) are driven by regional patterns of climate change bringing severe reductions in precipitation and/or high levels of evapotranspiration in the most highly populated regions, leading to very substantial reductions in water availability compared with demand. There is strong consensus across models that water scarcity is projected to increase across substantial parts of the world even though projections disagree on which specific areas would see this impact. Moreover, a projected decrease in water scarcity in some regions does not prevent the increase in water scarcity in other regions becoming severe. Hence there is *high confidence* that risks to water scarcity have the potential to become severe due to climate change. Consequences of water scarcity include potential competition and conflicts between water users (Vanham et al., 2018), damaging livelihoods, hindering socioeconomic development and reducing human well-being, for example through malnutrition resulting from inadequate water supplies leading to long-term health impacts such as child stunting (Cooper et al., 2019). The avoidance of these consequences at high levels of water scarcity would require transformational adaptations including large-scale interventions such as dams and water transfer infrastructure (Greve et al., 2018). Since these require many years or

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even decades for planning and construction, and are also costly and irreversible and can potentially lead to lock-in and maladaptation, the potential for inadequate policy decisions made in the context of high uncertainties in regional climate changes brings the risk of a shortfall in adaptation. Around 2050, at approximately 2°C global warming, the risk of a substantial adaptation shortfall and hence severe outcomes for water scarcity have a relatively high likelihood across large parts of the southern USA and Mexico, northern Africa, parts of the Middle-East, northern China, and southern Australia, as well as many parts of Northwest India and Pakistan (Greve et al., 2018).

Risks associated with water-related extreme events and disasters have the potential to become severe based on projections of large numbers of people or high values of assets being affected. The risks to people from disasters can often only be quantified in terms of the hazard and exposure (the number of people affected), rather than the full consequences such as number of deaths, injuries or other health outcomes, as these often depend on complex or unpredictable factors such as the effectiveness of emergency and humanitarian responses or the access to healthcare. With approximately 50 million people per year currently affected by flooding (Alfieri et al., 2017), we define severe outcomes as more than 100 million people affected by flooding. At 2°C global warming, between approximately 50 million and 150 million people are projected to be affected by flooding, with figures rising to 110 million to 330 million at 4°C global warming. These projections assume present-day population and no additional adaptation, so no changes in exposure. Increased flood risk is projected by the WHO to lead to an additional 48,000 deaths of children under 15 years due to diarrhoea by 2030, with Sub-Saharan Africa impacted the most (WHO, 2014). Other consequences of floods that already occur include deaths by drowning, loss of access to fresh water, vector-borne diseases, mental health impacts, loss of livelihoods and loss of or damage to property. Many of these consequences depend on the vulnerability of individuals, households or communities to flooding impacts, for example through the presence or absence of measures to safeguard health and livelihoods, such as through infrastructure services, insurance or community support. The risks associated with these consequences could increase if there were no local adaptations to counter the effect of increased levels of hazard by reducing exposure and/or vulnerability. Climate-related changes to extreme events that would lead to these severe outcomes include increased frequency and/or magnitude of river floods of flash floods due to heavy or long-lasting precipitation, rapid snowmelt, or catastrophic failure of glacial lake moraine dams. These climate conditions are projected to increase with global warming.

Risks to cultural uses of water can become severe if there is permanent loss of aspects of communities' cultures due to changes in water, including loss of areas of ice or snow with spiritual meanings, loss of culturally important places of access to such places, and loss of culturally important subsistence practices including by Indigenous People (Chapter 4). This includes mountain regions where changes in the cryosphere are having profound impacts (Cross-Chapter Paper 5). In these cases, severe outcomes would be defined locally rather than globally. Communities that lost a dominant environmental characteristic deeply associated with its cultural identity would be considered to be severely impacted. For example, due to the central role that travel on sea ice plays in the life of Inuit communities, providing freedom and mental well-being, loss of sea ice can be argued to represent environmental dispossession of these communities (Durkalec et al., 2015). Traditional ways of life are therefore threatened, and resulting changes would be transformative rather than adaptive. Similarly, changes in streamflow affecting the availability of species for traditional hunting can also negatively impact Indigenous communities (Norton-Smith et al.). Such changes are already being seen at current levels of warming, but studies remain somewhat limited in number, so this assessment is assigned *medium confidence* because of *medium evidence* and medium agreement. WGI conclude that it is *virtually certain* that further warming will lead to further reductions in Northern Hemisphere snow cover, and mass loss in individual glacier regions is projected to be between approximately 30% and 100% by 2100 under high-warming scenarios (Chapter 4). Streamflows are projected to change in most major river basins worldwide by several tens of percent at 4°C global warming (Chapter 4).

There is strong potential for increases in water scarcity, flooding, loss of snow and ice and changes in water bodies to lead to severe outcomes such as deaths from water-related diseases, drowning and starvation, long-term health impacts arising from malnutrition and diseases, loss of property, loss of existence or access to places of cultural significance, loss of livelihoods and loss of aspects of culture especially for Indigenous People with traditional lifestyles. The numbers of people affected are projected to range from hundreds of millions to several billion, depending on the level of global warming and socioeconomic futures. A key aspect of the risk is the high uncertainty in future regional precipitation changes in many regions of high vulnerability, including the potential for large and highly impactful changes, for which it may not be possible to provide adaptation measures before they become needed, leading to a high likelihood of adaptation deficits.

16.5.2.3.8 Risks to peace and to human mobility (RKR-H)

This RKR includes risks to peace within and among societies from armed conflict as well as risks to human mobility, epitomised by involuntary migration and displacement within and across state borders and involuntary immobility. Breakdown of peace and the inability of people to choose to move or stay challenge core elements of human security (Adger et al., 2014). Risks to peace also inform the agency and viability of mobility decisions. However, evidence does not indicate that human mobility constitutes a general risk to peace.

Breakdown of peace, materialised as overt or covert violence across social and spatial scales, constitutes a key risk because of its potential to cause widespread loss of life, livelihood and well-being. Such impacts are considered severe if they result in at least 1000 excess battle-related deaths in a country in a year. This threshold is consistent with the conventional definition of war (Pettersson and Öberg, 2020). However, because armed conflict routinely causes significant material destruction, triggers mass displacement, threatens health and food security, and undermines economic activity and living standards (Baumann and Kuemmerle, 2016; FAO et al., 2017; de Waal, 2018), risks to peace can be considered severe also when conflict has cascading effects on other aspects of well-being and amplifies vulnerability to other RKRs. Beyond the magnitude of such impacts, the rapidity with which armed conflict can escalate and the challenges of ending violence once it has broken out imply potentially very limited time and ability to respond for populations at risk.

Mobility is a universal strategy for pursuing well-being and managing household risks (Section 7.2.6; Cross-Chapter Box MIGRATE in Chapter 7, UN, 2018) and, where it occurs in a safe and orderly fashion, can reduce social inequality and facilitate sustainable development (Franco Gavonel et al., 2021). Involuntary mobility constitutes a key risk because it implies reduced human agency with high potential for significant economic losses and non-material costs, an unequal gender burden, and amplified vulnerability to other RKRs (Schwerdtle et al., 2018; Adger et al., 2020; Maharjan et al., 2020; Piggott-McKellar et al., 2020). Climate change also may erode or overwhelm human capacity to use mobility as a coping strategy, producing involuntarily immobile populations (Adams, 2016). A severe impact is when a large share of an affected population is forcibly displaced or prevented from moving, relative to normal mobility patterns, at local to global scale. However, because mobility may be a favourable mechanism for reducing risk or an adverse outcome of risk, depending on the circumstances under which it occurs, it is not possible to specify a simple quantitative threshold for when impacts become severe.

Complex causal pathways and lack of long-term projection studies presently prevent making confident quantitative judgements about how risks to peace and human mobility will materialise in response to specific warming levels, development pathways and adaptation scenarios. Literature concludes with *medium confidence* that risks to peace will increase with warming, with the largest impacts expected in weather-sensitive communities with low resilience to climate extremes and high prevalence of underlying risk factors (Theisen, 2017; Busby, 2018; Koubi, 2019; von Uexkull and Buhaug, 2021). However, climate-driven impacts on societies will depend critically on future political and socioeconomic development trajectories (*limited evidence*, *high agreement*), suggesting that risks due to climate change are relevant primarily for highly vulnerable populations and for pessimistic development scenarios. Overall risks to peace may decline despite warming if non-climatic determinants are reduced sufficiently in the future.

Regular human mobility will continue regardless of climate change, but mobility-related risks will increase with warming, notably in densely populated hazard-prone regions, in small islands and low-lying coastal zones, and among populations with limited coping capacity (RKR-A; Section CCP2.2.2; Chapter 7) (*high confidence*). Such risks can become severe even with limited levels of warming for populations with low adaptive capacity and whose settlements and livelihoods are critically sensitive to environmental conditions (*medium evidence*, *high agreement*). Likewise, risk of involuntary immobility could become severe for highly vulnerable populations with limited resources, even with moderate levels of warming (*limited evidence*, *high agreement*). Critically, population growth and shifting exposure will interact with warming to shape these risks (Davis et al., 2018; Hauer et al., 2020; Robinson, 2020a). Although climate-driven human mobility generally does not increase risks to peace (*medium confidence*), armed conflict is a major driver of forced displacement (*high confidence*).

Expert elicitation estimates that 4°C warming above pre-industrial levels will have severe and widespread effects on armed conflict with 26% probability, assuming no change from present levels in non-climatic drivers (Mach et al., 2019). That judgement refers to impacts that exceed the threshold for severity considered here, suggesting that global warming of 4°C would produce severe risks to peace under present societal conditions (*low confidence*). Future risks to peace will remain strongly influenced by socioeconomic development (Hegre et al., 2016). A study of Sub-Saharan Africa that accounts for both temperature and socioeconomic changes, 2015–2065, concludes that determinants other than rising temperatures, notably quality of governance, will remain most influential in shaping overall levels of violence even in the high-warming RCP8.5 scenario (Witmer et al., 2017).

A larger empirical literature offers indirect evidence that climate change may produce severe risks to peace within this century by demonstrating how climate variability and extremes affect contemporary conflict dynamics, especially in contexts marked by low economic development, high economic dependence on climate-sensitive activities, high or increasing social marginalisation, and fragile governance (*medium confidence*) (Sections 7.2.7, 16.2, Schleussner et al., 2016a; Von Uexkull et al., 2016; Busby, 2018; Harari and Ferrara, 2018; Ide et al., 2020; Scartozzi, 2020).

Climatic risks interact with economic, political and social drivers to create risks to human mobility both directly (through the threat of physical harm and destruction of property and infrastructure) and indirectly (via adverse impacts on livelihood and well-being). Extreme weather events are leading causes of forced displacement (Cross-Chapter Box MIGRATE in Chapter 7, IDMC, 2020). Projected increases in the frequency and severity of extreme events (Ranasinghe et al., 2021) in combination with future population growth in hazard-prone regions (e.g., Merkens et al., 2016) suggest that risks to mobility will increase in response to future global warming (Robalino et al., 2015; Davis et al., 2018; Rigaud et al., 2018). For example, moving from RCP2.6 to RCP8.5 (entailing ~0.5°C additional global warming by 2050) is projected to increase internal migration by 2050 from 51 [31–72] million to 118 [92–143] million people across South Asia, Latin America and Africa (Rigaud et al., 2018), although those estimates principally comprise migrants, whose decisions are also informed by non-climatic drivers, rather than involuntarily displaced people. Global levels of flood displacement are estimated to increase by 50% with each 1°C warming (Kam et al., 2021). Should future warming reduce adaptation options for vulnerable populations (Section 16.4), a consequence may be higher levels of involuntary migration and immobility (Grecequet et al., 2017; Otto et al., 2017). There is little evidence that climate-driven mobility negatively affects peace (Brzoska and Fröhlich, 2016; Burrows and Kinney, 2016; Freeman, 2017; Petrova, 2021).

There is *high agreement* that even moderate levels of future SLR will severely amplify involuntary migration and displacement in small islands and densely populated low-lying coastal areas in the absence of appropriate adaptive responses (*high confidence*) (Hauer, 2017; IPCC, 2019b; Hauer et al., 2020; McMichael et al., 2020, Sections 15.3.4, 16.4). In some contexts, climate change also may accelerate migration towards high-exposure coastal areas (Bell et al., 2021). Under a high-emissions RCP8.5 scenario (global median 0.7 m SLR by 2100), the number of people exposed to annual coastal flooding may more than double by 2100 compared with present numbers (Kulp and Strauss, 2019). In the

USA alone, SLR of 0.9 m could potentially put 4.2 million people at risk of inundation by the end of this century (Hauer, 2017). However, number of people exposed to SLR does not evenly translate to forcibly displaced populations (Hauer et al., 2020). Ascertaining how many people will move forcibly or as an adaptive response to SLR is inherently challenging because of the complex and highly individual nature of migration decisions (Black et al., 2013; Boas et al., 2019; Piguet, 2019; Bell et al., 2021). Implications of climate change for risks to human mobility across borders are even harder to quantify and highly uncertain, due to unknown developments in legal and political conditions that govern international migration (McLeman, 2019; Wrathall et al., 2019).

16.5.2.4 Synthesis of the Assessment of Representative Key Risks

Figure 16.10 provides a synthesis of the RKRs and the conditions that lead to severe risks over the course of the 21st century, as assessed in Sections 16.5.2.3.1–16.5.2.3.8 (see Table SM16.14 for further description). It identifies sets of conditions—defined by levels of warming, exposure/vulnerability and adaptation—that would produce severe risk with a particular level of confidence. The risks are of two scopes: broadly applicable, meaning that the risks described by a particular KR or RKR would be severe pervasively and even globally; and specific, meaning that these risks would apply to particular areas, sectors or groups of people.

Five main messages arise from this synthesis:

Severe risk is rarely driven by a single determinant (warming, exposure/vulnerability, adaptation), but rather by a combination of conditions that jointly produce the level of pervasiveness of consequences, irreversibility, thresholds, cascading effects, likelihood of consequences, temporal characteristics of risk and the systems' ability to respond (*medium* to *high confidence*). In other words, climate risk is not a matter of changing CIDs only, but of the confrontation between changing CIDs and changing socio-ecological conditions.

In most of the RKRs, severe risk for broadly applicable situations requires high levels of warming or exposure/vulnerability, or low adaptation. In many cases, it is associated with several of these conditions occurring simultaneously (e.g., high warming and high vulnerability). Examples include low-lying coastal areas (RKR-A; *medium confidence*), loss of livelihoods (RKR-D; *medium confidence*) or armed conflicts (RKR-H; *low confidence*).

High warming and exposure/vulnerability combined with low adaptation is, however, not necessarily required to lead to severe risk, and various other sets of conditions can lead to such an outcome. For example:

Without high levels of warming. This is especially the case for terrestrial and marine ecosystems (RKR-B) and water security (RKR-G) for which even medium to low levels of warming will generate severe risk, depending on the processes considered (e.g., mass population-level mortality and ecological disruption for ecosystems). This is also the case when more specific situations are considered, for example in the case of (in)voluntary mobility of vulnerable populations with limited resources (RKR-H), and for some critical infrastructure in already highly exposed and vulnerable contexts (RKR-C).

With high levels of adaptation. High levels of adaptation will not necessarily avoid severe risk, as is illustrated by the cases of coral-dependent and arctic coastal communities (RKR-A), some terrestrial and marine ecosystems (RKR-B), and water scarcity and the cultural uses of water (RKR-G).

All RKR assessments indicate that risks are higher in high-vulnerability development pathways, and in some cases high vulnerability can occur in high-income societies. Examples include the possibility of increasing coastal settlement and the location of critical infrastructure in highly exposed locations (RKR-A, RKR-C), including to floods (RKR-G) and risks to terrestrial and marine ecosystems (RKR-B). The assessment therefore shows that, depending on socioeconomic trends especially in terms of equity, social justice and income sustainability, as well as on the ability to shift towards more climate-resilient economic and settlement systems (e.g., at the coast), higher-income societies also are at serious risk of being substantially affected in the decades to century to come.

In terms of the time frames, most of the RKRs conclude that severe risks to many dimensions (ecosystems, health, etc.) are expected to occur by the end of the 21st century and across the globe. Some RKRs, however, highlight that severe risk could occur far earlier, for example as soon as a warming level of 1.5°C or 2°C is reached, which means potentially well before mid-century (IPCC, 2021). In some cases, risks are already considered severe, for example after major climatic events such as tropical storms (RKR-A).

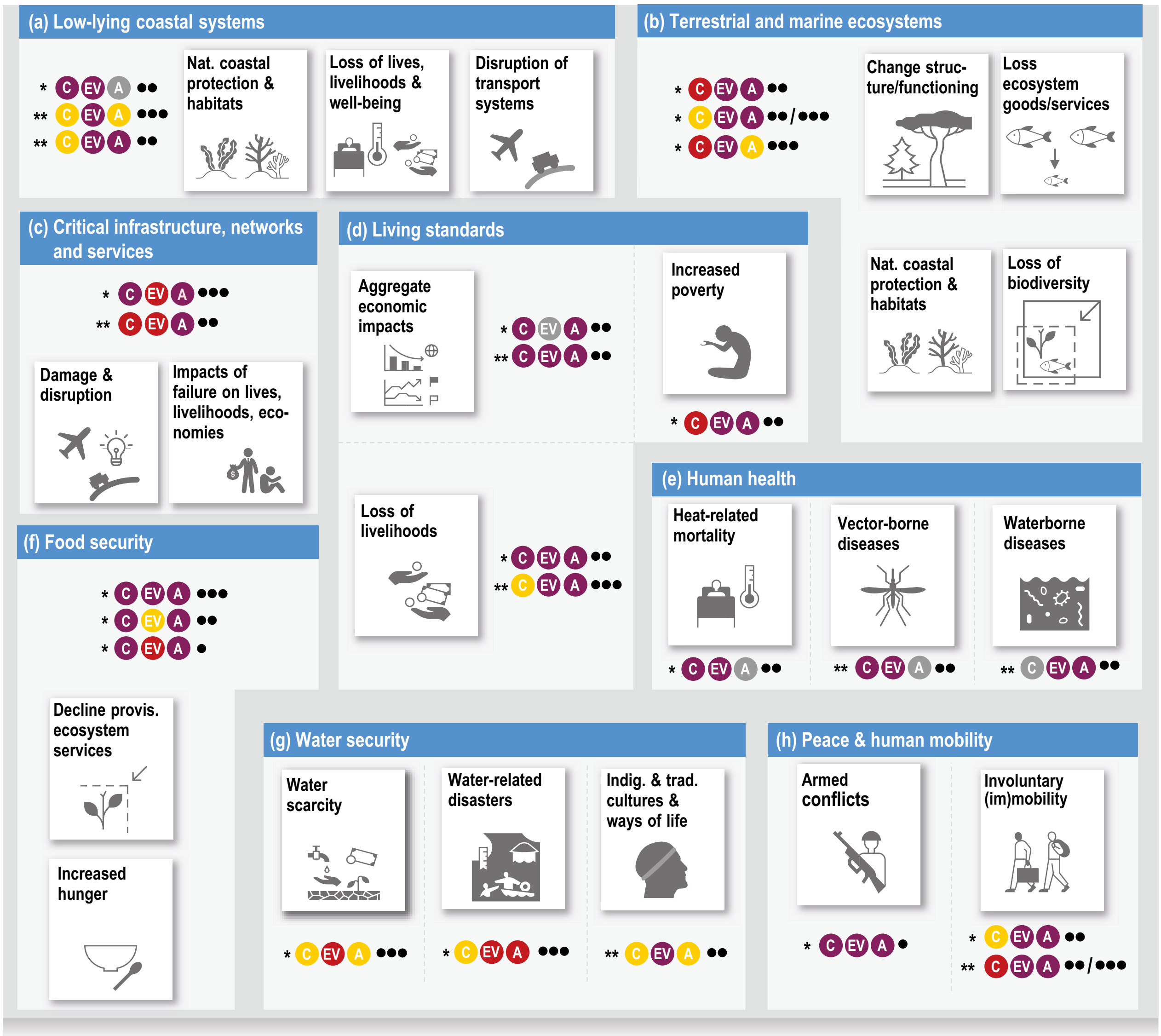
16.5.3 Variation of Key Risks across Levels of Global Warming, Exposure and Vulnerability, and Adaptation

This section builds on Sections 16.5.1 and 16.5.2 as well as on additional literature to illustrate how consequences associated with KRs and RKRs are projected to vary with three types of determinants: global average warming level, as a proxy for associated changes in climate hazards (CIDs, Ranasinghe et al., 2021); socioeconomic development pathway, as a means of capturing alternative future exposure and vulnerability conditions; and level of adaptation to reflect the extent to which successful adaptation is implemented. While these three dimensions are partly intertwined—for example, warming and adaptation scenarios are constrained by development pathways (Chapter 18)—this section assesses the influence of each dimension separately (Sections 16.5.3.2–16.5.3.4) to highlight how sensitivity varies across these dimensions for different KRs and RKRs. We then bring the dimensions together in an illustrative example (large deltas; Section 16.5.3.5).

16.5.3.1 Warming Level, Including Risks Avoided by Mitigation

Studies illustrating sensitivity to warming level typically do so by contrasting projected impacts for the same socioeconomic conditions but different climate pathways or temperature levels, often based on Representative Concentration Pathways (RCPs) (van Vuuren and Carter, 2014). We refer to future climate conditions either based on their global average warming level or as a 'high warming' scenario (based on RCP8.5), medium warming (RCP4.5 or RCP6.0) or low warming

Synthesis of the severity conditions for Representative Key Risks by the end of this century



Risk severity conditions by the end of this century

N.B.: only sets of conditions assessed in the chapter are reported

Type and level

- C Climate (warming); EV Exposure and Vulnerability: High / Medium / Low
- A Adaptation: High / Low
- Not fully assessed

Scope

- * Broadly applicable (risks are severe pervasively and even globally)
- ** Specific (risks are to particular areas sectors or groups of people)

N.B.: for details and examples, see Table SM16.24 in the supplementary information associated with the chapter.

Confidence levels

- ●●● High
- ●● Medium
- ● Low

Figure 16.10 | Synthesis of the severity conditions for Representative Key Risks by the end of this century. The figure does not aim to describe severity conditions exhaustively for each RKR, but rather to illustrate the risks highlighted in this report (Sections 16.5.2.3.1 to 16.5.2.3.8). Coloured circles represent the levels of warming (climate), exposure/vulnerability, and adaptation that would lead to severe risks for particular key risks and RKRs. Each set of three circles represents a combination of conditions that would lead to severe risk with a particular level of confidence, indicated by the number of black dots to the right of the set, and for a particular scope, indicated by the number of stars to the left of the set. The two scopes are 'broadly applicable', meaning applicable pervasively and even globally, and 'specific', meaning applicable to particular areas, sectors or groups of people. Details of confidence levels and scopes can be found in Section 16.5.2.3. In terms of severity condition levels (Section 16.5.2.3), for warming levels (coloured circles labelled 'C' in the figure), High refers to climate outcomes consistent with RCP8.5 or higher, Low refers to climate outcomes consistent with RCP2.6 or lower, and Medium refers to intermediary climate scenarios. Exposure-Vulnerability levels are determined by the RKR teams relative to the range of future conditions considered in the literature. For Adaptation, High refers to near maximum potential and Low refers to the continuation of today's trends. Despite being intertwined in reality, Exposure-Vulnerability and Adaptation conditions are distinguished to help understand their respective contributions to risk severity.

(RCP2.6 or 1.5°C scenarios). Because some of these scenarios assume no or minimal mitigation (RCP8.5, RCP6.0) while others do (RCP4.5, RCP2.6), differences in outcomes between them reflect risks avoided by mitigation (assuming consistent socioeconomic assumptions).

Some ecological risks (Chapter 2) are particularly sensitive to warming. For example, warm-water coral reefs are already experiencing High risk levels and are expected to face Very High risks under 1.5°C of global warming (Hoegh-Guldberg et al., 2018a; Bindoff et al., 2019). Some societal risks, such as human mortality due to extreme heat, also are sensitive to warming. A medium-warming scenario (relative to high warming) reduces projected global average mortality due to heat from seven deaths per 10,000 people yr^{-1} (7/10,000 yr^{-1}) by 2100 to ~1/10,000 yr^{-1}, assuming high-vulnerability societal conditions (Carleton et al., 2020). At the national level, without considering adaptation, reductions in a broader measure of mortality are projected across a range of countries including Colombia, the Philippines, and several in Europe (Guo et al., 2018), and exposure of the US population to high-mortality heatwaves is reduced by nearly half (Anderson et al., 2018a). Without considering changes in exposure or vulnerability, warming of 1.5–2°C (compared with 4–5°C) reduces global mortality impacts from an increase of 2.1–13.0% to 0.1–2.2% (Gasparrini et al., 2017; Vicedo-Cabrera et al., 2018a) and impacts in China from up to 4/10,000 yr^{-1} (Weinberger et al., 2017) to 0.3–0.5/10,000 yr^{-1} (Wang and Hijmans, 2019).

A low-warming scenario (relative to high warming) reduces aggregate economic impacts from around 7% of global GDP to less than 1% (Takakura et al., 2019), and changes impacts on the number of people suffering from hunger from an increase (by 7–55 million) to a decrease (by up to 6 million) (Janssens et al., 2020). Low versus high warming also reduces the coastal population at risk of flooding due to SLR from tripling by 2100 (relative to today) to doubling (Kulp and Strauss, 2019, Section 16.5.2.3.2). The SROCC estimates that SLR risks are reduced from Moderate-to-High to Moderate for large tropical agricultural deltas and resource-rich megacities, and from High and Very High to Moderate-to-High for Arctic human communities and urban atoll islands, respectively (Oppenheimer et al., 2019).

Higher levels of warming are projected to also generate higher income inequality between countries (e.g., Pretis et al., 2018; Takakura et al., 2019) as well as within them (Hallegatte et al., 2016) even though other drivers will be more important (Section 16.5.2.3.5). Similarly, climate and weather events are expected to play an increasing role in shaping risks to peace (*limited evidence, medium agreement)* and migration (*medium evidence, high agreement*) in the future, but uncertainty is high due to complex causal pathways and non-climate factors likely dominate outcomes (Section 16.5.2.3.8). There is *high agreement* that future SLR will amplify levels of forced migration from small islands and low-lying coastal areas in the absence of appropriate adaptive responses (Oppenheimer et al., 2019).

A synthesis of risk assessments in the recent IPCC Special Reports (Magnan et al., 2021) concludes that an integrated measure of today's global climate risk level will increase by the end of this century by two- to four-fold under low and high warming, respectively (based on aggregated scores developed in the study). An additional comparison of risk levels under +1.5°C and +2°C suggests that every additional 0.5°C of global warming will increase the risk level by about a third.

16.5.3.2 Exposure and Vulnerability Trends

Development pathways describe plausible alternative futures of societal change and are critical to future risks because they affect outcomes of concern both through non-climate and climate-related channels (*very high confidence*).

Studies illustrating sensitivity to development pathways typically do so by contrasting projected impacts for the same climate pathway or temperature level but different levels of socioeconomic exposure and vulnerability, for example based on SSPs (O'Neill et al., 2014; Van Vuuren et al., 2014). Or, they infer sensitivity to future development pathways based on differences in impacts across current populations with different levels of exposure or vulnerability. We refer to future conditions based on SSPs 1 or 5 as 'low exposure' or 'low vulnerability' conditions, and those based on SSPs 3 or 4 as 'high exposure' or 'high vulnerability' conditions (O'Neill et al., 2014; van Vuuren and Carter, 2014).

A wide range of climate change impacts depend strongly on development pathway (*high confidence*). A low (relative to high) exposure future, determined by limited population growth and urbanisation, results in about 30% fewer people exposed to extreme heat globally (Jones et al., 2018b) and about 50% fewer in Africa (Rohat et al., 2019a), similar to the effect of a medium versus high level of global warming. Low-exposure conditions also reduce the fraction of the population in Europe at very high risk of heat stress from 39% to 11% (Rohat et al., 2019b). Demographic differences lead to a reduction in the global population exposed to mosquitos acting as viral disease vectors by more than half (Monaghan et al., 2018) and exposure to wildfire risk by nearly half (Knorr et al., 2016).

Studies are increasingly going beyond exposure to incorporate future vulnerability, finding that it is often the dominant determinant of risk (*high confidence*). A low (relative to high) vulnerability future reduces the risk to global poverty by an order of magnitude, robustly across approaches that account for macroeconomic growth, structural change in the economy, inequality, and access to infrastructure services (Hallegatte and Rozenberg, 2017), or for the exposure of vulnerable populations to multi-sector climate-related risks (Byers et al., 2018). A low (relative to high) vulnerability future also reduces the global mean number of temperature-attributable deaths in 2080–2095 due to enteric infections by an order of magnitude (from >80,000 to <7000; (Chua et al., 2021)). Low future socioeconomic vulnerability to flooding reduces global fatalities and economic losses by 69–96% (Jongman et al., 2015). Low vulnerability as measured by indicators including per capita GDP, education, governance, water demand and storage potential reduces water insecurity by a factor of three (Koutroulis et al., 2019). A scenario with reduced barriers to trade reduces the number of people at risk of hunger due to climate change by 64% (Janssens et al., 2020). Structural transformation of the economy (shift of the workforce from highly exposed sectors such as agriculture and fishing to less exposed sectors such as services) lowers GDP impact projections by 25–30% in today's developing countries by 2100 (Acevedo et al., 2017).

The IPCC SRCCL supports the importance of societal conditions to climate-related risk (Hurlbert et al., 2019), concluding that risks of water scarcity in drylands (i.e., desertification), land degradation and food insecurity are close to High[3] beginning at 1.5°C under high-vulnerability conditions (SSP3), but remain close to Moderate up to slightly above 2°C for low-vulnerability conditions (SSP1). Specifically, risk of water scarcity in drylands (i.e., desertification) at 1.5°C warming is reduced in low vulnerability (relative to high vulnerability) conditions from High to Medium. Similarly, under a 2°C warming, risk is reduced from High to Moderate for food security and High to Moderate-to-High for land degradation.

While climate change will increase risk to society and ecosystems, future exposure and vulnerability conditions will also greatly impact outcomes of concern directly. Global economic damages to coastal assets from tropical cyclones are projected to increase by more than 300% due to coastal development alone, a much larger effect than projected climate change impacts through 2100 even in RCP8.5 (Gettelman et al., 2018). Similarly, global crop prices are more than three times more sensitive to alternative assumptions about changes in production technologies and demand than to alternative climate outcomes (Ren et al., 2016). Future water scarcity is driven mainly by both demographic change and socioeconomic changes affecting water demand and management. A measure of between-country inequality (Gini coefficient) would decline by more than 50% this century in low-vulnerability conditions, but would double in a high-vulnerability future (Crespo Cuaresma, 2017), outweighing the effect of climate (Taconet et al., 2020). Similarly, the global prevalence of armed conflict will roughly double this century in a high-vulnerability future, whereas it will drop by half in a low-vulnerability future (Hegre et al., 2016). In Sub-Saharan Africa, assumptions about governance and political rights are estimated to be far more important to the future risk of violent conflict than climate change (Witmer et al., 2017).

16.5.3.3 Climate Adaptation Scenarios

One approach to understand adaptation benefits for risk reduction is to contrast projected impacts for the same climate and development conditions but different levels of adaptation. For example, global-scale coastal protection studies considering both RCPs and SSPs suggest that, under a given RCP, the total flooded area may be reduced by 40% by using 1-m height dykes, compared with a no-adaptation baseline (Tamura et al., 2019). The global cost of SLR over the 21st century can be lowered by factor of two to four if local cost–benefit decisions consider migration an adaptation option, in addition to hard protection (Lincke and Hinkel, 2021). Under a low-warming scenario, it is estimated that adaptation (i.e., changes in crop variety and planting dates) could reduce the total number of people at risk of hunger globally by about 4%, and by about 10% in a high-warming scenario (Hasegawa et al., 2014). Impacts on heat-related mortality would be cut from 10 to 7 deaths per 10,000 people yr^{-1} in 2100 by adaptation actions beyond those assumed to be driven by income growth (Carleton et al., 2020). In a regional example, proactive adaptation efforts on infrastructure (especially roads, runways, buildings and airports) in Alaska, USA, could reduce damage-related expenditure by 45% under medium or high warming (Melvin et al., 2017).

Another approach infers the potential future effectiveness of adaptation based on current sensitivity of impacts to interventions. For example, the future disease burden of malaria is likely to be highly dependent on the future development of health services, deployment of malaria programs and adaptation. Investments in water and sanitation infrastructure are also recognised to have the potential to reduce severe risks of waterborne disease, although these improvements likely need to provide transformative change (Cumming et al., 2019). The potential for severe risks may also be substantially reduced through the development of vaccines for specific enteric diseases (Riddle et al., 2018), although most current vaccines target viral pathogens, incidence for which tends to be inversely correlated with ambient temperature (Carlton et al., 2016). In addition, international migration as well as forced movement of people across borders will be influenced by developments in legal and political conditions (McLeman, 2019; Wrathall et al., 2019), but the fact that these developments are unknown strongly limits any forecasts on the magnitude of adaptation benefits (Section 16.5.2.3.8).

Last, there is growing concern that even ambitious adaptation efforts will not eliminate residual risks from climate change (Section 16.4.2). A synthesis of risk assessments in the recent IPCC Special Reports (Magnan et al., 2021) concludes that high societal adaptation is expected to reduce the aggregated score—the proxy used in the study—of global risk from anthropogenic climate change by about 40% under all RCPs by the end of the century, compared with risk levels projected without adaptation. It, however, also shows that, even for the lowest warming scenario, a residual risk one-third greater than today's risk level would still remain (with a doubling of today's aggregated score under the high-emissions scenario).

3 The IPCC distinguishes between four qualitative risk levels, from Undetectable (risks that are undetected), to Moderate (detectable with at least *medium confidence*), High (significant and widespread) and Very high (very high probability of severe risks and significant irreversibility or persistence of impacts).

16.5.3.4 Illustration: Risk and Adaptation Pathways in Densely Populated and Agricultural Deltas

Large deltas, which are very dynamic risk hotspots of global importance and interest (Wigginton, 2015; Hill et al., 2020; Nicholls et al., 2020), serve well to illustrate how risk pathways develop over time, determined by climatic as well as non-climatic risk drivers and by adaptation. Deltas occupy less than 0.5% of the global land area but host over 5% of the global population (Dunn et al., 2019) and contribute major fractions of food production in many world regions (Kuenzer et al., 2020). Future risk in these areas is heavily driven by climate change but also greatly depends on past, current and future socioeconomic changes which influence future trends in exposure, vulnerability and adaptive capacity of natural and human systems (*high confidence*) (Oppenheimer et al., 2019). From a risk perspective, trends over the past decades have been unfavourable for many deltas, as most of them have experienced a simultaneous intensification of hazards, rise in exposure and stagnation or only limited reduction in vulnerability, particularly in low-income countries (*high confidence*) (Day et al., 2016; Tessler et al., 2016; Loucks, 2019; Oppenheimer et al., 2019; Hill et al., 2020).

16.5.3.4.1 Hazard trends in deltas

Deltas face multiple interacting hazards, many of which over the past decades have been intensified by local and regional anthropogenic developments (e.g., the construction of dams, groundwater extraction, or agricultural irrigation practices) and most of which are expected to be exacerbated by climate change (*high confidence*) (Giosan et al., 2014; Tessler et al., 2015; Tessler et al., 2016; Arto et al., 2019; Oppenheimer et al., 2019). The most important hazards include SLR, inundation, salinity intrusion, cyclones, storms and erosion, many of which occur in combination. The potential for flooding and inundation depends on the relative sea level rise (RSLR) which results from global and regional SLR as well as local subsidence within the deltas. Subsidence caused by natural and human drivers (mainly compaction and groundwater extraction) is currently the most important cause for RSLR in many deltas and can exceed the rate of climate-induced SLR by an order of magnitude (Oppenheimer et al., 2019). But in higher warming scenarios the relative importance of climate-driven SLR is expected to increase over time (Oppenheimer et al., 2019). In a global study covering 47 major deltas and assessing future trends of sediment delivery across four RCPs, three SSPs (1,2,3) and a projection of future dam construction, Dunn et al. (2019) find most deltas (33 out of the 47) will experience a mean decline of 38% in sediment flux by the end of the century when considering the average of the scenarios. Nienhuis et al. (2020) find in a global assessment that some deltas have gained land through increased sediment load (e.g., through deforestation), but recent land gains are unlikely to be sustained if SLR continues to accelerate. According to the latest assessments, it is *virtually certain* that global mean sea level will continue to rise over the 21st century, with SLR by 2100 *likely* to reach 0.28–0.55 m in a an SSP1–1.9 and 0.63–1.01 m in an SSP5–8.5 scenario relative to 1995–2014 (IPCC, 2021). The combined effects of local subsidence and GMSL rise result in a significant increase in the potential for inundation of low-lying deltas across all RCPs, with some variation according to regional sea level change rates, without significant further adaptation measures (*very high confidence*).

In terms of salt-water intrusion and salinisation, global comparative studies are still lacking but the general processes are well understood (e.g., White and Kaplan, 2017), and research on individual deltas is on the rise. In the Mekong Delta of Vietnam, one of the main rice-producing deltas globally, salinity intrusion has been observed to extend around 15 km inland during the rainy season and around 50 km during the dry season (Gugliotta et al., 2017), resulting in rice yield losses of up to 4 t ha^{-1} yr^{-1} (Khat et al., 2018). SLR, along with the expansion of dams and dry season irrigation upstream, is expected to further increase the salinity intrusion into the delta. This creates additional risk for food production as rice and other crops might be pushed beyond their adaptation limits in terms of salt tolerance, potentially affecting many of the 282,000 agriculture-based livelihoods in the Mekong Delta and increasing the pressure for cost-intensive adaptation (Smajgl et al., 2015). Genua-Olmedo et al. (2016) find for the Ebro that in high scenario (RCP8.5, and SLR of almost 1 m by 2100), SLR-induced salinity intrusion will lead to almost a doubling of salinity levels and a decrease of mean rice productivity by over 20% in a high-SLR scenario with almost 1 m of SLR by the end of the century.

16.5.3.4.2 Exposure trends in deltas

Next to the trends in hazards, future exposure of and in deltas is shaped particularly by the increase of population and infrastructure and the intensification of land use. Over the recent years, the population has been rising in major deltas, roughly along with overall national population trends (Szabo et al., 2016). In 2017, 339 million people lived in deltas with a high exposure to flooding, cyclones and other coastal hazards (Edmonds et al., 2020). Over 40% of the global population exposed to flooding from tropical cyclones lived in deltas, more than 90% of which in developing countries and emerging economies (ibid.). Looking into the future, population in low-elevation coastal zones is expected to increase by 2050 across all SSPs with diverging developments in the second half of the century, and at the end of the century will reach well over 1 billion people in SSP3 (Jones and O'Neill, 2016; Merkens et al., 2016). A major part of this population is expected to reside in deltas with large cities or mega-urban agglomerations such as the Pearl River Delta, China. One of the first studies using the SSP-RCP framework on the delta scale suggests a strong increase in intensive agricultural land by the middle of the century in three SSPs (2, 3, 5) in the Volta Delta, Ghana, while the Mahanadi, India, and the Ganges–Brahmaputra–Meghna do not show a significant further increase (Kebede et al., 2018). Hence, the amount of population and infrastructure as well as agricultural land is expected to rise further under certain SSPs, further increasing the exposure to future climate hazards.

16.5.3.4.3 Vulnerability trends in deltas

Deltas are characterised by multi-faceted vulnerabilities of their environment and human populations. Over 200 indicators are being used in the literature to characterise and analyse vulnerability in deltas, spanning social, ecological and economic aspects (Sebesvari et al., 2016). However, only a few studies model or dynamically assess trends in vulnerability, particularly for the future, at global scale, or take a comparative approach. But overall, a global trend assessment suggests that social vulnerability to climate hazards has been improving over the past years in all world regions hosting major deltas apart from Oceania, yet with emerging economies and developing countries in Africa showing less improvement than the Americas, Asia and Europe (Feldmeyer et al., 2017). An analysis of 48 major deltas finds that vulnerability therefore is a less dominant source of future increase in risk than exposure (Haasnoot et al., 2012). However, case study research from individual deltas suggests that delta populations, particularly those with agriculture-based livelihoods, have seen more limited vulnerability reduction due in particular to the impacts of environmental hazards, stress and disasters (*high confidence*). In the Mekong Delta, for instance, the strong economic growth since the beginning of Vietnam's reform process has not led to a reduction of vulnerability across the board for all socioeconomic groups (Garschagen, 2015). Rather, issues such as widespread landlessness or continued poverty have maintained and, in some respect, increased social vulnerability.

16.5.4 RKR Interactions

Multiple feedbacks between individual risks exist that have the potential to create cascades (WEF, 2018; IPCC, 2019c p. 680; Simpson et al., 2021) and then to amplify systemic risks and impacts far beyond the level of individual RKRs (*medium confidence*). Scientific research, however, remains limited on whether such interactions would result in increasing or decreasing the initial impact(s), and hence risk severity across systems. Given the scope of this chapter on increasing risk severity, here we focus on assessing RKR interactions that lead to increasing risk. Drawing directly on RKR assessments (Sections 16.5.2.3.2–16.5.2.3.8), this section cites those assessments rather than primary literature. The arrows in Figure 16.11 are derived from a qualitative analysis by three authors of Chapter 16 of the material provided by chapters on KRs and RKR assessments (Section 16.5.2.3), and do not result from any systematic and quantitative approach as done in some recent studies (e.g., WEF, 2018; Yokohata et al., 2019).

Interactions at the RKR level (Figure 16.11, panel A)—climate change will combine with pre-existing socioeconomic and ecological conditions (grey blocks on the left-hand-side of panel A in Figure 16.10) to generate direct and second-order effects (black plain arrows) both on the structure and/or functioning of ecosystems (RKR-B) and on some natural processes such as the hydrologic cycle (RKR-G), for example. This then translates into implications not only for biodiversity but also for natural resources that support livelihoods, which will in turn affect food security (especially food availability; RKR-F), water security (especially access to adequate quantities of acceptable quality water; RKR-G) and the living standards of already vulnerable groups and aggregate economic outputs at the global level (RKR-D). CIDs (IPCC, 2021) will also directly affect infrastructure that are critical to ensure some basic conditions for economies to function (RKR-C), for example through transportation within and outside the country, energy production and international trade. Such disturbances to socioecological systems and economies pose climate-related risks to human health (RKR-E) as well as to peace and human mobility (RKR-H). Indeed, while health is concerned with direct influence of climate change, for example through hotter air temperatures impacting morbidity and mortality or the spatial distribution of disease vectors such as mosquitos, it is also at risk of being stressed by direct and secondary climate impacts on living standards, food security and water security (RKR-D, RKR-F, RKR-G, respectively). Increased poverty, increased hunger and limited access to drinkable water are well-known drivers of poor health conditions. The role of impact cascades is even more prominent in the case of peace and human mobility (RKR-H), even though the scientific literature does not conclude on any clear and direct climate influence on armed conflict and human migration. Rather, climate-induced degradation of natural resources that are vital for subsistence agriculture and fisheries, transformational and long-term consequences on livelihoods (e.g., new risks, increasing precarious living conditions, gendered inequity, etc.), and erosion of social capital due to exacerbated tension within and between communities are considered among the main drivers of armed conflicts and forced displacement, therefore highlighting links with water security (RKR-G) and living standards (RKR-D), for example.

RKR assessments also suggest that some feedback effects are at work (arrows moving from the right to the left in panel A) that contribute to the potentially long-lasting effects of climate risks. RKR-H assessment, for example, states that there is *robust evidence* that major armed conflicts routinely trigger mass displacement, threaten health and food security, and undermine economic activity and livelihoods, often with lasting negative consequences for living standards and socioeconomic development, therefore linking back to risks to living standards (RKR-D), human health (RKR-E) and food security (RKR-F).

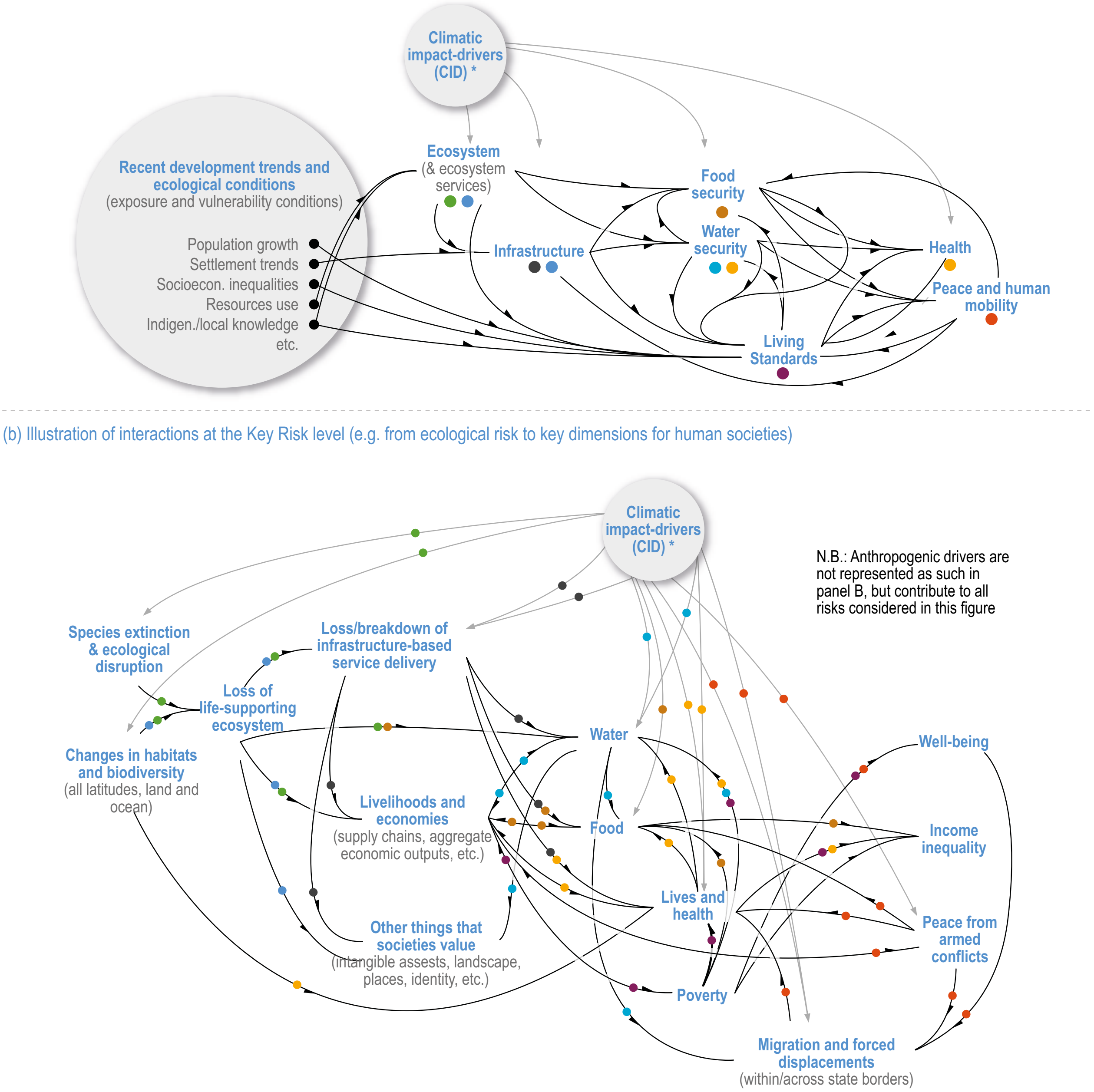
Interactions at the KR level (Figure 16.11, panel B)—panel B illustrates risk connections at the Key Risk level (Section 16.5.2.1) and as described in RKR assessments (Section 16.5.2.3). To only take one example here, risk to livelihoods and economies is influenced by the loss of ecosystem services (RKR-B) and the loss or breakdown of critical infrastructures (RKR-C), and it influences risks to human lives and health (RKR-E), food and water security (RKR-F, RKR-G), poverty (RKR-D) and peace and human mobility (RKR-H). As a third-order sequence, RKR assessments show that increased risk to peace and human mobility affects lives and health as well as food security, which in turn threaten livelihoods and economies.

The above suggests that some vicious cycle effects play a central role in explaining impact processes. Cascading effects can indeed lead to cumulative risks that partly feed various drivers of the emergence of severe risks (Section 16.5.1), such as the acceleration of ecosystem degradation, or the reaching of thresholds and irreversible states in human systems at a decade-to-century time horizon (e.g., when permanent inundation questions the habitability of some low-lying coasts; RKR-A). The extent and duration of risk cascades are, however, expected to substantially vary depending on warming levels and development pathways, both separately (Section 16.5.3) and when combined (Sections 16.6.1, 16.6.2) (Figure 16.10).

In addition, RKR assessments converge to suggest that regions that are already experiencing climate change impacts will experience severe impact cascades first (e.g., RKR-F), because they are in areas (i) that face development constraints and associated challenges such as poverty, inequity and social discrimination for example, and (ii) where climate change projections are the most intense for the next decades. That is especially a concern for Africa (RKR-F, RKR-G), Asia and Latin America (Chapters 9, 10, 12). RKR-E, for example, concludes

Illustration of some connections across key risks

(a) Interactions across the eight Representative Key Risk level



* CIDs are physical climate system conditions (e.g., means, events, extremes) that affect an element of society or ecosystems. Indicated changes are system-dependent and can be detrimenlal, beneficial, neutral, or a mixture of each (see IPCC WG1 contribution to AR6, Summary for Policy Makers).

Risk cascades **

- Across key risks
- Climate-driven

Representative Key Risks

- A (Low-lying coasts)
- B (Ecosystems)
- C (Infrastructure)
- D (Living standards)
- E (Human health)
- F (Food security)
- G (Water security)
- H (Peace and human mobility)

** Illustrative rather than comprehensive, and qualitative rather than quantitative, as suggested across the RKR assessments in this report.

Figure 16.11 | Illustration of some connections across key risks. Panel A describes all the cross-RKR risk cascades that are described in RKR assessments (Sections 16.5.2.3.2–16.5.2.3.8). Panel B builds on Section 16.5.2 and Table SM16.24 to provide an illustration of such interactions at the key risk level, for example from ecological risk to key dimensions for human societies. The arrows are representative of interactions as qualitatively identified in this chapter; they do not result from any quantitative modelling exercise.

that the likelihood of severe risks to human health is especially high for highly susceptible populations, particularly the poor and otherwise marginalised. RKR assessments, however, emphasise that middle- and high-income regions are also to be considered at serious risk because climate change is accelerating at the global level (IPCC, 2021), and because critical dimensions are exposed to severe risks such as major transportation (e.g., international airports) and energy (e.g., nuclear power plants) infrastructure for instance (RKR-C), and because of the interconnectedness of economies.

Finally, all RKR assessments suggest that enhanced adaptation has the potential to contain such feedback effects and cascading processes more broadly, and reduce the duration of the impacts on the system as a whole. There are, however, knowledge gaps on such a potential, as well as on the nature of impact cascades (positive, negative, neutral, mixed).

16.6 Reasons for Concern Across Scales

This section builds on Section 16.5 which identifies and assesses key risks (KRs) and representative key risks (RKRs), including conditions contributing to their severity (i.e., Figure 16.10), in two ways. First, we consider those risks in the context of the global goal for sustainable development which can be impacted, as expressed in the United Nations 2030 Agenda for Sustainable Development and the SDGs. This discussion supports further assessment in Chapter 18 on sustainable system transitions and climate resilient development pathways. Second, the potential global consequences are then elaborated in an updated assessment of five globally aggregated categories of risk, designated as Reasons for Concern (RFCs), that evaluates risk accrual by global warming level.

16.6.1 Key Risks and Sustainable Development

The United Nations 2030 Agenda for Sustainable Development, and the SDGs (UN, 2015), since 2015, have become an important vision for the United Nations member countries (Chimhowu, 2019) as well as for corporations to contribute towards sustainable growth (UNDP et al., 2016; Ike et al., 2019; van der Waal and Thijssens, 2020). Climate change risks, as embodied in the RKR and RFCs, can affect attainment of the SDGs and have consequences for lives and livelihoods (related to SDGs 1, 4, 8 and 9), health and well-being (related to SDGs 2, 3 and 6), ecosystems and species (related to SDGs 6, 14 and 15), economic (related to SDGs 1, 8 and 12), social and cultural assets (related to SDGs 5, 10, 11, 16 and 17), services including ecosystem services (related to SDGs 6, 7, 11, 12, 14 and 15), and infrastructure (related to SDGs 6, 7, 9, 11 and 12). This section assesses the level of linkages between key risks with sustainable development, in terms of the SDG targets and indicators. This informs on the key risks which are most relevant to consider with respect to the attainment of the SDGs.

16.6.1.1 Links between Key Risks and Sustainable Development Goals

Within the AR6 cycle, the three IPCC Special Reports have all considered the relationships between climate change impacts and actions and the SDGs. SR15 discussed priorities for sustainable development in relation to climate adaptation efforts (Section 5.3.1, SR15); synergies and trade-offs of climate adaptation measures (Section 5.3.2, SR15); and the effect of adaptation pathways towards a 1.5°C warmer world (Section 5.3.3 SR15). The SRCCL considered impacts of desertification on SDGs 1 (no poverty), 2 (zero hunger), 13 (climate), 15 (life on land) and 5 (gender) (IPCC, 2019a, Figure 3.9). Trade-offs and synergies between SDGs 2 (zero hunger) and 13 (climate action) at the global level were recognised (IPCC, 2019a, Section 5.6.6, Figure 5.16). Various integrated response options, interventions and investments were also evaluated within the SDG framework (IPCC, 2019a, Section 6.4.3). The SROCC (Chapter 5) concluded that climate change impacts on the ocean, overall, will negatively affect achieving the SDGs, with 14 (life below water) being most relevant (Singh et al., 2019).

Cross-Working Group Box SRM | Solar Radiation Modification

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Proposed solar radiation modification schemes

This cross-working group box assesses solar radiation modification (SRM) proposals, their potential contribution to reducing or increasing climate risk, as well as other risks they may pose (categorised as risks from responses to climate change in the IPCC AR6 risk definition in 1.2.1.1), and related perception, ethics and governance questions.

SRM refers to proposals to increase the reflection of shortwave radiation (sunlight) back to space to counteract anthropogenic warming and some of its harmful impacts (de Coninck et al., 2018) (Cross-Chapter Box 10; WGI Chapters 4, 5). A number of SRM options have been proposed, including: stratospheric aerosol interventions (SAI), marine cloud brightening (MCB), ground-based albedo modifications (GBAM) and ocean albedo change (OAC). Although not strictly a form of SRM, cirrus cloud thinning (CCT) has been proposed to cool the planet by increasing the escape of longwave thermal radiation to space and is included here for consistency with previous assessments

Cross-Working Group Box SRM (continued)

(de Coninck et al., 2018). SAI is the most-researched proposal. Modelling studies show SRM could reduce surface temperatures and potentially ameliorate some climate change risks (with more confidence for SAI than other options), but SRM could also introduce a range of new risks.

There is *high agreement* in the literature that for addressing climate change risks SRM cannot be the main policy response to climate change and is, at best, a supplement to achieving sustained net zero or net negative CO_2 emission levels globally (de Coninck et al., 2018; MacMartin et al., 2018; Buck et al., 2020; National Academies of Sciences and Medicine, 2021b). SRM contrasts with climate change mitigation activities, such as emission reductions and carbon dioxide removal (CDR), as it introduces a 'mask' to the climate change problem by altering the Earth's radiation budget, rather than attempting to address the root cause of the problem, which is the increase in greenhouse gases (GHGs) in the atmosphere. In addition, the effects of proposed SRM options would only last as long as a deployment is maintained—for example, requiring ca. yearly injection of aerosols in the case of SAI as the lifetime of aerosols in the stratosphere is 1–3 years (Niemeier et al., 2011) or continuous spraying of sea salt in the case of MCB as the lifetime of sea salt aerosols in the atmosphere is only about 10 d—which contrasts with the long lifetime of CO_2 and its climate effects, with global warming resulting from CO_2 emissions *likely* remaining at a similar level for a hundred years or more (MacDougall et al., 2020) and long-term climate effects of emitted CO_2 remaining for several hundreds to thousands of years (Solomon et al., 2009).

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Which scenarios?

The choice of SRM deployment scenarios and reference scenarios is crucial in assessment of SRM risks and its effectiveness in attenuating climate change risks (Keith and MacMartin, 2015; Honegger et al., 2021). Most climate model simulations have used scenarios with highly stylised large SRM forcing to fully counteract large amounts of warming in order to enhance the signal-to-noise ratio of climate responses to SRM (Kravitz et al., 2015; Sugiyama et al., 2018a; Tilmes et al., 2018; Krishna-Pillai et al., 2019).

The effects of SRM fundamentally depend on a variety of choices about deployment (Sugiyama et al., 2018b), including: its position in the portfolio of human responses to climate change (e.g., the magnitude of SRM used against the background radiative forcing), governance of research and potential deployment strategies, and technical details (latitude, materials, and season, among others, see WGI Section 4.6.3.3). The plausibility of many SRM scenarios is highly contested, and not all scenarios are equally plausible because of socio-political considerations (Talberg et al., 2018b), as with, for example, CDR (Fuss et al., 2014; Fuss et al., 2018). Development of scenarios and their selection in assessments should reflect a diverse set of societal values with public and stakeholder inputs (Sugiyama et al., 2018a; Low and Honegger, 2020), as depending on the focus of a limited climate model simulation, SRM could look grossly risky or highly beneficial (Pereira and al., 2021).

In the context of reaching the long-term global temperature goal of the Paris Agreement, there are different hypothetical scenarios of SRM deployment: early, substantial mitigation with no SRM, more limited or delayed mitigation with moderate SRM, unchecked emissions with total reliance on SRM, and regionally heterogeneous SRM. Each scenario presents different levels and distributions of SRM benefits, side effects and risks. The more intense the SRM deployment, the larger is the likelihood for the risks of side effects and environmental risks (e.g., Heutel et al., 2018). Regional disparities in climate hazards may result from both regionally deployed SRM options such as GBAM, and more globally uniform SRM such as SAI (Jones et al., 2018a; Seneviratne et al., 2018b). There is an emerging literature on smaller forcings of SAI to reduce global average warming, for instance, to hold global warming to 1.5°C or 2°C alongside ambitious conventional mitigation (Jones et al., 2018a; MacMartin et al., 2018), or bring down temperature after an overshoot (Tilmes et al., 2020). If emissions reductions and CDR are deemed insufficient, SRM may be seen by some as the only option left to ensure the achievement of the Paris Agreement's temperature goal by 2100.

Cross-Working Group Box SRM (continued)

Table Cross-Working Group Box SRM.1 | SRM options and their potential climate and non-climate impacts. Description, potential climate impacts, potential impacts on human and natural systems, and termination effects of a number of SRM options: stratospheric aerosol interventions (SAI), marine cloud brightening (MCB), ocean albedo change (OAC), ground-based albedo modifications (GBAM) and cirrus cloud thinning (CCT).

SRM option	SAI	MCB	OAC	GBAM	CCT
Description	Injection of reflective aerosol particles directly into the stratosphere or a gas which then converts to aerosols that reflect sunlight	Spraying sea salt or other particles in marine clouds, making them more reflective	Increase surface albedo of the ocean (e.g., by creating microbubbles or placing reflective foam on the surface)	Whitening roofs, changes in land use management (e.g., no-till farming, bioengineering to make crop leaves more reflective), desert albedo enhancement, covering glaciers with reflective sheeting	Seeding to promote nucleation of cirrus clouds, reducing optical thickness and cloud lifetime to allow more outgoing longwave radiation to escape to space
Potential climate impacts *other than reduced warming*	Change precipitation and runoff pattern; reduced temperature and precipitation extremes; precipitation reduction in some monsoon regions; decrease in direct and increase in diffuse sunlight at surface; changes to stratospheric dynamics and chemistry; potential delay in ozone hole recovery; changes in surface ozone and UV radiation	Change in land-sea contrast in temperature and precipitation, regional precipitation and runoff changes	Change in land–sea contrast in temperature and precipitation, regional, precipitation and runoff changes	Changes in regional precipitation pattern, regional extremes and regional circulation	Changes in temperature and precipitation pattern, altered regional water cycle, increase in sunlight reaching the surface
Potential impacts on human and natural systems	Changes in crop yields, changes in land and ocean ecosystem productivity, acid rain (if using sulphate), reduced risk of heat stress to corals	Changes in regional ocean productivity, changes in crop yields, reduced heat stress for corals, changes in ecosystem productivity on land, sea salt deposition over land	Unresearched	Altered photosynthesis, carbon uptake and side effects on biodiversity	Altered photosynthesis and carbon uptake
Termination effects	Sudden and sustained termination would result in rapid warming, and abrupt changes to water cycle. Magnitude of termination depends on the degree of warming offset	Sudden and sustained termination would result in rapid warming, and abrupt changes to water cycle. Magnitude of termination depends on the degree of warming offset	Sudden and sustained termination would result in rapid warming. Magnitude of termination depends on the degree of warming offset	GBAM can be maintained over several years without major termination effects because of its regional scale of application. Magnitude of termination depends on the degree of warming offset	Sudden and sustained termination would result in rapid warming. Magnitude of termination depends on the degree of warming offset
References (also see main text of this box)	Tilmes et al. (2018); Simpson et al. (2019); Visioni et al. (2017)	Latham et al. (2012); Ahlm et al. (2017); Stjern et al. (2018)	Evans et al. (2010); Crook et al. (2015a)	Zhang et al. (2016); Field et al. (2018); Seneviratne et al. (2018a); Davin et al. (2014); Crook et al. (2015a)	Storelvmo and Herger (2014); Crook et al. (2015a); Jackson et al. (2016); Gasparini et al. (2020); Duan et al. (2020)

SRM risks to human and natural systems and potential for risk reduction

Since AR5, hundreds of climate modelling studies have simulated effects of SRM on climate hazards (Kravitz et al., 2015; Tilmes et al., 2018). Modelling studies have shown SRM has the potential to offset some effects of increasing GHGs on global and regional climate, including the increase in frequency and intensity of extremes of temperature and precipitation, melting of Arctic sea ice and mountain glaciers, weakening of Atlantic meridional overturning circulation, changes in frequency and intensity of tropical cyclones, and decrease in soil moisture (WGI, Chapter 4). However, while SRM may be effective in alleviating anthropogenic climate warming either locally or globally, it would neither maintain the climate in its present-day state nor return the climate to a pre-industrial state (climate averaged over 1850–1900, see WGI Chapter 1, Box 1.2) in all regions and in all seasons even when used to fully offset the global mean warming

Cross-Working Group Box SRM (continued)

(*high confidence*) (WGI Chapter 4). This is because the climate forcing and response to SRM options are different from the forcing and response to GHG increase. Because of these differences in climate forcing and response patterns, the regional and seasonal climates of a world with a global mean warming of 1.5°C or 2°C achieved via SRM would be different from a world with similar global mean warming but achieved through mitigation (MacMartin et al.., 2019). At the regional scale and seasonal time scale, there could be considerable residual climate change and/or overcompensating change (e.g., more cooling, wetting or drying than just what is needed to offset warming, drying or wetting due to anthropogenic greenhouse gas emissions), and there is *low confidence* in understanding of the climate response to SRM at the regional scale (WGI, Chapter 4).

SAI implemented to partially offset warming (e.g., offsetting half of global warming) may have potential to ameliorate hazards in multiple regions and reduce negative residual change, such as drying compared with present-day climate, that is associated with fully offsetting global mean warming (Irvine and Keith, 2020), but may also increase flood and drought risk in Europe compared with unmitigated warming (Jones et al., 2021). Recent modelling studies suggest it is conceptually possible to meet multiple climate objectives through optimally designed SRM strategies (WGI, Chapter 4). Nevertheless, large uncertainties still exist for climate processes associated with SRM options (e.g., aerosol–cloud–radiation interaction) (WGI, Chapter 4) (Kravitz and MacMartin, 2020).

Compared with climate hazards, many fewer studies have examined SRM risks—the potential adverse consequences to people and ecosystems from the combination of climate hazards, exposure and vulnerability—or the potential for SRM to reduce risk (Curry et al., 2014; Irvine et al., 2017). Risk analyses have often used inputs from climate models forced with stylised representations of SRM, such as dimming the sun. Fewer have used inputs from climate models that explicitly simulated injection of gases or aerosols into the atmosphere, which include more complex cloud radiative feedbacks. Most studies have used scenarios where SAI is deployed to hold average global temperature constant despite high emissions.

There is *low confidence* and large uncertainty in projected impacts of SRM on crop yields due in part to a limited number of studies. Because SRM would result in only a slight reduction in CO_2 concentrations relative to the emission scenario without SRM (Chapter 5, WGI), the CO_2 fertilisation effect on plant productivity is nearly the same in emissions scenarios with and without SRM. Nevertheless, changes in climate due to SRM are likely to have some impacts on crop yields. A single study indicates MCB may reduce crop failure rates compared with climate change from a doubling of CO_2 pre-industrial concentrations (Parkes et al., 2015). Models suggest SAI cooling would reduce crop productivity at higher latitudes compared with a scenario without SRM by reducing the growing season length, but benefit crop productivity in lower latitudes by reducing heat stress (Pongratz et al., 2012; Xia et al., 2014; Zhan et al., 2019). Crop productivity is also projected to be reduced where SAI reduces rainfall relative to the scenario without SRM, including a case where reduced Asian summer monsoon rainfall causes a reduction in groundnut yields (Xia et al., 2014; Yang et al., 2016). SAI will increase the fraction of diffuse sunlight, which is projected to increase photosynthesis in forested canopy, but will reduce the direct and total available sunlight, which tends to reduce photosynthesis. As total sunlight is reduced, there is a net reduction in crop photosynthesis with the result that any benefits to crops from avoided heat stress may be offset by reduced photosynthesis, as indicated by a single statistical modelling study (Proctor et al., 2018). SAI would reduce average surface ozone concentration (Xia et al., 2017) mainly as a result of aerosol-induced reduction in stratospheric ozone in polar regions, resulting in reduced downward transport of ozone to the troposphere (Pitari et al., 2014; Tilmes et al., 2018). The reduction in stratospheric ozone also allows more UV radiation to reach the surface. The reduction in surface ozone, together with an increase in surface UV radiation, would have important implications for crop yields but there is *low confidence* in our understanding of the net impact.

Few studies have assessed potential SRM impacts on human health and well-being. SAI using sulphate aerosols is projected to deplete the ozone layer, increasing mortality from skin cancer, and SAI could increase particulate matter due to offsetting warming, reduced precipitation and deposition of SAI aerosols, which would increase mortality, but SAI also reduces surface-level ozone exposure, which would reduce mortality from air pollution, with net changes in mortality uncertain and depending on aerosol type and deployment scenario (Effiong and Neitzel, 2016; Eastham et al., 2018; Dai et al., 2020). However, these effects may be small compared with changes in risk from infectious disease (e.g., mosquito-borne illnesses) or food security due to SRM influences on climate (Carlson et al., 2020). Using volcanic eruptions as a natural analogue, a sudden implementation of SAI that forced the El Niño-Southern Oscillation (ENSO) system may increase risk of severe cholera outbreaks in Bengal (Trisos et al., 2018; Pinke et al., 2019). Considering only mean annual temperature and precipitation, SAI that stabilises global temperature at its present-day level is projected to reduce income inequality between countries compared with the highest warming pathway (RCP8.5) (Harding et al., 2020). Some integrated assessment model scenarios have included SAI (Arino et al., 2016; Emmerling and Tavoni, 2018; Heutel et al., 2018; Helwegen et al., 2019; Rickels et al., 2020) showing the indirect costs and benefits to welfare dominate, since the direct economic cost of SAI itself is expected to be relatively low (Moriyama et al., 2017; Smith and Wagner, 2018). There is a general lack of research on the wide scope of potential risk or risk

Cross-Working Group Box SRM (continued)

reduction to human health, well-being and sustainable development from SRM and on their distribution across countries and vulnerable groups (Carlson et al., 2020; Honegger et al., 2021).

SRM may also introduce novel risks for international collaboration and peace. Conflicting temperature preferences between countries may lead to counter-geoengineering measures such as deliberate release of warming agents or destruction of deployment equipment (Parker et al., 2018). Game-theoretic models and laboratory experiments indicate that a powerful actor or group with a higher preference for SRM may use SAI to cool the planet beyond what is socially optimal, imposing welfare losses on others, although this cooling does not necessarily imply that excluded countries would be worse off relative to a world of unmitigated warming (Ricke et al., 2013; Weitzman, 2015; Abatayo et al., 2020). In this context, counter-geoengineering may promote international cooperation or lead to large welfare losses (Heyen et al., 2019; Abatayo et al., 2020).

Cooling caused by SRM would increase the global land and ocean CO_2 sinks (*medium confidence*), but this would not stop CO_2 from increasing in the atmosphere or affect the resulting ocean acidification under continued anthropogenic emissions (*high confidence*) (WGI Chapter 5).

Few studies have assessed potential SRM impacts on ecosystems. SAI and MCB may reduce risk of coral reef bleaching compared with global warming with no SAI (Latham et al., 2013; Kwiatkowski et al., 2015), but risks to marine life from ocean acidification would remain, because SRM proposals do not reduce elevated levels of anthropogenic atmospheric CO_2 concentrations. MCB could cause changes in marine net primary productivity by reducing light availability in deployment regions, with important fishing regions off the west coast of South America showing both large increases and decreases in productivity (Partanen et al., 2016; Keller, 2018).

There is large uncertainty in terrestrial ecosystem responses to SRM. By decoupling increases in atmospheric greenhouse gas concentrations and temperature, SAI could generate substantial impacts on large-scale biogeochemical cycles, with feedbacks to regional and global climate variability and change (Zarnetske et al., 2021). Compared with a high-CO_2 world without SRM, global-scale SRM simulations indicate reducing heat stress in low latitudes would increase plant productivity, but cooling would also slow down the process of nitrogen mineralisation, which could decrease plant productivity (Glienke et al., 2015; Duan et al., 2020). In high-latitude and polar regions, SRM may limit vegetation growth compared with a high-CO_2 world without SRM, but net primary productivity may still be higher than pre-industrial climate (Glienke et al., 2015). Tropical forests cycle more carbon and water than other terrestrial biomes, but large areas of the tropics may tip between savanna and tropical forest depending on rainfall and fire (Beer et al., 2010; Staver et al., 2011). Thus, SAI-induced reductions in precipitation in Amazonia and central Africa are expected to change the biogeography of tropical ecosystems in ways different from both present-day climate and global warming without SAI (Simpson et al., 2019; Zarnetske et al., 2021). This would have potentially large consequences for ecosystem services (Chapter 2 and Chapter 9). When designing and evaluating SAI scenarios, biome-specific responses need to be considered if SAI approaches are to benefit rather than harm ecosystems. Regional precipitation change and sea salt deposition over land from MCB may increase or decrease primary productivity in tropical rainforests (Muri et al., 2015). SRM that fully offsets warming could reduce the dispersal velocity required for species to track shifting temperature niches, whereas partially offsetting warming with SAI would not reduce this risk unless rates of warming were also reduced (Trisos et al., 2018; Dagon and Schrag, 2019). SAI may reduce high-fire-risk weather in Australia, Europe and parts of the Americas, compared with global warming without SAI (Burton et al., 2018). Yet SAI using sulphur injection could shift the spatial distribution of acid-induced aluminium soil toxicity into relatively undisturbed ecosystems in Europe and North America (Visioni et al., 2020). For the same amount of global mean cooling, SAI, MCB and CCT would have different effects on gross and net primary productivity because of different spatial patterns of temperature, available sunlight, and hydrological cycle changes (Duan et al., 2020). Large-scale modification of land surfaces for GBAM may have strong trade-offs with biodiversity and other ecosystem services, including food security (Seneviratne et al., 2018a). Although existing studies indicate SRM will have widespread impacts on ecosystems, risks and potential for risk reduction for marine and terrestrial ecosystems and biodiversity remain largely unknown.

A sudden and sustained termination of SRM in a high CO_2 emissions scenario would cause rapid climate change (*high confidence*; WGI Chapter 4). More scenario analysis is needed on the potential likelihood of sudden termination (Kosugi, 2013; Irvine and Keith, 2020). A gradual phase-out of SRM combined with emission reduction and CDR could avoid these termination effects (*medium confidence*) (MacMartin et al., 2014; Keith and MacMartin, 2015; Tilmes et al., 2016). Several studies find that large and extremely rapid warming and abrupt changes to the water cycle would occur within a decade if a sudden termination of SAI occurred (McCusker et al., 2014; Crook et al., 2015b). The size of this 'termination shock' is proportional to the amount of radiative forcing being masked by SAI. A sudden termination of SAI could place many thousands of species at risk of extinction, because the resulting rapid warming would be too fast for species to track the changing climate (Trisos et al., 2018).

Cross-Working Group Box SRM (continued)

Public perceptions of SRM

Studies on the public perception of SRM have used multiple methods: questionnaire surveys, workshops, and focus group interviews (Burns et al., 2016; Cummings et al., 2017). Most studies have been limited to Western societies, with some exceptions. Studies have repeatedly found that respondents are largely unaware of SRM (Merk et al., 2015). In the context of this general lack of familiarity, the public prefers CDR to SRM (Pidgeon et al., 2012), is very cautious about SRM deployment because of potential environmental side effects and governance concerns, and mostly rejects deployment for the foreseeable future. Studies also suggest conditional and reluctant support for research, including proposed field experiments, with conditions of proper governance (Sugiyama et al., 2020). Recent studies show that the perception varies with the intensity of deliberation (Merk et al., 2019), and that the public distinguishes different funding sources (Nelson et al., 2021). Limited studies for developing countries show a tendency for respondents to be more open to SRM (Visschers et al., 2017; Sugiyama et al., 2020), perhaps because they experience climate change more directly (Carr and Yung, 2018). In some Anglophone countries, a small portion of the public believes in chemtrail conspiracy theories, which are easily found in social media (Tingley and Wagner, 2017; Allgaier, 2019). Since researchers rarely distinguish different SRM options in engagement studies, there remains uncertainty in public perception.

Ethics

There is broad literature on ethical considerations around SRM, mainly stemming from philosophy or political theory, and mainly focused on SAI (Flegal et al., 2019). There is concern that publicly debating, researching and potentially deploying SAI could involve a 'moral hazard', with potential to obstruct ongoing and future mitigation efforts (Morrow, 2014; Baatz, 2016; McLaren, 2016), while empirical evidence is limited and mostly at the individual, not societal, level (Burns et al., 2016; Merk et al., 2016; Merk et al., 2019). There is *low agreement* whether research and outdoors experimentation will create a 'slippery slope' towards eventual deployment, leading to a lock-in to long-term SRM, or can be effectively regulated at a later stage to avoid undesirable outcomes (Hulme, 2014; Parker, 2014; Callies, 2019; McKinnon, 2019). Regarding potential deployment of SRM, procedural, distributive and recognitional conceptions of justice are being explored (Svoboda and Irvine, 2014; Svoboda, 2017; Preston and Carr, 2018; Hourdequin, 2019). With the SRM research community's increasing focus on distributional impacts of SAI, researchers have started more explicitly considering inequality in participation and inclusion of vulnerable countries and marginalised social groups (Flegal and Gupta, 2018; Whyte, 2018; Táíwò and Talati, 2021), including considering stopping research (Stephens and Surprise, 2020; National Academies of Sciences and Medicine, 2021a). There is recognition that SRM research has been conducted predominantly by a relatively small number of experts in the Global North, and that more can be done to enable participation from diverse peoples and geographies in setting research agendas and research governance priorities, and undertaking research, with initial efforts to this effect (e.g., Rahman et al., 2018), noting unequal power relations in participation could influence SRM research governance and potential implications for policy (Whyte, 2018; Táíwò and Talati, 2021; Winickoff et al., 2015; Frumhoff and Stephens, 2018; Biermann and Möller, 2019; McLaren and Corry, 2021; National Academies of Sciences and Medicine, 2021b)

Governance of research and of deployment

Currently, there is no dedicated, formal international SRM governance for research, development, demonstration or deployment (see WGIII Chapter 14). Some multilateral agreements—such as the UN Convention on Biological Diversity or the Vienna Convention on the Protection of the Ozone Layer—indirectly and partially cover SRM, but none is comprehensive, and the lack of robust and formal SRM governance poses risks (Ricke et al., 2013; Talberg et al., 2018a; Reynolds, 2019a). While governance objectives range broadly, from prohibition to enabling research and potentially deployment (Sugiyama et al., 2018b; Gupta et al., 2020), there is agreement that SRM governance should cover all interacting stages of research through to any potential, eventual deployment with rules, institutions and norms (Reynolds, 2019b). Accordingly, governance arrangements are co-evolving with respective SRM technologies across the interacting stages of research, development, demonstration and—potentially—deployment (Rayner et al., 2013; Parker, 2014; Parson, 2014). Stakeholders are developing governance already in outdoors research, for example for MCB and OAC experiments on the Great Barrier Reef (McDonald et al., 2019). Co-evolution of governance and SRM research provides a chance for responsibly developing SRM technologies with broader public participation and political legitimacy, guarding against potential risks and harms relevant across a full range of scenarios, and ensuring that SRM is considered only as a part of a broader portfolio of responses to climate change (Stilgoe, 2015; Nicholson et al., 2018). For SAI, large-scale outdoor experiments even with low radiative forcing could be transboundary, and those with deployment-scale radiative forcing may not be distinguished from deployment, such that MacMartin and Kravitz (2019) argue for continued reliance on modelling until a decision on whether and how to deploy is made, with modelling helping governance development. For further discussion of SRM governance, see Chapter 14, WGIII.

Many linkages between SDG 13 (climate action) and other SDGs have been identified (*very high confidence*) (Blanc, 2015; Kelman, 2015; Northrop et al., 2016; Hammill and Price-Kelly, 2017; ICSU, 2017; Mugambiwa and Tirivangasi, 2017; Dzebo et al., 2018; Major et al., 2018; Nilsson et al., 2018; Sanchez Rodriguez et al., 2018). In addition, interactions between different climate change actions and SDGs, and interactions among SDGs themselves, have also been assessed (Nilsson et al., 2016; IPCC, 2018a; McCollum et al., 2018; Fuso-Nerini et al., 2019; IPCC, 2019b; Cernev and Fenner, 2020). The Cross-Chapter Box GENDER in Chapter 18 assessment indicates the importance of gender considerations in achieving success and benefits in adaptation efforts. Aligning climate change adaptation to the SDGs could bring potential co-benefits and increased efficiency in funding, and reduce the gap between adaptation planning and implementation (*very high confidence*) (IPCC, 2018a; Sanchez Rodriguez et al., 2018; IPCC, 2019b; IPCC, 2019a).

Progress towards meeting the SDGs has been recognised to be able to reduce global disparities and support more climate resilient development pathways (IPCC WGII AR5, Chapter 13, p. 818; discussed further in Chapter 18). Nevertheless, we are still lagging in achieving the 2030 Goals (OECD, 2019; Sachs et al., 2021), and this affects societal vulnerability, readiness and risk response capacities (IPCC, 2019a, Chapters 6, 7, Chapters 6 and 8, this report). We assess the risk literature for linkages between key risks (grouped by RKRs) and the indicators of the SDGs (UN, 2015) using text analysis (details in SM16.5) to identify the potential level of effect of different risks on the SDGs. Some 940 documents were analysed. The SDG status is associated with projected climate hazards, also called climatic impact drivers (CIDs) (Ranasinghe et al., 2021) (panel a), and RKRs (panel c), summarising hazard and exposure with vulnerability aspects, as expressed by challenges in achieving the SDGs (panel d), on a regional level (Figure 16.12).

16.6.1.2 Results, Implications and Gaps

Linkages between the 17 SDGs and the eight RKRs (Figure 16.12 bottom left panel) are mapped to the regional SDG status (Figure 16.12 bottom right panel) and related to the CIDs (Figure 16.12 top left panel). Interconnections between CIDs and RKRs are complicated by the possibility of concurrent weather events, extremes and longer-term trends. Risks are compounded by existing vulnerabilities (Iwama et al., 2016; Thomas et al., 2019b; Birkmann et al., 2021) and cascading consequences (Pescaroli and Alexander, 2015; Pescaroli and Alexander, 2018; Yokohata et al., 2019) (see, for example, Sections 3.4.3.5, 5.12, 6.2.6, 7.2.2.2) as well as interactions. The level of challenges faced in attaining the SDGs is one metric for assessing vulnerability and lack of capacity to manage risks (Cernev and Fenner, 2020). Other metrics are also available (Parker et al., 2019; Garschagen et al., 2021b; Birkmann et al., 2022). From Figure 16.12, aside from SDG13 (climate action), the strongest connections and risk challenges are with zero hunger (SDG2), sustainable cities and communities (SDG11), life below water (SDG14), decent work and economic growth (SDG8), no poverty (SDG1), clean water and sanitation (SDG6) and good health and well-being (SDG3) (*high confidence*). Other SDGs have strong linkages with specific RKRs, for example, terrestrial and marine ecosystems with life on land (SDG15); infrastructure (RKR-C) with industry, innovation and infrastructure (SDG9) and affordable and clean energy (SDG7); living standards (RKR-D) with gender equality (SDG5); and peace and human mobility (RKR-H) with peace, justice and strong institutions (SDG 16) (*high confidence*).

On a global scale, priority areas for regions can be evaluated from the intersection of climate hazards, risks and the level of challenges in SDG attainment (Moyer and Hedden, 2020; Sachs et al., 2021). The greatest linkages and effects on the SDGs will be due to risks to water (RKR-G), living standards (RKR-D), coastal socio-ecological systems (RKR-A) and peace and human mobility (RKR-H) (*high confidence*) (details in SM16.5).

In particular, coastal socio-ecological systems (RKR-A), living standards (RKR-D), food security (RKR-F), water security (RKR-G) and peace and human mobility (RKR-H), have strong linkages with SDG 2 (zero hunger), for which there are significant to major challenges for all regions (*high confidence*). Almost all the RKRs are strongly linked to SDGs 8 (decent work and economic growth) and 11 (sustainable cities and communities) (*high confidence*), where regions such as Africa, Asia, and Central and South America face significant to major challenges in attaining targets. All regions also face major to significant challenges affecting SDGs 14 (life below water) and 15 (life on land), which relate to terrestrial and ocean ecosystems (RKR-B) (*high confidence*).

The analysis of RKR linkages to SDGs is also useful in identifying gaps and susceptibilities, especially for developing future climate resilient development targets. This aspect is discussed further in Chapter 18. Gaps may arise as SDG targets and indicators are not specifically focused on systems affected by climate change risks or impacts. For example, in the SRCCL Section 7.1.2, Hurlbert et al. (2019) noted the absence of an explicit goal for conserving freshwater ecosystems and ecosystem services in the SDGs. Such gaps (Tasaki and Kameyama, 2015; Guppy et al., 2019) are inevitable as the current SDG targets and indicators focus on overall sustainable development. As another example, projected increases in frequency and intensity of hot temperature extremes are likely to result in increased heat-related illness and mortality, yet heat extremes are not called out as an SDG indicator under SDGs 3 (good health and well-being) or 13 (climate action). The gaps on climate-related metrics for impacts on health are just beginning to be evaluated (Lloyd and Hales, 2019, see also Section 7.1.6). The current SDG 13 (climate action) targets also do not specifically track the possibility of differential impacts on society from disasters and extreme weather events (RFC2). For example, the first indicator (Section 13.1.1.1), 'Number of deaths, missing persons and directly affected persons attributed to disasters per 100,000 population', does not include any requirement for disaggregated data, unlike several other socioeconomic and population SDG indicators, making it difficult to track the different effects that climate-related disasters are expected to have on men, women and children across different segments of society, relevant for distributional impacts (RFC3) (see also Section 8.3, Cross-Chapter Box GENDER in Chapter 18). The risk consequences identified and discussed in each RKR (Section 16.5.2) provide useful entry points for identifying indicators and metrics for monitoring and evaluating specific impacts of key climate change risks. In addition, the sector and region chapters have considered various adaptation responses relevant to the SDGs (see, for example, Sections 3.6, 4.7.5, 5.13.3, 8.2.1.6, 10.6.1, 13.11.4, 14.6.3) with relevant metrics for evaluation.

Linkages between the projected climatic impact-drivers (CIDs) by region, Sustainable Development Goals (SDGs) by region, and the Representative Key Risks (RKRs)

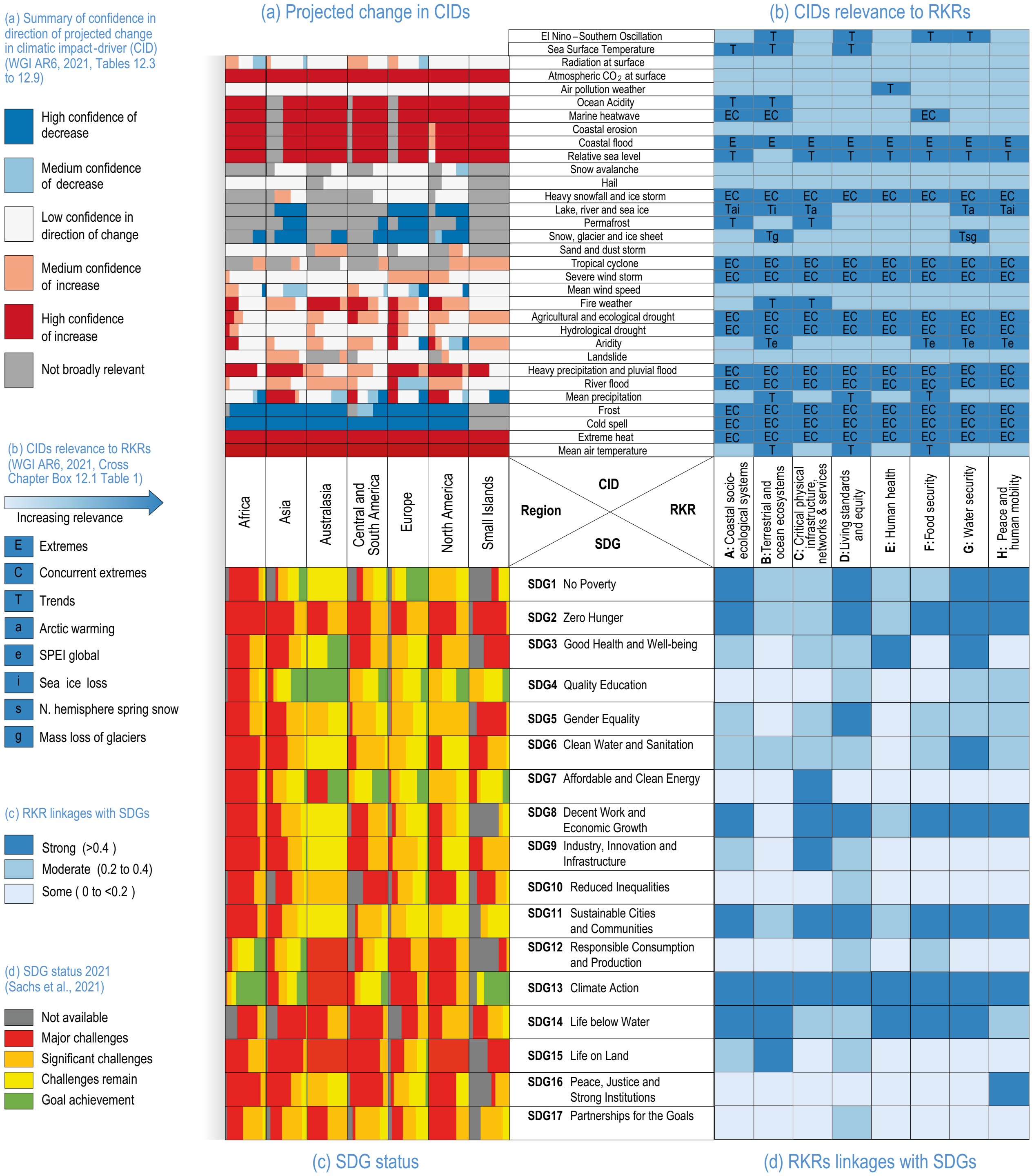

Figure 16.12 | Linkages between the projected climatic impact drivers (CIDs) by region, Sustainable Development Goals (SDGs) by region, and the representative key risks (RKRs).

In summary, key risks, and the consequences arising from them, are directly linked to and will affect specific indicators of the SDGs (*high confidence*). They also will be indirectly linked to, and thus affect, the SDGs overall, due to the interactions between the key risks (Section 16.5) and between the SDGs themselves (*very high confidence*). These results support previous findings that climate change impacts pose a risk to achieving sustainability (Ansuategi et al., 2015; Chirambo, 2016; ICSU, 2017; Pradhan et al., 2017; Gomez-Echeverri, 2018; IPCC, 2018a; IPCC, 2019b; IPCC, 2019a; Cernev and Fenner, 2020). Not all observed or expected consequences arising from the key risks are fully captured by the SDG indicators, nor were they designed to be. Therefore, for monitoring and assessing the climate risk impacts, it is useful to consider specific climate change impact indicators and metrics (Enenkel et al., 2020) to capture any realised impacts.

In the near term, the strength of connection between the RKRs and the SDGs, with respect to existing SDG challenges, indicate probable systemic vulnerabilities and issues in responding to climatic hazards (UN-IATFFD, 2019; Leal Filho et al., 2020; Weaver et al., 2020; Tiedemann et al., 2021) (*high confidence*). In the medium to long term (associated with global warming levels of between 2°C and 2.7°C under SSP2–4.5 scenario), if such vulnerabilities and challenges cannot be substantially reduced, the hazards and risks resulting from the projected CIDs (Figure 16.12b, c) will further stress systems relevant for sustainable development, based on current experience of the COVID-19 pandemic (UN-IATFFD, 2021, see also Cross-Chapter Box COVID in Chapter 7; Sections 8.2, 8.3) (*medium confidence*, based on *medium evidence*, *high agreement*).

The potential impacts of the various climate hazards, the occurrence of extreme events, and the projected trends of climate hazards give rise to complex risks for ecological and human systems, which are compounded by the exposure, vulnerability and sustainability challenges faced in different regions of the world. The potential global consequences are elaborated in the next section, which describes the framework and approach for the assessment of the five RFCs.

16.6.2 Framework and Approach for Assessment of RFCs and Relation to RKRs

The RFC framework communicates scientific understanding about accrual of risk in relation to varying levels of warming for five broad categories: risk associated with (1) unique and threatened systems, (2) extreme weather events, (3) distribution of impacts, (4) global aggregate impacts and (5) large-scale singular events (Smith et al., 2001; Mastrandrea and Schneider, 2004; Schneider and Mastrandrea, 2005). The RFC framework was first developed during the Third Assessment Report (Smith et al., 2001) along with a visual representation of these risks as 'burning embers' figures, and this assessment framework has been further developed and updated in subsequent IPCC reports including AR5 (IPCC, 2014; Oppenheimer et al., 2014) and the recent IPCC Special Reports (SR15 (IPCC, 2018a); SRCCL (IPCC, 2019; SROCC (IPCC, 2019)).

Relationship between RKRs and RFCs

RFCs reflect risks aggregated globally that together inform the interpretation of DAI with the climate system. The five RFC categories are maintained as previously defined for consistency with earlier assessments. Compared with the synthesis of risk across RKRs in Section 16.5, we note that the RKRs and RFCs are complementary methods that aggregate individual risks into different but interconnected categories (Figure 16.13).

We draw important distinctions between RFC and RKR. First, RFCs assess risks that might be of global concern, while RKRs also include risks that may be of concern only locally or for specific population groups (Figure 16.13). RFCs focus on the full range of increasing risk, and locate transitions between four categories of risk: undetectable, moderate, high, and very high. RKRs focus on severe risks, and attempt to elaborate when/where severe impacts may occur. RKR assessments focus on the conditions under which some risks would become severe over the course of this century, while RFCs evaluate changes in risk levels against gradual increase in temperature levels. The RKR analysis used specific definitions of severity including quantified thresholds where possible, and this is distinct from the approach based on the combined elements of risk used in the RFC expert elicitation process. Severity as defined in the RKRs is associated with high or very high risk levels but does not align precisely with either of those categories, and a further difference arises from a more explicit emphasis on irreversibility and adaptation limits in the very high risk category in the RFCs. Thus, RKR and RFC neither map directly to one another in terms of content, nor in terms of the response metric.

The treatment of vulnerability and adaptation is different in the RKR and RFC assessments. The RKR assessment considered specifically three alternative levels of vulnerability, whereas the RFC process did not explicitly differentiate risk by level of vulnerability. Therefore, the global warming levels at which the various RKR assessments identify risk of severe impacts are not directly comparable to risk transitions identified in the RFC assessments. In addition, RKRs consider implications of low versus high adaptation in order to illustrate the potential role of ambitious adaptation efforts to limit risk severity; RFCs consider risks in a no/low adaptation scenario only, although there is some discussion of the potential role of adaptation in assessing the transition to very high risk. Last, both RKRs and RFCs focus on the 21st century scale, though recognising risk will continue to increase after 2100, but treat this timing issue differently: RKRs assess severe risks over the course of this century and distinguish risks that are already severe, that will become severe by the mid-century, or that will become severe by the end of the century; while RFCs assess risk level irrespective of their timing, but according to different temperature levels.

Many of the elements of risk which contribute to RKRs also contribute to risk within one or more RFCs. In turn, elements of risk within some RFCs, such as extreme weather and changes in the Earth system contribute to risk within one or more RKR. Hence, RFCs may incorporate elements of many different RKRs, and vice versa. There are therefore common elements between some particular RKRs and RFCs: for example, risks to terrestrial and ocean ecosystems (RKR-B) contribute strongly to RFC1 (Unique and Threatened Systems) and RFC4

(Global Aggregate Impacts), while RFC2 (extreme weather events) has implications for all RKRs, including direct linkages with critical physical infrastructure, networks and services (RKR-C). Furthermore, risks emerging from the interaction of RKRs also contribute to the RFCs, but are only qualitatively described in Section 16.5.4. For example, the effects of risks to terrestrial and ocean ecosystems (RKR-A) affect living standards and equity (RKR-C), as does the associated decline in ecosystem services which then impacts livelihoods (RKR-D).

Elicitation Methodology

The method used to develop judgements on levels of risk builds on the approach described in WGII AR5 Chapter 19 (Oppenheimer et al., 2014) and outlined in more detail in the work of O'Neill et al. (2017), while integrating advances in the AR6 SRs including expert judgement (SRCCL, Zommers et al., 2020). We provide further details on the underlying judgements of risk level compared with previous assessments by indicating key risk criteria associated with each judgement: magnitude of adverse consequences, likelihood of adverse consequences, temporal profile of the risk, and ability to respond to the risk (Section 16.5.1). The definitions of risk levels used to make the expert judgements are presented in Table 16.7 (Section 16.5.1).

A brief summary of the framework that was used to carry out the risk assessment, synthesis and expert elicitation is presented here, and details are provided in SM16.6. Expert judgements about the qualitatively defined levels of risk (i.e., undetectable, moderate, high, and very high) reached at various levels of global average warming are informed by evidence of observed impacts illustrated in Section 16.2 and variations in individual key risks under different scenarios of climate change, socioeconomics and adaptation effort in Section 16.5. We follow the methodological advances from SRCCL Chapter 7 (Hurlbert et al., 2019), which used an expert elicitation protocol for developing the burning embers (Zommers et al., 2020). Specifically, we used expert participants from within the AR6 author team and a protocol based on the modified Delphi technique (Mukherjee et al., 2015) and the Sheffield Elicitation Framework (Oakley and O'Hagan, 2010; Gosling, 2018). This approach (Figure 16.14) includes a two-round elicitation process with a first round of independent anonymous judgements about the global warming level at which risk levels transition from one to the next, and a final round of group discussion and deliberation to develop consensus. The results are then reported, and additional references are made to findings from other relevant chapters in this report. Then, authors who had not participated in the elicitation as part of independent appraisal review the results.

The resulting risk transition or 'ember' diagram illustrates the progression of socio-ecological risk from climate change as a function of global temperature change, taking into account the exposure and vulnerability of people and ecosystems, as assessed by literature-based expert judgement. Section 16.6.3 presents these diagrams for each RFC, providing information about the most important literature-based evidence that experts used to make their judgements. Similar

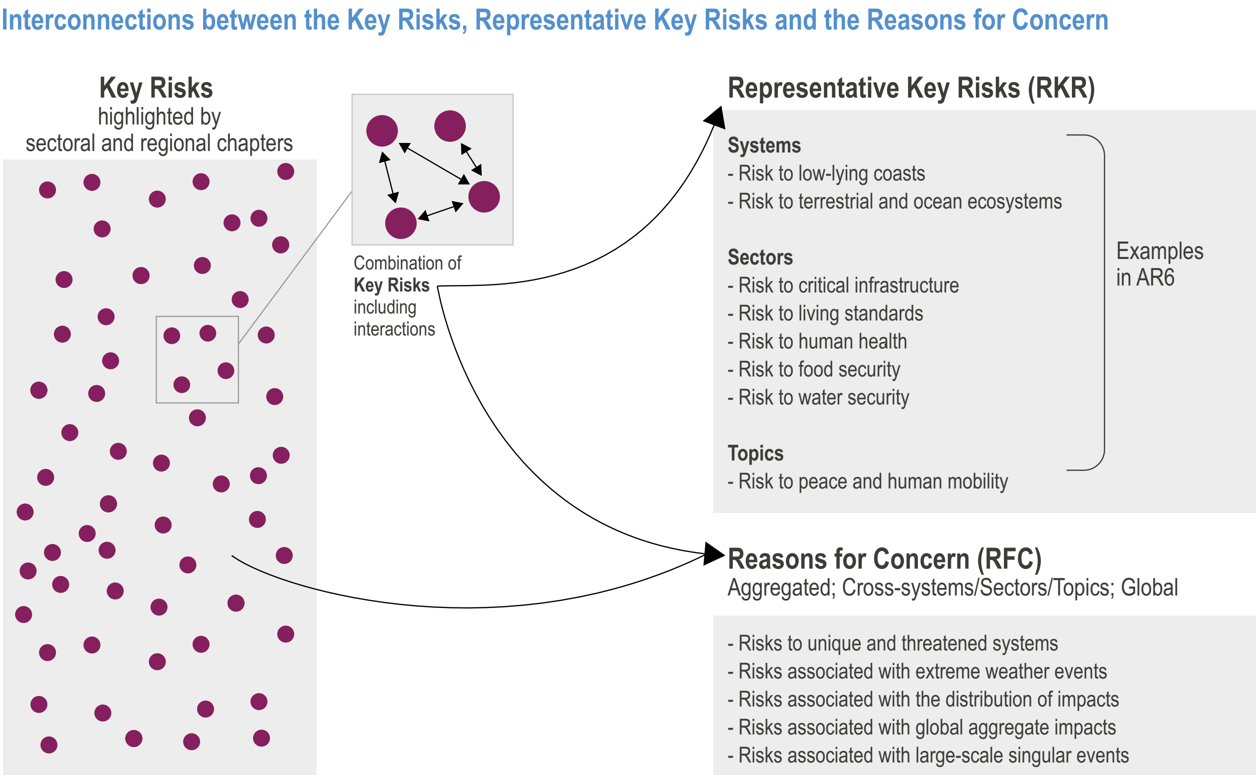

Figure 16.13 | Interconnections between the key risks, representative key risks and Reasons for Concern.

Table 16.7 | Definition of risk levels for Reasons for Concern.

Level	Definition
Undetectable (white)	No associated impacts are detectable and attributable to climate change.
Moderate (yellow)	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 (red)	Severe and widespread impacts that are judged to be high on one or more criteria for assessing key risks.
Very high (purple)	Very high risk of severe impacts and the presence of significant irreversibility or the persistence of climate-related hazards, combined with limited ability to adapt due to the nature of the hazard or impacts/risks.

assessments for selected individual KRs are discussed in Chapters 2, 7, 9, 12, 13 and 14.

Representation of warming levels

The RFC assessment reflects the latest understanding of warming reported in WGI AR6. Global surface temperature was 1.09 [0.95 to 1.20]°C higher in 2011–2020 than 1850–1900, with stronger warming over land (1.59 [1.34 to 1.83]°C) than over the ocean (0.88 [0.68 to 1.01]°C) (WGI AR6 Cross Chapter Box 2.3 Table 1, Eyring et al. in Gulev et al., 2021). Warming levels are commonly reported and studied in the impacts literature using two scales of spatially averaged temperature rise, global surface air temperature (GSAT), commonly produced by General Circulation Models (GCMs) when projecting climate changes, and global mean surface temperature (GMST), commonly used in empirical studies. Both have the same reference point of pre-industrial of 1850–1900. The ember diagrams presented here use GSAT, which is consistent with most literature of projected risk (largely based on the output of climate models). To the extent that the embers also draw on the observed impacts literature using GMST, this potential variation is minimal as the average levels of GSAT and GMST have been shown to match closely (for further discussion on this, see Cross-Chapter Box CLIMATE in Chapter 1). Hence, the diagrams are presented with a single *y*-axis representing global temperature change, generally referring to global temperature rise irrespective of when it occurs; however, the majority of the literature assessed considers alternative levels of warming during the 21st century. For example, a warming level of 2°C might occur in the 2050s, in the 2080s or in 2100 (see next section).

Furthermore, climate-related hazards associated with each of the RFCs are assessed in WGI AR6 Cross-Chapter Box 12.1 Table 1 (Tebaldi et al., 2021), which synthesises information from various chapters of WGI on 35 such hazards according to global warming levels (GWLs) to inform understanding of their potential changes and associated risks with temperature levels in general.

Temporal dimension

When are the risks shown in the embers projected to occur? The issues associated with assessing transient risks are discussed in Chapter 3, SR15 (IPCC, 2018a). Some of the literature, however, does explore the dynamics within human and natural systems (i.e., the way in which

Expert elicitation approach for assessment of RFC risk level transitions

Figure 16.14 | Expert elicitation approach for assessment of RFC risk level transitions. A more detailed description of the methodology used in this elicitation is provided in SM16.6.

systems respond when a transient level of warming is first reached, and then further, how they continue to develop if that transient level of warming is then maintained indefinitely). We note that this important factor is captured in the RFC assessment (and ember diagrams), since the timing of risk accrual is one of the criteria for the assessment of the level of risk (Section 16.5.1). Risks that are known to evolve only over very long-time scales contribute less to the level of risk than those which are known to occur rapidly. This is because SLR also depends on the dynamics of global warming, including the rate of change of radiative forcing, and time lags of several decades, including between atmospheric and ocean warming, and in reaching equilibrium sea level state (Oppenheimer et al., 2019; Fox-Kemper et al., 2021). However, longer-term risks that would arise if those transient temperatures were maintained are also included, and this is particularly important in RFC5 (large-scale singular events). Note that risks that take place over a very long time scale are considered to be of lower concern than more imminent risks. However, changes of very large magnitude can still be very important even if far away in time, especially if these changes are irreversible (or reversible only on extremely long time scales) (see Section 16.5.1).

Although the embers do not indicate the decade in which certain risks are projected to occur, clearly this depends strongly on the level of mitigation action as well as the degree of adaptation. Hence, the ember diagram (Figure 16. 15) is shown alongside a graphic illustrating possible global temperature time series emerging from alternative future scenarios assessed by WGI AR6 which imply different levels of mitigation effort. For example, in a scenario with a high level of mitigation effort (SSP1–1.9) reaching net zero emissions in the 2050s, it is *extremely likely* that global warming remains below 2°C and more than 50% *likely* that it will remain below 1.6°C (AR6 WGI 4.3.1.1, Meinshausen et al., 2020). On the other hand, a level of 2°C warming is *extremely likely* to be exceeded during the 21st century under the three scenarios assessed by WGI AR6 in which GHG emissions do not fall below current levels before mid-century (i.e., SSP2–4.5, SSP3–7.0, SSP-8.5) (WGI AR6 4.3.1.1, Lee et al., 2021). WGI AR6 has assessed that 'global surface temperature averaged over 2081–2100 is *very likely* to be higher by 1.0°C–1.8°C under the lowest CO_2 emission scenario considered in this report (SSP1–1.9) and by 3.3°C–5.7°C under the highest CO_2 emission scenario (SSP5–8.5)'. However, almost all scenarios assessed by IPCC AR6 WGI reach 1.5°C global warming level in the early 2030s (WGI AR6 SPM, IPCC, 2021).

Temperature overshoot

The concept of temperature overshoot, defined as 'exceedance of a specified global warming level followed by a decline to or below that level during a specified period of time' is a relevant consideration for this RFC risk assessment; however, the effect of overshoot has not explicitly been considered in the burning ember assessment because of the limited literature basis. However, despite the lack of directly assessed overshoot scenarios, the current literature provides several salient examples of irreversible changes that are projected to occur once global temperatures reach a particular level. For example, coral reefs are unable to survive repeated bleaching events that are too close together, leading to irreversible loss of the reefs even if bleaching were to cease (see Section 16.6.3.1 RFC1). Species extinction is irreversible, and Chapter 2 assesses that, at ~1.6°C, >10% of species are projected to become endangered as compared with >20% at ~2.1°C (median), representing high and very high biodiversity risk, respectively (*medium confidence*) (Section 2.5.4). Similarly, WGI AR6 finds that 'Over the 21st century and beyond, abrupt and irreversible regional changes in the water cycle, including changes in seasonal precipitation, streamflow and aridity, cannot be excluded'. Thus, information about irreversibility provides information about the potential outcome of temperature overshoot scenarios. Other types of losses, such as loss of human or species life, are irreversible even if the loss process ceases in the future. The less resilient a system is, the more likely it is to suffer irreversible damage during a temperature overshoot; the more resilient it is, the more likely it is to be able to withstand the overshoot or recover afterwards. Very high levels of risk, as assessed here in the RFC, are associated with a wide range of criteria for risk assessment including irreversibility. While not all very high risks are irreversible, in general, risks reaching a very high level include a component of irreversible risks that would persist during and after an overshooting of a given temperature level.

Risks associated with socioeconomic development, mitigation and maladaptation

The ember diagrams in Figure 16. 15 capture only the risks arising from exposure of vulnerable socio-ecological systems to climatic hazards across a range of socioeconomic futures. They do not capture any risk component arising solely from changes in population or level of development. Importantly, they also do not capture additional risks that may arise from the human response to climate change, including climate change mitigation or unintended negative consequences of adaptation-related responses (i.e., maladaptation) (Section 17.5.1). Such risks are discussed in SRCCL Chapter 7, for example, adverse effects of the very large-scale use of land and water for primary bioenergy production on food production and biodiversity (Hurlbert et al., 2019). Contributions of mitigation or maladaptation to risk can be important, however, and are discussed further in the context of specific RFCs in Section 16.6.3. In general, such components of risk are difficult to quantify, and can be minimised by good design of climate change mitigation and adaptation. Thus, the effect is excluded from the ember diagrams to allow a clearer representation of the accrual of climate change risk with global warming.

Emergent risk

AR5 Oppenheimer et al. (2014) defined 'emergent risk' as a risk that arises from the interaction of phenomena in a complex system. While emergent risk is a relevant consideration for this RFC risk assessment, this type of risk has not been explicitly accounted for in the burning ember assessment because of the limited literature basis. Unlike known or identified risks, emergent risks are characterised by the uncertainty of consequences and/or probabilities of occurrence. The International Risk Governance Council (IRGC) suggests three categories of emergent risks: (1) high uncertainty and a lack of knowledge about potential impacts and interactions with risk-absorbing systems; (2) increasing complexity, emergent interactions and systemic dependencies that can lead to nonlinear impacts and surprises; and (3) changes in context (for example, social and behavioural trends, organisational settings, regulations, natural environments) that may alter the nature, probability and magnitude of expected impacts. Feedback processes between climatic change, human interventions involving mitigation and adaptation actions, and processes in natural systems can be classified as emergent risks if they pose a threat to human security.

16.6.3 Global Reasons for Concern

In this section, we present the results of the expert elicitation in the form of the burning embers diagram, alongside a description of the recent literature and scientific evidence for each of the RFCs in turn. The consensus transition values are illustrated in Figure 16. 15 , an updated version of the burning embers diagram that describes the additional risk due to climate change for each RFC when a temperature level is reached and then sustained or exceeded (Table SM16.20 presents the consensus values of the transition range and median estimate in terms of global warming level by risk level for each of the five RFC embers). The shading of each ember provides a qualitative indication of the increase in risk with temperature, and we retain the colour scheme employed in the most recent versions of this figure, where white, yellow, red and purple indicate undetectable, moderate, high and very high additional risk, respectively. These transitions were assessed under conditions of low to no adaptation compared with today, in accordance with definitions provided in 16.3 (i.e., adaptation consists of fragmented, localised, incremental adjustments to existing practices), though the effect of adaptation on risk for individual RFCs and related literature is discussed further below.

The following subsections present the expert assessment and judgements made during the elicitation process to identify consensus transition values for each RFC. The description of these transitions is further extended with additional references to findings from underlying chapters in this report, and reviewed by Chapter 16 authors as part of independent appraisal. No changes were made to the transition values assessed through the expert elicitation.

16.6.3.1 Unique and Threatened Systems (RFC1)

This RFC addresses the potential for increased damage to or irreversible loss of a wide range of physical, biological and human systems that are unique (i.e., restricted to relatively narrow geographical ranges and have high endemism or other distinctive properties) and are threatened by future changes in climate (Smith et al., 2001; Smith et al., 2009; Oppenheimer et al., 2014). The specific examples of such systems given in previous IPCC assessment reports has remained broadly consistent, with AR4 including 'coral reefs, tropical glaciers, endangered species, unique ecosystems, biodiversity hotspots, small island states, and indigenous communities' (Smith 2009), AR5 including '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), and SR15 Chapter 3 including 'ecological and human systems that have restricted geographic ranges constrained by climate related conditions and have high endemism or other distinctive properties. Examples include coral reefs, the Arctic and its Indigenous People, mountain glaciers and biodiversity hotspots'. In this cycle, we retain the definition used in SR15 as most explicit and inclusive of the previous definitions.

AR5 (Oppenheimer et al., 2014) assessed the transition from undetectable to moderate risk for RFC1 to lie below recent global temperatures (1986–2005, which at the time was considered to correspond to a global warming level of 0.6°C above pre-industrial levels; AR6 WGI now considers this time period of 1986–2005 to correspond to a global warming or approximately 0.7°C). At that time, there was 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 within this RFC. SR15 Section 3.5.2.1 (Hoegh-Guldberg et al., 2018b), concurred with *high confidence* that the transition to moderate risk had already occurred before the time of writing.

The transitions here are informed by these assessments, along with the assessment in Chapter 2 on species high extinction risk and on ecosystem transitions. It also draws substantially from information in Cross-Chapter Paper 1 and Table SM16.22 on risks to unique and threatened biological systems. Some unique and threatened systems, such as coral reefs and sea-ice-dependent ecosystems, were already showing attributable impacts with *high confidence* (see Table SM16.22 , Cross-Chapter Paper 1 and Chapter 2) based on data collected in the mid to latter 20th century, when global warming of 0.5°C above pre-industrial levels had taken place, as noted already in AR3. In this AR6 assessment, the temperature range for the transition from undetectable to moderate risk is still located at a median value of 0.5°C above pre-industrial levels, with *very high confidence.* Since impacts were first detected in coral reef systems in the 1980s when warming of ~0.4°C of global warming had occurred (SR15 Chapter 3), this provides the temperature at which the transition begins. The September Arctic sea ice volume has declined by 55–65% between 1979 and 2010 (AR6 WGI, Schweiger et al., 2019) as global warming increased from around 0.36°C in 1979 to around 0.9°C in 2010. These provide evidence of a start to the transition from undetectable to moderate risk at 0.4°C above pre-industrial levels. Recent evidence of observed impacts on mountaintop ecosystems and sea-ice-dependent species, and of range shifts in multiple ecosystems during 1990–2000, which AR6 WGI now assesses as corresponding to a global warming of 0.69°C (see WGI AR6 Cross-Chapter Box 2.3, Figure 1, Gulev et al., 2021), provides evidence for an upper limit to this transition of 0.7°C with *very high confidence*. Overall, the transition is located at a median of 0.5°C with lower and upper limits of 0.4°C and 0.7°C, respectively, with *very high confidence.*

AR5 assessed the transition from moderate to high risk to lie around 1°C above 1986–2005 levels (which corresponded at that time to 1.6°C above pre-industrial levels but has been reassessed by AR6 WGI to correspond to 1.7°C) to reflect projected '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.' SR15 relocated the transition slightly from 1.6°C to 1.5°C, owing to increased literature projecting the effects of climate change upon Arctic sea ice and new literature assessing projected impacts of climate change on biodiversity at 1.5°C warming.

In this AR6 assessment, the transition from moderate to high is based on the high level of observed impacts, and the areas projected to begin undergoing major transformations by 1.5°C (see Cross-Chapter Paper

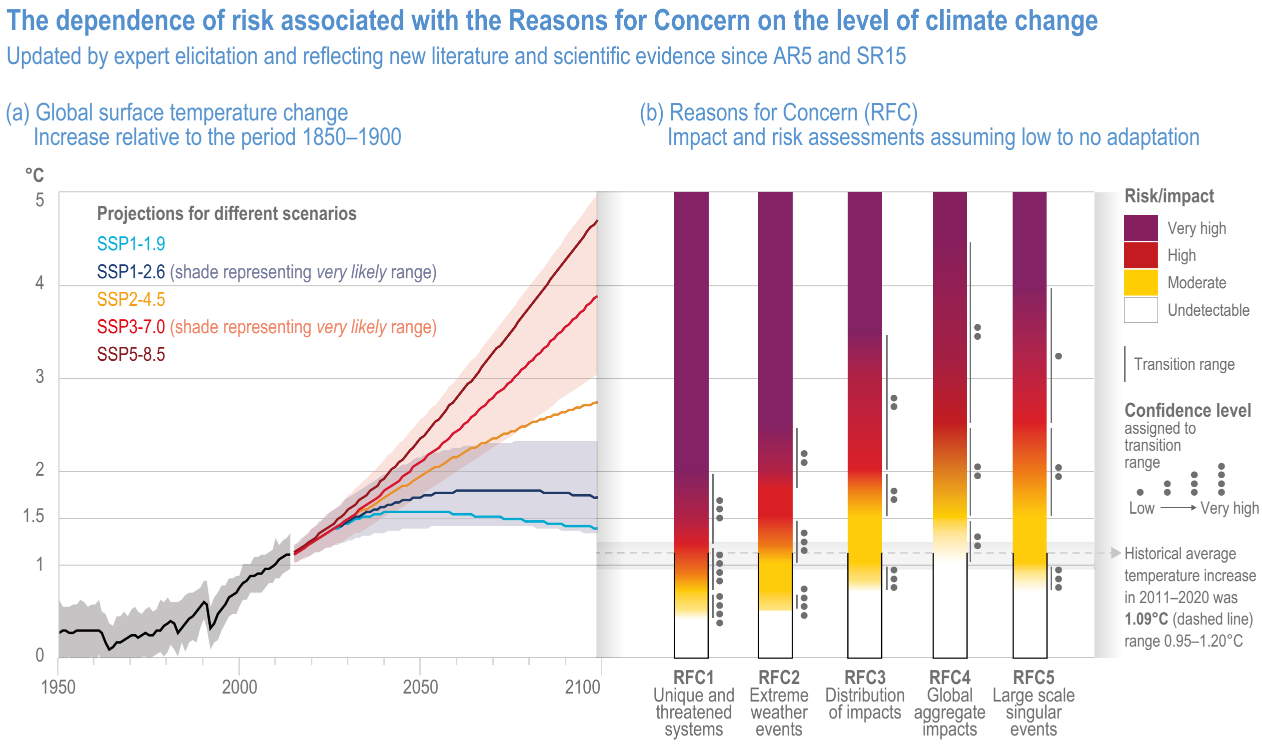

Figure 16.15 | The dependence of risk associated with the Reasons for Concern (RFCs) on the level of climate change, updated by expert elicitation and reflecting new literature and scientific evidence since AR5 and SR15.

(a) Global surface temperature (GST), relative to pre-industrial, 1850–1900 (WGI AR6 Figure SPM.8d). (IPCC, 2021a).

(b) Embers are shown for each RFC, assuming low to no adaptation (i.e., adaptation is fragmented, localised, incremental adjustments to existing practices). The dashed horizontal line denotes the present global warming of 1.09°C (IPCC WGI Figure SPM.8a) which is used to separate the observed, past impacts below the line from the future projected risks above it. **RFC1 Unique and threatened systems**: ecological and human systems that have restricted geographic ranges constrained by climate-related conditions and have high endemism or other distinctive properties. Examples include coral reefs, the Arctic and its Indigenous People, mountain glaciers and biodiversity hotspots. **RFC2 Extreme weather events**: risks/impacts to human health, livelihoods, assets and ecosystems from extreme weather events such as heatwaves, heavy rain, drought and associated wildfires, and coastal flooding. **RFC3 Distribution of impacts**: risks/impacts that disproportionately affect particular groups owing to uneven distribution of physical climate change hazards, exposure or vulnerability. **RFC4 Global aggregate impacts**: impacts to socio-ecological systems that can be aggregated globally into a single metric, such as monetary damages, lives affected, species lost or ecosystem degradation at a global scale. **RFC5 Large-scale singular events**: relatively large, abrupt and sometimes irreversible changes in systems caused by global warming, such as ice sheet disintegration or thermohaline circulation slowing. Comparison of the increase of risk across RFCs indicates the relative sensitivity of RFCs to increases in GSAT. The levels of risk illustrated reflect the judgements of IPCC author experts from WGI and WGII.

1, Chapter 2 and SR15 (IPCC, 2018a)). A substantial number of unique and threatened systems are assessed to be in a high risk state owing to the influence of anthropogenic climate change by the 2000–2010 period, when global warming had reached approximately 0.85°C (range 0.7–1°C) (see WGI AR6 Cross-Chapter Box 2.3, Gulev et al., 2021) using the 1995–2014 figure as a proxy for 2000–2010).

The most prominent example of a system assessed to be already in a high risk state is that of coral reefs, which are already degrading rapidly. Observed impacts on coral reefs increased significantly during 2014–2017 (Table SM16.22 , corresponding to a global warming of about 0.9°C). This includes mass bleaching in the Indian Ocean in 1998, 2010, 2015 and 2016 when bleaching intensity exceeded 20% in surveyed locations in the western Indian Ocean, eastern Indian Ocean and western Indonesia. In the tropical Pacific Ocean, climate-driven mass bleaching was reported in all countries in the region, with most bleaching reports coinciding with 2014–2017 marine heatwaves. Fifty percent of coral within shallow-water reefs of the northern and central two-thirds of the Great Barrier Reef were killed in 2015/2016. Subsequent coral recruitment in 2018 was reduced to only 11% of the long-term average, representing an unprecedented shift in the ecology of the northern and middle sections of the reef system to a highly degraded state. A second key example are sea-ice-dependent systems in the Arctic. During August to October of 2010–2019, corresponding to a global warming of about 0.9°C, average Arctic sea ice area has declined in area by 25% relative to 1979–1988 (*high confidence*, AR6 WGI, Figure 9.13). September Arctic sea ice volume has declined by about 72% between 1979 and 2016, with the latter deemed a conservative estimate (AR6 WGI, Schweiger et al., 2019).

Other important examples of observed impacts on unique ecosystems that indicate that risks are already at a high level (Table SM16.22) include mass tree mortalities, now well recorded in multiple unique forest and woodland ecosystems around the world. Sections 2.4.3.3 and 2.4.5 report that, between 1945 and 2007, drought-induced tree mortality (sometimes associated with insect damage and wildfire) has caused the mortality of up to 20% of trees in western North America, the African Sahel, and North Africa, linked to a warming of 0.3–0.9°C above pre-industrial levels, and is implicated in more than 100 other cases of drought-induced tree mortality in Africa, Asia, Australia, Europe, and North and South America (*high confidence*). Species in biodiversity hotspots already show changes in response to climate change (CCP1, *high confidence*). Román-Palacios and Wiens (2020) attribute local extinctions of several taxonomic groups between the latter 20th century and 2003–2012, (corresponding to warming of less than 0.85°C) to climate-change-related temperature extremes for up to 44% (0–75%) of species. Widespread declines of up to 35% in the species richness of the unique pollinator group, bumble bees, between 1901–1974 and 2000–2014 are also attributed to climate change, via increasing exceedance of their thermal tolerance limits across Europe and North America (Soroye et al., 2020). The first extinctions attributed to climate change have been now detected with the present 1.2°C warming, including that of the Bramble Cay melomys (*Melomys rubicola*), a sub-species of the lemuroid ringtail possum (*Hemibelideus lemuroides*), and golden toad (*Incilius periglenes*) (Chapter 2). An increasing frequency or unprecedented occurrence of mass animal mortality due to climate-change-enhanced heatwaves has also been observed in recent years on more than one continent, including temperature-vulnerable terrestrial birds and mammals in South Africa and Australia (Ratnayake et al., 2019; McKechnie et al., 2021). There have also been 90% declines in sea-ice-dependent species such as sea lions and penguins in the Antarctic (Table SM16.22). A strong effect of climate change on the observed contraction of ranges of polar fish species and strong expansion of ranges of arcto-boreal or boreal fish was observed between 2004 and 2012 (Frainer et al.., 2017). Even if current human-driven habitat loss is excluded, many hotspots are projected to cease to be refugia (i.e., to remain climatically suitable for >75% of the species they contain which have been modelled), at 1.0–1.5°C (Cross-Chapter Paper 1).

Based on observed and modelled impacts to unique and threatened systems, including in particular coral reefs, sea-ice-dependent systems and biodiversity hotspots, AR6 assesses that the transition to high risks for RFC1 have already occurred at a median level of 0.9°C, with a lower bound at 0.7°C and an upper bound at the present-day level of global warming of 1.2°C (WMO, 2020) (*very high confidence*).

Identification of the transition to very high risk is associated by definition with the reaching of limits to natural and/or societal adaptation. Adaptation which occurs naturally is already included in the risk assessment, but experts also discussed the effect of additional human-planned adaptation in reducing risk levels in RFC1. This additional adaptation could help species to survive *in situ* despite a changing climate (for example, by reducing current anthropogenic stresses such as over-harvesting), or facilitate the ability of species to shift geographic range in response to changes in climate, and the potential benefits of nature-based solutions and restoration (see Cross-Chapter Box NATURAL, Section 2.6.5.1).

When considering planned adaptation, the main option often considered in terrestrial ecosystems is the expansion of the protected area network, which is broadly beneficial in increasing the resilience of ecosystems to climate change (e.g., Hannah et al., 2020). However, this action is not effective if the unique and threatened systems in question reach a hard limit to adaptation (as in the case of the loss of Arctic summer sea ice, the submergence of a small island, the contraction and elimination of a species' climatic niche from a mountaintop, or the degradation of a coral reef) (Section 16.4). Furthermore, adaptation benefits deriving from restoration rapidly diminish with increasing temperature (Cross-Chapter Paper 1). One study quantifies how land management (in terms of protecting existing ecosystems or restoring lost ones) might reduce extinctions in biodiversity hotspots or globally significant terrestrial biodiversity areas more generally (Warren et al., 2018b). While the latter suggests that substantial benefits can result globally in terrestrial systems, allowing less unique systems to persist at higher levels of warming but only under a high adaptation scenario in which globally applied terrestrial ecosystem restoration and protected area expansion takes place, this is less likely for many of the unique and threatened terrestrial systems which are more vulnerable than the globally significant biodiversity areas treated in that study (which excludes coral reefs and Arctic sea-ice-dependent systems). Such high levels of adaptation globally are likely infeasible owing to competition for land use with food production (Pörtner et al., 2021). Novel targeted adaptation interventions for coral reefs such as artificial upwelling and local radiation management show some promise for reducing the adverse effects of thermal stress and resulting coral bleaching (Condie et al., 2021), but are far from implementation (Sawall et al., 2020; Kleypas et al., 2021). Larger benefits in this RFC could theoretically accrue only if adaptation action became ubiquitous and extensive, which experts considered infeasible at the scales required. Small island communities are confronted by socio-ecological limits to adaptation well before 2100, especially those reliant on coral reef systems for their livelihoods, even for a low-emissions pathway (Chapter 3) (*high confidence*). At warming levels beyond 1.5°C, the potential to reach biophysical limits to adaptation due to limited water resources are reported for small islands (*medium confidence*) and unique systems dependent on glaciers and snowmelt (Chapter 4) (*medium confidence*).

AR5 assessed with *high confidence* that the transition from high to very high risks for RFC1 lies around 2°C above 1986–2005 levels (then considered to correspond to 2.6°C above pre-industrial 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 in Arctic sea-ice-dependent systems. Using the additional literature which became available on projected risks to Arctic sea ice, biodiversity and ecosystems at 1.5°C versus 2°C warming above pre-industrial levels, SR15 assessed that the transition from high to very high risks in RFC1 lay between 1.5°C and 2°C above pre-industrial levels.

In AR6, risks are considered to start to transition from high to very high risks above 1.2°C warming (present day, WMO, 2020), with a median value of 1.5°C, owing in particular to the observation of a present-day onset of ecosystem degradation in coral reefs, which are projected in the SR15 report 'to decline by a further 70–90% at 1.5°C (*very high confidence*)' . The literature for projected increases in risk to other unique and threatened systems and their limited ability to adapt above 2°C warming is substantial and robust, and the confidence level in very high risk remains high. At 2°C, 18% of 34,000 insects are projected to lose >50% climatically determined geographic range, as compared with 6% at 1.5°C (Warren et al., 2018a). The risk of species

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extinction increases with warming in all climate change projections, for all native species studied in biodiversity hotspots (Cross-Chapter Paper 1, *high confidence*), being roughly threefold greater for endemic than more widespread species for global warming of 3°C above pre-industrial levels than 1.5°C) (Manes et al., 2021, Cross-Chapter Paper 1) (*medium confidence*). The Arctic is projected to be practically ice free in September in some years for global warming of between 1.5°C and 2°C (WGI AR6 Section 9.3.1.1, Fox-Kemper et al., 2021), undermining the persistence of ice-dependent species such as polar bears, ringed seals and walrus (Meredith et al., 2019), and adversely affecting Indigenous communities. Warming of 1.5°C is also assessed (Chapter 3) to reduce the habitability of small islands, due to the combined impacts of several key risks (*high confidence*). Hence, the transition from high to very high risk in these systems is assessed to occur with *high confidence* beginning at 1.2°C, passing through a median value of 1.5°C, and completing (i.e., reaching its upper bound) at 2°C warming.

16.6.3.2 Extreme Weather Events (RFC2)

This RFC addresses the risks to human health, livelihoods, assets and ecosystems from extreme weather events such as heatwaves, heavy rain, drought and associated wildfires, and coastal flooding (Hoegh-Guldberg et al., 2018b). Previous assessments of this RFC have focused mainly on changes to the hazard component of the risk, using the projected increase in hazard as an indicator of higher risk. However, in AR6 an expanding (although still smaller) body of evidence now allows also incorporation of the exposure and/or vulnerability components of risk and, to a limited extent, their trends.

AR5 identified a transition from undetectable to moderate risk below 'recent' temperatures (i.e., during 1986–2005, which then corresponded to a global warming of 0.6°C above pre-industrial levels). SR15 Section 3.5.2.2 (Hoegh-Guldberg et al., 2018b) concluded that differences of 0.5°C in global warming led to detectable changes in extreme weather and climate events on the global scale and for large regions. IPCC WGI AR6 Chapter 11 confirms this assessment and concludes that 'new evidence strengthens the conclusion from SR15 that even relatively small incremental increases in global warming (+0.5°C) cause statistically significant changes in extremes on the global scale and for large regions'. Substantial literature is available for comparisons at +1.5°C versus +2°C of global warming, but the conclusions are assessed to also apply at lower global warming levels and smaller increments of global warming given the identified linearity of regional responses of several extremes in relation to global warming (Seneviratne et al., 2016; Wartenburger et al., 2017; Tebaldi and Knutti, 2018) and the identification of emergence of global signals in climate extremes for global warming levels as small as 0.1°C (Seneviratne and Hauser, 2020, WGI AR6, Chapter 11, Figure 11.8; WGI Cross-Chapter Box 12.1). Further analyses are consistent with this assessment, based on model simulations (Fischer and Knutti, 2015; Schleussner et al., 2017; Kirchmeier-Young et al., 2019a; Seneviratne and Hauser, 2020) and observational evidence (Zwiers et al., 2011; Dunn et al., 2020). A global warming of +0.5°C above pre-industrial conditions corresponds approximately to climate conditions in the 1980s (Chapter 2, Figure 2.11), a time frame at which detectable changes in some extremes were established at the global scale based on observations (Dunn et al., 2020). Heat-related mortality has also been assessed to have increased considerably because of climate change (Ebi et al., 2021; Vicedo-Cabrera et al., 2021). The onset, and also median location of the transitions of risk (Figure 16.15) from undetectable to moderate, is therefore considered to be 0.5°C. Further strong new evidence shows that changes in extremes emerged during the 1990s and 2000s (Dunn et al., 2020) by which time +0.7°C of global warming had taken place (IPCC SR15, Chapter 1; WGI AR6, Chapter 2). In AR5 Section 19.6.3.3 (Oppenheimer et al., 2014), a transition to moderate risk was assessed to have taken place at the then 'recent' global warming level of 0.6°C, with *high confidence*. Owing to the increase in evidence, there is now *very high confidence* that the median value of the transition from undetectable to moderate risk is at 0.5°C and led by heat extremes, with the lower estimate set at 0.5°C as well, and upper estimate at 0.7°C.

Further evidence of more recent observed changes in extreme weather and climate events, and their potential for associated adverse consequences across many aspects of society and ecosystems, has continued to accrue (WGI AR6 Chapter 11; WGI AR6 Chapter 12). Since a necessary condition for 'moderate' levels of risk is the detection and attribution of observed impacts, the following text provides an overview of some salient examples of this evidence. In particular, WGI AR6 Chapter 11 (Seneviratne et al., 2021) concludes that some recent hot extreme events that happened in the past decade (2010s) would have been *extremely unlikely* to occur without human influence on the climate system. Global warming in that decade reached approximately 1.09°C on average (IPCC WGI AR6 Chapter 2).

Assessment of a high level of risk requires a higher level of magnitude, severity and spatial extent of the risks. Events prior to that already had substantial impacts, such as the 2003 European heatwave (IPCC SREX Chapter 9). Examples of impactful events in the early 2010s (at ca. 0.95°C of global warming; WGI AR6 Chapter 2, Gulev et al., 2021) include the 2010 Russian heatwave (Barriopedro et al., 2011) and the 2010 Amazon drought (Lewis et al., 2011). Later impactful events include, among others, the 2013 heatwave in eastern China (Sun et al., 2014), the 2017 tropical cyclone Harvey (Risser and Wehner, 2017; Van Oldenborgh et al., 2017) and the 2018 concurrent North Hemisphere heatwaves in Europe, North America and Asia (Vogel et al., 2019). Very recent events with severe and unprecedented impacts attributed to anthropogenic climate change indicate that thresholds to high risks may already have been crossed at recent levels of global warming (ca. 1.1–1.2°C), including the Siberian fires and the 2019 Australian bushfires that were linked to extreme heat and drought conditions (Van Oldenborgh et al., 2017) and extreme precipitation linked to increased storm activity in the USA (Van Oldenborgh et al., 2017). Severe and unprecedented impacts occurred with current low levels of adaptation (Section 16.2.3.4). The global-scale risk of wildfire considerably degrading ecosystems and increasing illnesses and death of people has been assessed to transition from undetectable to moderate over the range 0.6–0.9°C with *high confidence* (Chapter 2, Table SM2.5, Figure 2.11).

In addition, long-term trends in various types of extremes are now detectable (WGI AR6 Chapter 11, Seneviratne et al., 2021). This includes increases in hot extremes over most land regions (*virtually certain*), increases in heavy precipitation at the global scale and over most regions with sufficient observations (*high confidence*), and increases in agricultural and ecological droughts in some regions (*medium confidence*) (WGI AR6 Chapter 11). There has also been overall a *likely* increase in the probability of compound events, such as an increase in concurrent heatwaves and droughts (*high confidence*) (WGI AR6 Chapter 11). There is *medium confidence* that weather conditions that promote wildfires (fire weather) have become more probable in southern Europe, northern Eurasia, the USA and Australia over the last century (WGI AR6 Chapter 11; SRCCL Chapter 2, Jolly et al., 2015; Abatzoglou and Williams, 2016). Furthermore, food security and livelihoods are being affected by short-term food shortages caused by climate extremes (Section 5.12.1; Chapter 16, Food Security RKR) which have affected the productivity of all agricultural and fishery sectors (*high confidence*). The frequency of sudden food production losses has increased since at least mid-20th century on land and sea (*medium evidence*, *high agreement*). Droughts, floods and marine heatwaves contribute to reduced food availability and increased food prices, threatening food security, nutrition and livelihoods of millions (*high confidence*). Changes in sea surface temperatures drive simultaneous variation in climate extremes, increasing the risk of multi-breadbasket failures (Cai et al., 2014; Perry et al., 2017). Droughts induced by the 2015–2016 El Niño, partially attributable to human influences (*medium confidence*), caused acute food insecurity in various regions, including eastern and southern Africa and the dry corridor of Central America (*high confidence*). Human-induced climate change warming also worsened the 2007 drought in southern Africa, causing food shortages, price spikes and acute food insecurity in Lesotho (Verschuur et al., 2021). In the fisheries and aquaculture sector, marine heatwaves are estimated to have doubled in frequency between 1982 and 2016, as well as increasing in intensity and length, with consequences for fish mortality (Chapter 5; Smale et al., 2019; Laufkötter et al., 2020). In the northeast Pacific, a recent 5-year warm period impacted the migration, distribution and abundance of key fish resources (*high confidence*). At 1°C warming, the number of people affected by six categories of extreme events was found to have already increased by a factor of 2.3 relative to pre-industrial (Lange et al., 2020).

The general picture is one of annual or more frequent occurrences of severe extremes with widespread impacts (as also reflected in Section 16.2), and of multiple extremes, meeting the criteria for the 'severe and widespread' nature of risks that is required for classification at a 'high' level of risk. This is consistent with AR5 Chapter 19 (Oppenheimer et al., 2014), and gives *high confidence* that the lower threshold for entering high risks associated with extreme weather events is +1°C, and that the best estimate is that this transition already occurred now that global warming has reached its present-day level of ca. 1.2°C (WMO, 2020), slightly above the 1.09°C average conditions in the 2010s, that is, 2011–2020 (IPCC WGI AR6 Chapter 2, Gulev et al., 2021).

A range of literature projects further substantial increases in several extreme event types with a global warming of +1.5°C, notably hot extremes in most regions, heavy precipitation in several regions, and drought in some regions (IPCC SR15; WGI AR6 , Chapter 11). In particular, heavy precipitation and associated flooding are projected to intensify and be more frequent in most regions in Africa and Asia (*high confidence*), North America (*medium* to *high confidence* depending on the region) and Europe (*medium confidence*). Also, more frequent and/or severe agricultural and ecological droughts are projected in a few regions in all continents except Asia, compared with 1850–1900 (*medium confidence*); increases in meteorological droughts are also projected in a few regions (*medium confidence*). Increases at 1.5°C of global warming are projected in marine heatwaves (Laufkötter et al., 2020) and the occurrence of fire weather (IPCC, 2019a). Heat-related mortality is assessed to increase from moderate to high levels of risk under about 1.5°C warming under SSP3, a socioeconomic scenario with large challenges to adaptation (Ebi et al., 2021) especially in urban centres (Chapter 6). An additional 350 million people living in urban areas are estimated to be exposed to water scarcity from severe droughts at 1.5°C warming (Sections 6.1, 6.2.2; CCP2 Coastal Cities). In summary, there is *high confidence* that the best estimate for the transition from moderate to high risk is 1.2°C of global warming, with 1°C as lower estimate and 1.5°C as upper estimate. The latter would be set to 1.3°C for an assessment at *medium confidence*.

As in RFC1, one of the criteria for identification of very high risks is limits to adaptation. Though the literature explicitly considering societal adaptation to extreme weather events is limited, there is evidence that investments in hydro-meteorological information, early-warning systems and anticipatory forecast-based finance are a cost-effective way to prevent some of the most adverse effects of extreme events (Coughlan de Perez et al., 2016; Fakhruddin and Schick, 2019; Merz et al., 2020). Despite a lack of systematic methods for assessing general adaptation effectiveness, there is some evidence of risk reduction for particular places and hazards, especially flood and heat vulnerability (Section 16.3.2.4), including investment in flood protection, building design and monitoring and forecasting, air conditioning, reduced social vulnerability, and improved population health. One study finds declining global mortality and economic loss due to extreme weather events over the past four decades (Formetta and Feyen, 2019) especially in low-income countries. Using SSP2 as a proxy for expanded adaptation, Ebi et al. (2021) assess that the transition to high risk for heat-related mortality increases to 1.8°C (compared with 1.5°C with less adaptation under SSP3). There is evidence of adaptation avoiding heat-related mortality at low levels of global warming, using early-warning and response systems and sustainable alterations of the thermal environment at the individual, building, urban and landscape levels (Jay et al., 2021). Despite the evidence that adaptation can reduce risks of heat stress, the impact of projected climate change on temperature-related mortality is expected to be a net increase under a wide range of climate change scenarios, even with adaptation (Chapter 7, *high confidence*). Much of the adaptation literature focuses on coping with long-term gradual climate change and largely does not take into account the increased difficulty of adapting to climate extremes and general higher variability in climate that is projected to occur in the future. However, expanding and more coordinated adaptation, including wider implementation and multi-level coordination, has the potential to reduce the risks to crops from heatwaves at intermediate (but not high) levels of warming.(IPCC AR5 Ch7, Ahmed et al., 2018; Ahmed et al., 2019, Section 16.3.2.2; EEA, 2019; Raza et al., 2019; Tripathi and Sindhi, 2020).

The transition from high to very high risk for the RFC2 was not assessed in the AR5 or in SR15. Some new evidence suggests, however, that very high risks associated with weather and climate extremes would be reached at higher levels of global warming. In particular, changes in several hazards would be more widespread and pronounced at 2°C compared with 1.5°C global warming, including increases in multiple and concurrent extremes (IPCC WGI AR6 SPM; IPCC WGI AR6 Chapter 11, IPCC WGI AR6 Chapter 12). On average over land, high temperature events that would have occurred once in 50 years in the absence of anthropogenic climate change are projected to become 13.9 times more likely with 2°C warming, and 39.2 times more likely with 4°C warming (IPCC AR6 WGI SPM Figure SPM.6, IPCC, 2021), indicating a nonlinear increase with warming. Chapter 2 assessed that risk of wildfire transitions from moderate to high over the range 1.5°C to 2.5°C warming (*medium confidence*, Table SM2.5 , Figure 2.11). The intensity of heavy precipitation events increases overall by about 7% for each additional degree of global warming (IPCC AR6 WGI SPM), while their frequency increases nonlinearly. Events that would have occurred once every 10 years in a climate without human influence are projected to become 1.7 times more likely with 2°C warming, and 2.7 times more likely with 4°C warming (IPCC AR6 WGI SPM Figure SPM.6). Several AR6 regions are projected to be affected by increases in agricultural and ecological droughts at 2°C of global warming, including western North America, central North America, northern Central America, southern Central America, the Caribbean, northern South America, northeastern South America, South American Monsoon, southwestern South America, southern South America, West and Central Europe, the Mediterranean, western Southern Africa, eastern Southern Africa, Madagascar, eastern Australia and southern Australia (IPCC WGI AR6, Chapter 11, Seneviratne et al., 2021). This is a substantially larger number compared with projections at 1.5°C (IPCC WGI AR6, Chapter 11, Seneviratne et al., 2021). In these drying regions, events that would have occurred once every 10 years in a climate without human influence are projected to happen 2.4 times more frequently at 2°C of global warming (IPCC WGI AR6 SPM Figure SPM.6). Urban land exposed to floods and droughts is *very likely* to have more than doubled between 2000 and 2030, and the risk of flooding accelerates after 2050 (Chapter 4). At 2°C of global warming, there are also significant projected increases in fluvial flood frequency and resultant risks associated with higher populations exposed to these flood risks (Alfieri et al., 2017; Dottori et al., 2018).

Heat-related mortality is assessed to increase from high to very high by 3°C under SSP3, a socioeconomic scenario with large challenges to adaptation (Ebi et al., 2021). SRCCL assessed that very high risks would be reached in association with wildfire above 3°C of global warming (IPCC, 2019a). Chapter 2 has assessed that risk of fire weather itself transitions from high to very high over the range 3°C to 4.5°C warming (*medium confidence*, Table SM2.5, Figure 2.11). Matthews et al. (2017) show that, at 1.5°C of global warming, about 40% of all megacities would be affected at least 1 d yr^{-1} with a heat index above 40.6°C (i.e., with 40.6°C 'feels-like' temperatures, accounting for moisture effects). This number would reach about 65% of megacities at 2.7°C and close to 80% at 4°C. In addition, there is evidence for a higher risk of concurrent heat extremes at different locations with increasing global warming (Vogel et al., 2019), meaning that several cities could be affected by deadly heatwaves simultaneously. Laufkötter et al. (2020) found that marine heatwave events would become annual to decadal events under 3°C of global warming, with consequences for aquaculture (Chapter 5). Gaupp et al. (2019) conclude that risks of simultaneous crop failure across worldwide breadbasket regions, due to changes in maximum temperatures in the crop-growth-relevant season or cumulative precipitation in relevant time frames, increase disproportionately between 1.5°C and 2°C of global warming. Populations exposed to extreme weather and climate events may consume inadequate or insufficient food, leading to malnutrition and increasing the risk of disease (Chapter 5, *high confidence*). Hence, there is the potential for very high risks associated with changes in climate extremes for food security in the low adaptation case, already above 2°C of global warming. Finally, studies suggest that regional thresholds for climate extremes could be reached at 2°C of global warming, for instance in the Mediterranean (Guiot and Cramer, 2016). Samaniego et al. (2018) conclude that soil moisture droughts in that region would become two to three times longer than at the end of the 20th century at 2°C, and three to four times longer (125 d long yr^{-1}) at 3°C of global warming. There is clear evidence of very high risk at 3°C global warming for wildfires, marine heatwaves and heatwaves in megacities (the latter being set at 2.7°C).

Based on the available evidence, we assess that there is *medium confidence* that the transition to very high risk would happen at a median value 2°C of global warming, considering the increased risk for breadbasket failure and irreversible impacts associated with changes in extremes at this warming level (e.g., damages to ecosystems, health impacts, severe coastal storms), but that due to the disproportionate increases in risk between 1.5°C and 2°C this transition begins already at 1.8°C. The higher range for this transition is set with *medium confidence* at 2.5°C in this low/no adaptation scenario, owing to the further projected nonlinear increases in risks associated with high temperature events above 2°C (WGI AR6 Figure SPM.6, IPCC, 2021; Cross-Chapter Box 12.1, Ranasinghe et al., 2021), and also the limits to adaptation associated with dealing with a rapid escalation of extreme weather events globally during this century; extreme events are particularly difficult to adapt to and thus more often exceed hard limits to adaptation, particularly in natural ecosystem settings (Section 16.4).

16.6.3.3 Distribution of Impacts (RFC3)

RFC3 reflects how key risks are distributed unevenly across regions and different population groups, due to the non-uniform spatial distributions of physical climate change hazards, exposure and vulnerability across regions. It addresses how risks disproportionately affect particularly vulnerable societies and socio-ecological systems, including disadvantaged people and communities in countries at all levels of development. AR5 concluded that low-latitude and less developed areas generally face greater risk than higher-latitude and more developed countries, including for food- and health-related risks. This conclusion remains valid and is now supported by greater evidence across a range of sectors and geographic regions.

Note that the assessment here is largely based on the national and regional distribution of impacts, rather than sub-national distribution or explicit consideration of vulnerable elements of society. Climate risks are also strongly related to inequalities, often but not always intersecting with poverty (Section 16.1), geographic location, and political and socio-cultural aspects. Thus, countries with high inequality tend to be more vulnerable, and more exposed, to climate hazards (Section 16.1). While the literature assessed here tends to be insufficiently granular to resolve local inequalities, it does confirm the AR5 finding that low-latitude and less developed areas generally face greater risk.

AR6 continues to highlight the uneven regional distribution of projected climate change risks. Biodiversity loss is projected to affect a greater number of regions with increasing warming, and to be highest in northern South America, southern Africa, most of Australia, and northern high latitudes (Section 2.5.1.3, *medium confidence*). Climate change is projected to increase the number of people at risk of hunger in mid-century, concentrated in Sub-Saharan Africa, South Asia and Central America (Chapter 5, *high confidence*), increasing undernutrition, stunting and related childhood mortality particularly in Africa and Asia and disproportionately affecting children and pregnant women (Chapter 7, *high confidence*), strongly mediated by socioeconomic factors (Sections 7.2.4.4, 7.3.1, *very high confidence*). Strong geographical differences in heat-related mortality are projected to emerge later this century, mainly driven by growth in regions with tropical and subtropical climates (Section 7.3.1, *very high confidence*).

In AR5 and SR15, the transition from undetectable to moderate risk was located below what were at the time 'recent' temperatures of between 0.5°C and 0.8°C above pre-industrial levels, with *medium* to *high confidence*, based on evidence of distributional impacts on crop production and water resources. New literature has continued to confirm this transition has already taken place, including more recent observed impacts for regions and groups within the food and water sectors, strongly linked to Representative Key Risks for health, water and food security (Sections 16.2, 16.5, 5.4.1, 5.5.1, 5.8.1, 5.12; Chapter 7).

In AR6, moderate risks have already been assessed to have occurred in Africa for economic growth and reduced inequality, biodiversity and ecosystems, mortality and morbidity due to heat extremes and infectious disease, and food production in fisheries and crop production (Figure 9.6). In Europe, moderate risks to heat stress, mortality and morbidity have already been reached, as well as for water scarcity in some regions (Figure 13.30, Figure 13.3 1). In Australasia, moderate risks are assessed as present already for heat-related mortality risk as well as cascading effects on cities and settlements, and also very high risks already present in coral reef systems, and high risks to kelp forests and alpine biodiversity (Figure 17.6). In North America, moderate risks have already been reached for freshwater scarcity, water quality (Figure 14.4), agriculture, forestry, tourism, transport, energy and mining, and construction (Figure 14.10).

For this assessment, the transition to moderate risk was assessed to have occurred between 0.7°C and 1.0°C of warming with *high confidence*, demonstrating that a moderate level of risk exists at present. The 0.2°C increase in this temperature range as compared with AR5 reflects the fact that AR6 WGI has assessed that the level of global warming reached by 1986–2005 was 0.52–0.82°C (as opposed to 0.55–0.67°C in previous assessments), and also reflects the opportunity for observations to be have made of the observed consequences of the additional rise in temperature that has taken place since the literature underpinning the AR5 assessment was published.

In AR5, the transition from moderate to high risk was assessed to occur between 1.6°C and 2.6°C above the pre-industrial levels with *medium confidence*. In SR15, new literature on projected risks allowed this range to be narrowed to 1.5–2°C. There is now substantial literature providing *robust evidence* of larger regional risks at 2°C warming than 1.5°C and in a range of systems, including crop production (with risks of simultaneous crop failure) (Thiault et al.; Gaupp et al., 2019), aquaculture and fisheries (Cheung et al., 2018b; Froehlich et al., 2018; Stewart-Sinclair et al., 2020), nutrition-related health (Springmann et al., 2016; Lloyd et al., 2018; Sulser et al., 2021) and exposure to stressors such as drought, floods (Alfieri et al., 2017; Hirabayashi et al., 2021) and extreme heat (Dosio et al., 2018; Harrington et al., 2018; Sun et al., 2019). One study (Gaupp et al., 2019) found that the risk of simultaneous crop failure in maize is estimated to increase from 6% to 40% at 1.5°C relative to the historical baseline climate. In particular, further research on projected regional yield declines of wheat and maize between 1.5°C and 2°C, especially in Africa, has accrued Asseng et al. (2015), including in Ethiopia (Abera et al., 2018) with associated economic effects (Wang et al., 2019). Optimum maize production areas in East Asia are projected to reduce in area by 38% for global warming of 1.5–2.0°C (He et al., 2019). A study of Jamaica also estimated that warming of less than 1.5°C will have an overall negative impact on crop suitability and a general reduction in the range of crops, but above 1.5°C, irreversible changes to Jamaica's agriculture sector were projected (Rhiney et al., 2018).

Projections of increasing flood risk associated with global warming of 1.5°C and 2°C continue to highlight regional disparities, with larger-than-average increases projected in Asia and Africa (Hirabayashi et al., 2021), including in China, India and Bangladesh (Alfieri et al., 2017). Similarly, nearly 80% of the 8–80 million additional people projected to be at risk of hunger owing to climate change are located in Africa and Asia (Springmann et al., 2016; Lloyd and Oreskes, 2018; Nelson et al., 2018). Schleussner et al. (2016b) analysed hotspots of multi-sectoral risks with 1.5°C and especially 2°C warming, and highlighted projected crop yield reductions in West Africa, Southeast Asia, and Central and northern South America; a reduction in water availability in the Mediterranean; and widespread bleaching of tropical coral reefs.

High risks to crop production are assessed to occur in Africa with ~1.5–2°C warming (Figure 9.6), to agriculture in North America with ~1.5°C warming (Figure 14.10), and with ~2.8°C in Europe (Figure 13.30). High risks of mortality and morbidity due to heat extremes and infectious disease are assessed to be reached in Africa with ~1.5°C warming (Figure 9.6); heat stress, mortality and morbidity in Europe are assessed to reach a high level of risk at ~2°C (Figure 13.30). Heat-related mortality risk transitions to a high level by ~1.5–2°C warming in Australasia, while cascading effects on cities reach high risk with ~1.2°C warming (Figure 17.6). Risks to water scarcity, forestry, tourism and transportation in North America are projected to reach high levels with ~2°C warming (Figure 14.4, Figure 14.10).

Two complementary multi-sectoral analyses indicate that South Asia and Africa become hotspots of multi-sectoral climate change risk, largely due to changes in water-related indicators which also affect crop production (Arnell et al., 2018; Byers et al., 2018). For instance, Byers et al. (2018) found that the doubling in global exposure to multi-sector risks that accrues as warming increases from 1.5°C to 2°C is concentrated in Asian and African regions (especially East Africa), which together account for 85–95% of the global exposure.

Considering this evidence, for this assessment, the temperature range for the transition from moderate to high risk is located between 1.5°C and 2°C above pre-industrial levels, with *high confidence* in the lower bound of 1.5°C, but *medium confidence* in the upper bound of 2°C, because simulation studies do not account for climate variability and therefore risks could be higher.

Very high risk implies limited ability to adapt. Adaptation potential not only differs across sectors and regions, but also occurs on different time scales depending on the nature and implementation level of the adaptation option under consideration and the system in which it is to be deployed. The costs of adaptation actions that would be needed to offset projected climate change impacts for major crop production are projected to rise once global warming reaches 1.5°C (Iizumi et al., 2020). It has been estimated that the number of additional people at risk of hunger with 2.0°C global warming could be reduced from 40 million to 30 million by raising the level of adaptation action (Baldos and Hertel, 2014), but beyond this level of warming residual impacts are projected to escalate (Iizumi et al., 2020). Chapter 5 assessed the potential of existing farm management practices to reduce yield losses, finding an average 8% loss reduction in mid-century and 11% by end-century (Section 5.4.4.1), which is insufficient to offset the negative impacts from climate change, particularly in currently warmer regions (Section 5.4.3.2). The literature indicates that, globally, crop production may be sustained below 2.0°C warming with adaptation, but negative impacts will prevail at 2.0°C warming and above in currently warm regions (Section 5.4.4.1). Importantly, residual damage (that which cannot be avoided despite adaptation) is projected to rise around 2.0°C global warming (Iizumi et al., 2020). Evidence of constraints and limits for food, fibre and other ecosystem products for the different regions is evident for the various regions (Section 16.4.3.1) indicating limited ability to adapt. Adaptation costs are also higher relative to GDP in low-income countries, for example for the building of sea dikes (Brown et al., 2021).

In previous reports, the transition from high to very high risk for the distribution of impacts was not assessed due to limited available literature, but there is now sufficient evidence to do so. A range of literature quantifies the increasing regional probability of drought as compared with the present day, with projected increases in the area exposed to drought (Carrão et al., 2018; Pokhrel et al., 2021), as well as in the duration (Naumann et al., 2018) and frequency of droughts, with higher warming levels. Naumann et al. (2018) showed that, for drying areas, drought durations are projected to rise from 2 months per °C below 1.5°C to 4.2 months per °C near 3°C warming. Most of Africa, Australia, southern Europe, southern and central USA, Central America, the Caribbean, northwest China, and parts of Southern America are projected to experience more frequent droughts. Adverse effects of climate change on food production are projected to become much more severe (Section 5.4.3.2) when global temperatures rise more than 2°C globally, but there are predicted to be much more negative impacts experienced sooner on food security in low to mid-latitudes (Richardson et al., 2018a) (Section 5.4.1). For instance, climate change by 2050 is projected to increase the number of people at risk of hunger by between 8 and 80 million with 2–3°C warming compared with no-climate-change conditions (Baldos and Hertel, 2014; Hasegawa et al., 2018; Nelson et al., 2018; Janssens et al., 2020). In addition to effects upon crop yield, agricultural labour productivity, food access and food-related health are projected to be negatively impacted by 2–3°C warming (Springmann et al., 2016; de Lima et al., 2021). Regionally, substantial regional disparity in risks to food production is projected to persist at these higher levels of warming. Risks for heat-related morbidity and mortality, ozone-related mortality, malaria, dengue, Lyme disease and West Nile fever are projected to increase regionally and globally (Chapter 7) with potential infestation areas for disease-carrying vectors in multiple geographic regions that could be five times higher at 4°C than at 2°C (Liu-Helmersson et al., 2019).

Very high risks to crop production are assessed to occur in Africa above ~2.5°C warming (Figure 9.6) and below 4°C in Europe (Figure 13.29). Very high risks of mortality and morbidity due to heat extremes and infectious disease are assessed to occur in Africa with 2.5°C warming (Figure 9.6); heat stress, mortality and morbidity in Europe are assessed to reach a very high level of risk at ~3.2°C (Figure 13.30). Heat-related mortality risk and cascading effects on cities both transition to a very high level by ~2.5°C warming in Australasia (Figure 11.7). Risks to water scarcity in North America are projected to reach very high levels with 3.5°C warming (Figure 14.4). Hence, this assessment concludes with *medium confidence* that a transition from high to very high risks, in terms of distribution of impacts, begins at 2°C global warming, with a full transition to very high risks completed by 3.5°C. However, it should be noted that many studies upon which this assessment has been based have not taken into account the impacts of extreme weather events and oscillations in sea surface temperatures; hence, risks at a given level of global warming might be underestimated in the literature.

16.6.3.4 Global Aggregate Impacts (RFC4)

This RFC considers impacts to socio-ecological systems that can be aggregated globally into a single metric, such as monetary damages, lives affected, species lost or ecosystem degradation at a global scale (Oppenheimer et al., 2014; O'Neill et al., 2017). RFC4 shares underlying key risk components with other RFCs (e.g., RFC1 and RFC2, see O'Neill et al., 2017) and thus draws on a similar literature as those assessments; however, this RFC focuses on impacts that reach levels of concern at the global level and also weighs the composite effect of risk elements ranging from economic to biodiversity.

In AR5 Section 19.6.3.5 (Oppenheimer et al., 2014), the transition from undetectable to moderate risk was assessed between 1.6°C and 2.6°C above pre-industrial levels (i.e., 1°C and 2°C above the 1986–2005 level) based on impacts to both Earth's biodiversity and the overall global economy with *medium confidence*. The risk transition between moderate and high risk was set around 3.6°C above pre-industrial levels (i.e., 3°C above the 1986–2005 level), based on literature finding extensive species vulnerability and biodiversity damage with associated loss of ecosystem goods and services at 3.5°C (Foden et al., 2013; Warren et al., 2013). In SR15 Section 3.5.2.4 (Hoegh-Guldberg et al., 2018b), economic literature on potential socioeconomic threshold events and empirical studies of global economic damages, combined with new evidence on biome shifts, extinction risk, species range loss (especially noting the integral role of insects in ecosystem function) and ecosystem degradation, were assessed, and the upper bound of the transition to moderate risk was lowered to 1.5°C warming above pre-industrial levels, and the transition from moderate and high risk was lowered to between 1.5°C and 2.5°C (*medium confidence*). The boundary between high risk and very high risk was not assessed in either of these reports because the temperature threshold was beyond the scope of the assessment in the case of SR15 and literature available for this highest transition in AR5 was limited.

Since AR5, many new global estimates of the aggregate, economy-wide risks of climate change have been produced, though, as was the case in AR5, these continue to exhibit a low level of agreement, including for today's level of global warming, due primarily to differences in methods. Cross-Working Group Box ECONOMIC in this chapter includes a more thorough discussion of advancements and limitations of global economic impact estimates and methodologies, finding significant variation in estimates that increases with warming, indicating higher risk in terms of economic costs at higher temperatures (*high confidence*). Climate change has been found to exacerbate poverty through declines in agricultural productivity, changes in agricultural prices and extreme weather events (Hertel and Lobell, 2014; Hallegatte and Rozenberg, 2017). In terms of biodiversity risks, the literature indicates that losses in terrestrial and marine ecosystems increase substantially between 1.5°C and 2°C of warming (Hoegh-Guldberg et al., 2018b). Since SR15, further evidence of degradation of biodiversity and ecosystem services and ocean acidification at the global aggregate level has continued to accrue due to climate change (see Chapter 2).

For this RFC, the transition from undetectable to moderate risk to global aggregate impacts is assessed with *medium confidence* to occur between 1.0°C (start of transition) and 1.5°C (completion of transition) with a median judgement of transition at 1.3°C, based on evidence of a combination of economic consequences, widespread impacts to climate-sensitive livelihoods, changes in biomes, and loss of terrestrial and marine biodiversity. The start of the transition from undetectable to moderate risk is located at recent temperatures based on observed impacts to biodiversity (Section 16.2.3.1). Experts noted aggregate impacts on biodiversity are detectable, with damages that have had global significance (e.g., drought, pine bark beetles, coral reef ecosystems). Consistent with the start of this transition at 1°C, a similar elicitation conducted in Chapter 2 assessed that risks to biodiversity globally have already transitioned to a moderate level with 1°C warming, while risks of widespread tree mortality are already moderate with 0.9°C warming and moderate risks of ecosystem structure change began with warming of 0.5°C (Table SM2.5, Figure 2.11). Human-induced warming has slowed growth of agricultural productivity over the past 50 years in mid- and low latitudes (Chapter 5; Hurlbert et al., 2019). Although there is not yet strong evidence of attributable loss of life and livelihoods at the global level (Sections 16.5.2.3.4, 16.5.2.3.5), experts found that regional evidence of such observed impacts was still relevant to defining the beginning of the transition (e.g., Table SM16.22, Chapter 9). Informing the median value and upper bound of the transition to moderate risk, empirical studies and scenario analyses have found that regions with high dependence on climate-sensitive livelihoods like agriculture, fisheries and forestry would be severely impacted even at low levels of warming under conditions of low adaptation (RKR-D, Lobell et al., 2011; Hoegh-Guldberg et al., 2018b).

The transition to high risk is assessed with *medium confidence* to occur between 1.5°C (start of transition) and 2.5°C (completion of transition) with a median judgement of transition at 2.0°C. Though economic estimates exhibit wide variation and *low agreement* at warming levels above 1.5°C, many estimates are nonlinear, with marginal economic impacts increasing with temperature (see Cross-Working Group Box ECONOMIC in this Chapter). At 1.5°C warming, most aggregate global impacts to GDP are negative across different estimation methods, including bottom-up estimation (e.g., Takakura et al., 2019), meta-analysis (e.g., Howard and Sterner, 2017) and empirical estimations (e.g., Pretis et al., 2018; Kalkuhl and Wenz, 2020). At 2°C Watts et al. (2021) estimate a relative decrease in effective labour by 10%, which would have profound economic consequences. Byers et al. (2018) found that global exposure to multi-sector risks approximately doubles between 1.5°C and 2°C, while the percentage of the global population exposed to flooding is projected to rise by 24% with 1.5°C warming and by 30% with 2.0°C warning (Hirabayashi et al., 2021).

Section 16.5.2.3.4 (RKR-D, underlying key risk on poverty) reports that, under medium warming pathways, climate change risks to poverty would become severe if vulnerability is high and adaptation is low (*limited evidence*, *high agreement*). At and beyond 1.5°C, approximately 200 million people with livelihoods derived from small-scale fisheries would face severe risk, given sensitivity to ocean warming, acidification and coral reef loss (Cheung et al., 2018a; Froehlich et al., 2018; Free et al., 2019). Warming between 1.5°C and 2°C could expose 330–396 million people to lower agricultural yields and associated livelihood impacts (Byers et al., 2018; Hoegh-Guldberg et al., 2018a), due to a high dependency of climate-sensitive livelihoods to agriculture globally (World Bank, 2020). Models project that climate change will increase the number of people at risk of hunger in 2050 by 8–80 million people globally, with the range depending on the level of warming (1.5–2.9°C) and SSPs (Nelson et al., 2018; Mbow et al., 2019; Janssens et al., 2020). Higher atmospheric concentrations of carbon dioxide reduce the nutritional quality of wheat, rice and other major crops, potentially affecting millions of people at a doubling of carbon dioxide relative to pre-industrial (*very high confidence*) (Section 7.3.1). Global ocean animal biomass is projected to decrease on average by 5% per 1°C increase; hence, a 2.5°C level of warming is associated with ~13% decline in ocean animal biomass, which would considerably reduce marine food provisioning, fisheries distribution and revenue value, with further consequences for ecosystem functioning (Chapter 5, *medium confidence*).

Losses in terrestrial and marine biodiversity increase substantially beyond 1.5°C of warming (Hoegh-Guldberg et al., 2018b). Section 16.5.2.3.2 (RKR-B, risks to terrestrial and marine ecosystems) finds that substantial biodiversity loss globally, abrupt local ecosystem mortality impacts, and ecological species disruption are all projected at global warming levels below 3°C, with insular systems and biodiversity hotspots at risk below 2°C (*medium confidence*). Insects play a critical role in providing vital ecosystem services that underpin human systems, with major losses of their climatically determined geographic range at 2°C warming implying adverse effects on ecosystem functioning. Consistent with the transitions presented here, a similar burning ember developed in Chapter 2 assessed a transition from moderate to high risks globally for marine and terrestrial biodiversity (e.g., widespread death of trees, damages to ecosystems, and reduced provision of ecosystem services, and structural change, including biome shifts) beginning between 1.0°C and 2.0°C warming (Table SM2.5, Figure 2.11).

Though explicit treatment of adaptation is limited in the RFC4 impacts literature (i.e., studies that compare risks for specific adaptation scenarios in terms of globally aggregated impacts with quantified findings), there is evidence of the potential for investments in improved hydro-meteorological information and early-warning systems to avoid some of the most adverse social and economic impacts from extreme weather events in both developed and developing countries, with benefits at a globally significant level (Hallegatte, 2012). Studies of adaptation in the agriculture sector (e.g., changing crop variety, timing of crop planting, new types of irrigation, etc.) and infrastructure (e.g., coastal protection, hardening of critical infrastructure, flood and climate-resistant building materials and water storage) show large potential benefits in terms of reduced impacts to lives and livelihoods (van Hooff et al., 2015; Mees, 2017). At higher warming levels, however, potential adaptations to address biodiversity loss are expected to be limited due to the projected rate and magnitude of change as well as the resources required (Hannah et al., 2020).

The transition to very high risks is assessed to occur within a range of 2.5–4.5°C with *medium confidence* over the range, and *low confidence* assessed over a narrowed 'best estimate' range of 2.7–3.7°C. The lower end of the range reflects the loss of an increasingly large fraction of biodiversity globally. Chapter 2 has assessed a transition from high to very high risks globally for biodiversity (marine and terrestrial) completing at ~2.5°C warming, noting widespread death of trees, damages to ecosystems, and reduced provision of ecosystem services over the temperature range 2.5–4.5°C (Table SM2.5, Figure 2.11) and, similarly, a transition from high to very high risks of ecosystem structure change (including biome shifts) between 3°C and 5°C warming (Table SM2.5, Figure 2.11). A global study of 115,000 common species projects climatically determined geographic range losses of over 50% in 49% of insects, 44% of plants and 26% of vertebrates with global warming of 3.2°C, implying an associated effect on provisional and regulating ecosystem services that support human well-being, including pollination and detritivory (Warren et al., 2018a). The risk of abrupt impacts on ecosystems as multiple species approach tolerance limits simultaneously is projected to threaten up to 15% of ecological communities with 4°C of warming (Trisos et al., 2020). Under a 4°C warming scenario, models project global annual damages associated with SLR of $31,000 billion yr^{-1} in 2100 (Brown et al., 2021)

In terms of global economic impact, while an emerging economic literature is addressing many gaps and critiques of previous damage estimates for high warming (e.g., Jensen and Traeger, 2014; Burke et al., 2015; Lontzek et al., 2015; Moore and Diaz, 2015; Lemoine and Traeger, 2016; Moore et al., 2017a; Cai and Lontzek; Takakura et al., 2019, discussed further in Cross-Working Group Box ECONOMIC; Carleton et al., 2020; Méjean et al., 2020; Rode et al., 2021), there remains wide variation across disparate methodologies, though the spread of estimates increases with warming in all methodologies, indicating higher risk in terms of economic costs at higher temperatures (*high confidence*). Section 16.5.2.3.4 (RKR-D) finds that risks to aggregate economic output would become severe at the global scale at high warming (~4.4°C) and minimal adaptation (*medium confidence*), defining severity as 'the potential for persistent annual economic losses due to climate change to match or exceed losses during the world's worst historical economic recessions'. Furthermore, climate change impacts on income inequality could compound risks to living standards (*high confidence*, 16.5.2.3.4). Chapter 4 finds that, at 4°C, 4 billion people are projected to be exposed to physical water scarcity (*medium confidence*).

16.6.3.5 Large-scale Singular Events (RFC5)

This RFC, large-scale singular events (sometimes called tipping points or critical thresholds), considers abrupt, drastic and sometimes irreversible changes in physical, ecological or social systems in response to smooth variations in driving forces (accompanied by natural variability) (Oppenheimer et al., 2014; O'Neill et al., 2017). SR15 Section 3.5.2.5 presented four examples, including the cryosphere (West Antarctic ice sheet, Greenland ice sheet), thermohaline circulation (slowdown of the Atlantic Meridional Overturning Circulation), the El Niño-Southern Oscillation (ENSO) as a global mode of climate variability, and the role of the Southern Ocean in the global carbon cycle (Hoegh-Guldberg et al., 2018b). While most of the literature assessed here focuses on the resultant changes to climate-related hazards such as sea level rise, in this assessment, evidence about the implications of accelerated sea level rise for human and natural systems is also considered. If sea level rise is accelerated by ice sheet melt, the associated impacts are projected to occur decades earlier than otherwise, directly affecting coastal systems including cities and settlements by the sea (CCP2) and wetlands (Chapter 2). The associated disruption to ports is projected to severely compromise global supply chains and maritime trade with local–global geo-political and economic consequences. To compensate for this acceleration, adaptation would need to occur much faster and at a much greater scale than otherwise, or indeed than has previously been observed (CCP2). The costs of accommodating port growth and adapting to sea level rise amount to USD 22–768 billion before 2050 globally (*medium evidence*, *high agreement*) (see Sections 2.1, 2.2; Cross-Chapter Box SLR in Chapter 3).

In AR5 Section 19.6.3.6 (Oppenheimer et al., 2014), the boundary between undetectable and moderate risk is set at levels between 0.6°C and 1.6°C above pre-industrial levels (i.e., 0°C and 1°C above the 1986–2005 level) with *high confidence*, based on emerging early-warning signals of regime shifts in Arctic and warm water coral reef systems. The risk transition boundary between moderate and high risk was set between 1.6°C and 3.6°C above pre-industrial levels (i.e., 1°C and 3°C above the 1986–2005 level), with *medium confidence* based on projections of ice sheet loss, with faster increase between 1°C and 2°C than between 2°C and 3°C. The literature available at the time did not allow AR5 to assess the boundary between high and very high risk.

In SR15 Section 3.5.2.5 (Hoegh-Guldberg et al., 2018b), new assessments of the potential collapse of the West Antarctic ice sheet (WAIS) initiated by marine ice sheet instability (MISI) resulted in lowering the upper end of the transition from undetectable and moderate risk from 1.6°C to 1°C warming above pre-industrial levels, and lowering the upper end of the transition from moderate to high risk to 2.5°C. Although SR15 did not produce embers beyond 2.5°C, authors reported that the transition to very high risk was assessed as lying above 5°C in light of growing literature on ice sheet contributions to SLR.

Cross-Working Group Box ECONOMIC | Estimating Global Economic Impacts from Climate Change

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This Cross-Working Group Box assesses literature estimating the potential global aggregate economic costs of climate change and the social cost of carbon (SCC), where the former are sometimes referred to as estimates of global 'climate damages' and the latter are estimates of the potential monetised impacts to society of an additional metric ton of carbon dioxide emitted to the atmosphere. These measures include the economic costs of climate change that could be felt in market sectors such as agriculture, energy services, labour productivity and coastal resources, as well as non-market impacts such as other types of human health risks (including mortality effects) and ecosystems. Global economic impacts estimates can inform decisions about global climate management strategy, while SCC estimates can inform globally incremental emissions decisions. In practice, economic damage estimates have been used to explore economically efficient ('economically optimal') global emissions pathways (e.g., Nordhaus and Moffat, 2017), while SCCs have been used to inform federal and state-level policy assessment in some countries (Greenstone et al., 2013; Rose and Bistline, 2016), but the type of SCC and application matters (Rose, 2017). This literature has been assessed in previous WGII reports (e.g., Arent et al., 2014), and this box serves this need for this report. The assessment in this box was performed jointly across WGII and WGIII, building on the foundation of WGII AR6 Chapter 16's 'Risk to living standards' assessment (Section 16.5.2.3.4), which includes consideration of severe risks to global aggregate economic output, and WGIII AR6 Chapter 3's assessment of the benefits of mitigation. It also informs Chapter 16's global aggregate impacts Reasons for Concern and supports Chapter 18's assessment of global emissions transitions, risk management and climate resilient development. In keeping with the broad risk framing presented in Chapter 1 of this report, other lines of evidence regarding climate risks, beyond monetary estimates, should be considered in decision making, including key risks and Reasons for Concern.

Methods for estimating global economic costs of climate impacts

There are several broad approaches to estimating climate damages, including biophysical process models, structural economic models, statistical methods (also called empirical or econometric) and hybrid approaches, with each methodology having strengths and weaknesses. Process models simulate physical, natural science and/or engineering processes and their response to climate variables, which are then monetised (e.g., Anthoff and Tol, 2014; Sieg et al., 2019; Narita et al., 2020). Process approaches have the advantage of being explicit and interpretable, though they can be computationally intensive; may omit relevant impact channels, interactions and market dynamics affecting valuation; and often lack a rigorous empirical basis for calibration (Fisher-Vanden et al.). Structural economic modelling represents climate impacts on inputs, production, household consumption, aggregate investment, and markets for economic sectors and regional economies (e.g., Reilly et al., 2007; Roson and Van der Mensbrugghe, 2012; Anthoff and Tol, 2014; Dellink et al., 2019; Takakura et al., 2019), often using computable general equilibrium (CGE) frameworks. Structural models can evaluate how market and non-market impacts might enter and transmit through economies, and adaptation responses within input and output markets, consumer and investment choices, and inter-regional trade (e.g., Darwin and Tol, 2001; Dellink et al., 2019; Takakura et al., 2019). Statistical methods estimate economic impacts in a given sector (e.g., Auffhammer, 2018) or in aggregate (e.g., Dell et al., 2014; Burke et al., 2015; Hsiang et al., 2017; Pretis et al., 2018; Kahn et al., 2019), inferred from observed changes in economic factors, weather and climate, with responses and net results constrained by available data. Since AR5, hybrid approaches have taken different forms to integrate process, statistical and/or structural methods, and represent a potentially promising means of leveraging the strengths of different approaches (e.g., Moore and Diaz, 2015; and Hsiang et al., 2017; Moore et al., 2017a; Ricke et al., 2018; Yumashev et al., 2019; Chen et al., 2020b). There is also a small literature that uses expert elicitation to gather subjective assessments of climate risks and potential economic impacts (Nordhaus, 1994; IPCC, 2019a; Pindyck, 2019).

In addition to differences in methods, there are also differences in scope—geographic, sectoral and temporal. Global estimates are frequently based on an aggregation of independent sector and/or regional modelling and estimates; however, there are examples of estimates from global modelling that simulate multiple types of climate impacts and their potential interactions within a single, coherent framework (e.g., Roson and Van der Mensbrugghe, 2012; Dellink et al., 2019; Takakura et al., 2019). Differences in scope also represent strengths and weaknesses between the methodologies, with narrower scope allowing for more detailed assessment, but missing potential interactions with the scope not covered (e.g., other geographic areas, sectors, markets or periods of time).

Comprehensive economic estimates are challenging to produce for many reasons, including complex interactions among physical, natural and social systems; pervasive climate, socioeconomic and system response uncertainties; and the heterogeneous nature of climate impacts that vary across space and time. Critiques and commentaries of global estimation methods (Pindyck, 2013; Stern, 2013; van den Bergh and Botzen, 2015; Cropper et al., 2017; Diaz and Moore, 2017; Pindyck, 2017; Rose et al., 2017; Stoerk et al., 2018; DeFries et al., 2019; Pezzey, 2019; Calel et al., 2020; Warner et al., 2020; EPRI, 2021; Grubb et al., 2021; Newell et al., 2021) include, among other things, concerns about statistical methods estimating weather but not climate relationships, making out-of-sample extrapolations,

Cross-Working Group Box ECONOMIC (continued)

and model specification uncertainty, concerns about the observational grounding of structural modelling, and overall concerns about the lack of adaptation consideration, as well as representation and evaluation of potential large-scale singular events such as ice sheet destabilisation or biodiversity destruction, some questioning the ability to generate robust estimates (i.e., estimates insensitive to reasonable alternative inputs and specifications), and general concerns about methodological details, transparency and justification.

Additional methodological challenges to address (see, for instance, EPRI, 2021; Piontek et al., 2021) include how to capture and represent uncertainty and variability in potential damage responses for a given climate and societal condition, combine estimates from different methods and sources (including aggregating independent sectoral and regional results), assess sensitivity and evaluate robustness of estimates (including sensitivity to model specification), capture interactions and spillovers between regions and sectors, estimate societal welfare implications (versus gross domestic product [GDP] changes) of market and non-market impacts, consider distributional effects, represent micro- and macro-adaptation processes (and adaptation costs), specify non-gradual damages and nonlinearities, and improve understanding of potential long-run economic growth effects. Note that the treatment of time preference, risk aversion and equity considerations have important welfare implications for the aggregation of both potential economic impacts and climate change mitigation costs.

In addition to updated and new methods and estimates, newer literature has explored non-gradual damages, such as climatic and socioeconomic tipping points (Lontzek et al., 2015; Méjean et al., 2020), potential damage to economic growth (e.g., Burke et al., 2015; Moore and Diaz, 2015), valuing uncertainty in potential damages (Jensen and Traeger, 2014; Lemoine and Traeger, 2016; Cai and Lontzek) and representing adaptation (Takakura et al., 2019; Carleton et al., 2020; Rode et al., 2021). Going forward, to help advance science and decisions, a key research priority is to understand and evaluate methodological strengths and weaknesses in damage estimation, and reconcile the differences affecting comparability in such a way that it informs use of the different lines of evidence. This will require greater transparency and assessment of details and assumptions in individual methods, communication and evaluation of alternatives for specifying or calibrating climate damage functional representations with respect to climate and non-climate drivers and potential nonlinearities, including evaluating data sufficiency for levels within and beyond observations and for characterising physical system dynamics, and evaluating the sensitivity of results to model specification and input parameter choices (Cropper et al., 2017). Improving the robustness of economic impact estimates is an active area of research. Below we describe the latest estimates.

Global estimates of the economic costs of climate impacts

Since AR5, many new estimates of the global economic costs of climate change have been produced. Figure Cross-Working Group Box ECONOMIC.1 shows a wide spread of estimates, with growing variance at higher levels of warming, both within and across methodology types (i.e., statistical, structural or meta-analysis). Meta-analysis is used here to refer to studies that treat other studies' estimates as data points in an attempt to derive a synthesised functional form.

Global aggregate economic impact estimates (Figure Cross-Working Group Box ECONOMIC.1) are generally found to increase with global average temperature change, as well as vary by other drivers, such as income and population and the composition of the economy. Most estimates are nonlinear with higher marginal economic impacts at higher temperature, although some recover declining marginal economic impacts, and functional forms cannot be determined for all studies. The drivers of nonlinearity found in economic impact estimates, and the differences in nonlinearity across estimates (e.g., convex versus concave, degree of curvature), are not well understood, with methodology construction, assumptions and data all being potential factors. Relative to AR5, there have been more estimates and greater variation in estimates, including some recent estimates significantly higher than the range reported in AR5. For most of the studies shown in Figure Cross-Working Group Box ECONOMIC.1, the visible variation within a study represents alternative socioeconomic projections and climate modelling, not economic impacts response uncertainty for a given socioeconomic and climate condition. Response uncertainty could be significant, as indicated by some of the results shown in the figure (e.g., Burke et al., 2015; Rose et al., 2017), but methodological differences in how uncertainty is characterised (model specification, errors and confidence intervals versus distributions of results) limit comparability and assessment. Note that modelling factors between global temperature change and the economic impact calculation, such as regional temperature pattern assumptions or assumed SLR dynamics, can also impact calculated estimates (e.g., Warren et al.., 2021 PAGE09 estimates versus those in Rose et al.., 2017, Chen et al.., 2020 PAGE-ICE estimates versus Burke et al.., 2015).

From Figure Cross-Working Group Box ECONOMIC.1, we find a large span of damage estimates, even without considering uncertainty/confidence in damage responses, including for today's level of warming (about 1°C). There is also evidence that some regions benefit from low levels of warming, leading to net benefits globally at these temperatures. The size of the span of estimates grows with global warming level, with variation across statistical estimates larger than variation in structural estimates. The structural and meta-analyses estimates appear to be in closer agreement, but that outcome is contingent on the meta-analyses' data considerations and approach. Meta analyses to date have not assessed the alternative methods and dealt with the lack of comparability between methods.

Cross-Working Group Box ECONOMIC (continued)

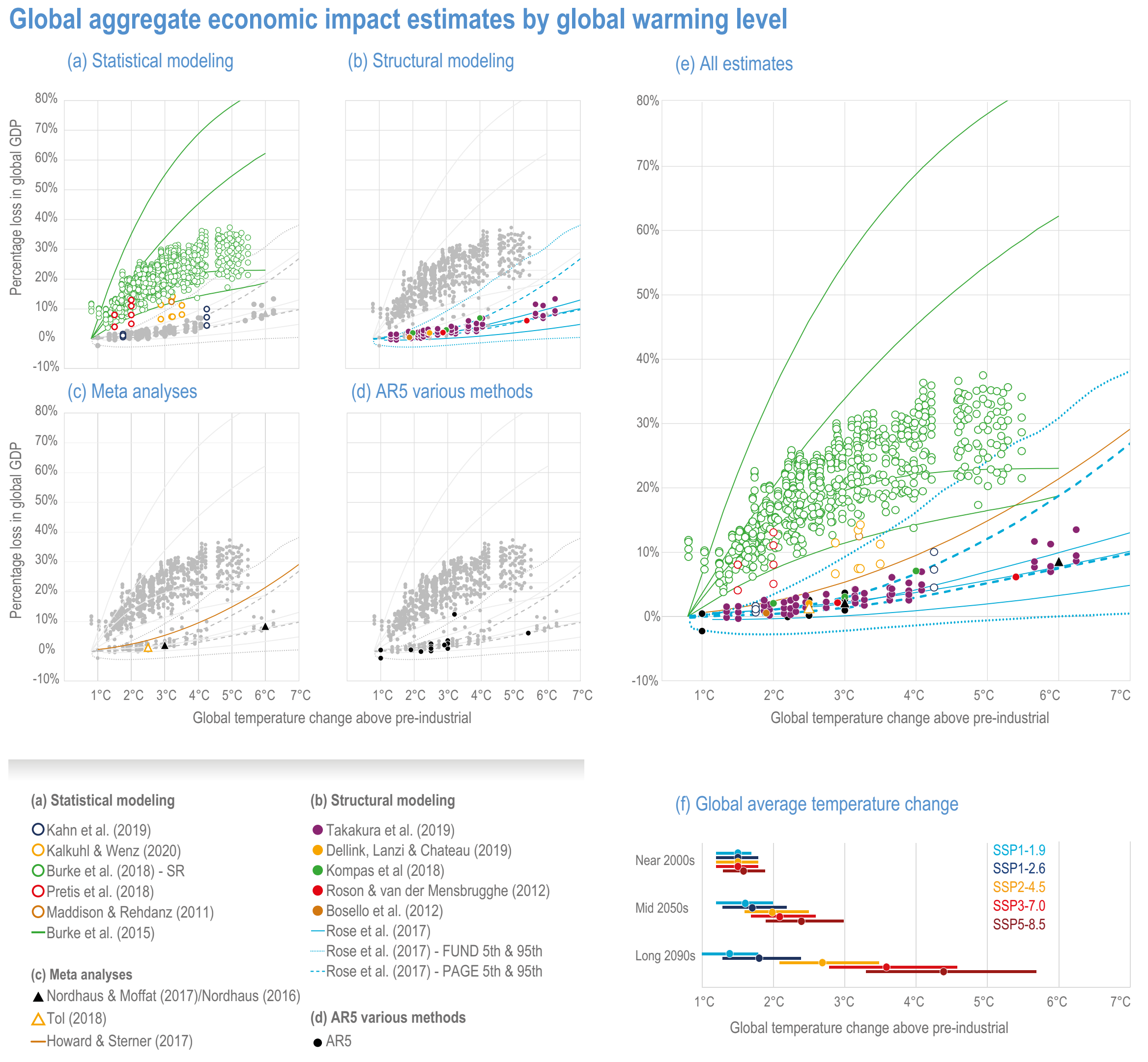

Figure Cross-Working Group Box ECONOMIC.1 | Global aggregate economic impact estimates by global warming level (annual % global GDP loss relative to GDP without additional climate change). Top row panels present estimates by methodology type: (a) statistical modelling, (b) structural modelling and (c) meta-analyses, with all estimates from a paper in the same colour and estimates from methodologies other than that highlighted by the panel in grey for reference. Second row left panel (d) presents AR5 estimates. Second row right panel (e) presents all estimates in one figure, with the same colours as panels (a–d) using outlined dots for the statistical modelling estimates, solid dots for structural modelling estimates, and triangles for meta-analysis estimates. In all panels, lines represent functions, with dashed and dotted lines 5th and 95th percentile functions from structural modelling. To avoid duplication, estimates from papers using the economic impacts estimates or model formulations already represented in the figure are not included (e.g., Diaz and Moore, 2017; Chen et al., 2020b; Glanemann et al., 2020; Warren et al., 2021). The exception is Burke et al. (2018), with the different estimates shown representing variation across climate scenarios for a given aggregate economic impacts specification from Burke et al. (2015)—the 'pooled, short run' statistical specification. Results shown for the latter are estimates with the author's different statistical model specifications (and a fixed climate scenario, SSP5). From top to bottom, the Burke et al. (2015) estimates are for the 'pooled, long run', 'differentiated, long run', 'pooled, short run' (authors' base case) and 'differentiated, short run' statistical specifications. For Howard and Sterner (2017), the authors' preferred function is shown. Overall, estimates shown in the figure can correspond to different future years, reflecting different socioeconomic conditions and climate pathways to a global warming level. Global average temperature change bars relative to the period 1850–1900 are shown below the economic cost estimates to provide context to potential future warming. Shown are the WGI AR6 assessed best estimates and 90% intervals for the illustrative emissions scenarios considered for the near term 2021–2040, mid-term 2041–2060 and long term 2081–2100.

Cross-Working Group Box ECONOMIC (continued)

Differences in methodology type and scope complicate comparison, assessment and synthesis (Cropper et al., 2017; Diaz and Moore, 2017; EPRI, 2021; Piontek et al., 2021). In particular, structural economic modelling and empirical aggregate output modelling are fundamentally different, which has been identified as an issue affecting the comparability of results (Cropper et al., 2017). The different methodologies affect outcomes, with global aggregate estimates based on statistical methodologies typically higher than those from structural modelling (Figure Cross-Working Group Box ECONOMIC.1). This is, in part, due to the relationships in observational data captured by statistical modelling, assumed persistence of impacts in statistical modelling, broader adaptation responses in structural modelling, and differences in the representation of future societies and how they might evolve, respond and interact. Within statistical modelling, results are also found to be very sensitive to the statistical model specification (e.g., Burke et al., 2015; Newell et al., 2021). Within structural modelling, differences in representations of biophysical changes and economic structural dynamics contribute to differences across structural estimates (e.g., Rose et al., 2017).

The wide range of estimates, and the lack of comparability between methodologies, does not allow for identification of a robust range of estimates with confidence (*high confidence*). Evaluating and reconciling differences in methodologies is a research priority for facilitating use of the different lines of evidence (*high confidence*). However, the existence of higher estimates than AR5 indicate that global aggregate economic impacts could be higher than previously estimated (*low confidence* due to the lack of comparability across methodologies and robustness of estimates).

While Figure Cross-Working Group Box ECONOMIC.1 summarises global aggregate estimates, the literature exhibits significant heterogeneity in regional economic impacts that are also sensitive to methodology, model specification and societal assumptions (with, for instance, larger estimates due to the assumed size of society, but offsetting adaptive capacity improvements and adaptation responses). Regional results illustrate the potential for overall net benefits in more temperate regions at lower levels of warming with potential lower energy demand and comparative advantages in agricultural markets; however, at higher levels of warming, net losses are estimated. In addition, economic impacts for poorer households and poorer countries represent a smaller share in aggregate quantifications expressed in GDP terms than their influence on well-being or welfare (Byers et al., 2018; Hallegatte et al., 2020).

Social cost of carbon methods and estimates

The global economic impact estimates discussed in the previous section serve as a key input into the calculation of the value of potential net damages caused by a marginal ton of carbon dioxide emissions, or the SCC. To compute an SCC, damage estimates are commonly combined in a multi-century modelling framework with socioeconomic and emissions projections, a physical model of the climate, including a SLR component, and assumptions about the discount rate, with current frameworks having highly stylised representations of these components. Though we do not present quantitative estimates here, due to the challenge of comparability, for economic impacts methodologies (as discussed above) as well as other SCC estimation elements, large variations in SCC estimates are found in the literature assessed due to, among other things, differences in modelling component representations, input and parameter assumptions, considerations of uncertainty, and discounting, inflation, and emissions year (e.g., Tol, 2009; Tol, 2018; Pezzey, 2019; Iese et al., 2021). There are also different 'variants' of SCC estimates that differ conceptually, and in magnitude, depending on the reference condition for evaluating the impact of a marginal metric ton—is it being evaluated relative to a no-climate-policy baseline, an economically efficient pathway that weighs the benefits and costs of emissions mitigation, or a pathway based on a particular climate policy or goal such as 2°C or a concentration target (Rose et al., 2017)? The variant of SCC has implications for its applicability to different policy contexts (Rose and Bistline, 2016).

In addition to the economic impacts methodological challenges discussed above with respect to aggregate economic impact estimates, the additional components needed for SCC calculations give rise to a new set of technical issues and critiques, including incorporation of uncertainties in the components beyond climate damages, links between components, and discounting (van den Bergh and Botzen, 2015; Cropper et al., 2017; Diaz and Moore, 2017; Pindyck, 2017; Rose et al., 2017; EPRI, 2021). For component-specific discussions and assessment, see Cropper et al. (2017), Rose et al. (2017) and EPRI (2021).

Substantial progress has been made in recent years to better reflect complexities in the global economy, the climate system, and their interaction. For example, recent studies have explored damages to natural capital (Bastien-Olvera and Moore, 2021), the influence of imperfect substitutability between environmental services and market goods (Sterner and Persson, 2008; Weitzman, 2012; Drupp and Hänsel, 2021), the implications of heterogeneous climate change impacts across income groups (Dennig et al., 2015; EPRI, 2021; Errickson et al., 2021), the potential for persistent climate impacts to economic growth instead of effects on levels of economic output (Dietz and Stern, 2015; Moore and Diaz, 2015; Ricke et al., 2018; Kikstra et al., 2021; Newell et al., 2021), valuing the risks of climate tipping points (Cai and Lontzek, 2019; Rising et al., 2020), valuing uncertainty under risk aversion (Jensen and Traeger, 2014; Lemoine and Traeger,

Cross-Working Group Box ECONOMIC (continued)

2016), and modelling a distinction between intertemporal inequality aversion and risk aversion in the social welfare utility function (Crost and Traeger, 2013; Jensen and Traeger, 2014; Daniel et al., 2015). These new studies have, in general, raised estimates of the SCC (Crost and Traeger, 2013; Jensen and Traeger, 2014; Gerlagh and Michielsen, 2015; Moore and Diaz, 2015; Faulwasser et al., 2018; Guivarch and Pottier, 2018; Budolfson et al., 2019; Cai and Lontzek, 2019; Dietz and Venmans, 2019; Kalkuhl and Wenz, 2020), in some cases by an order of magnitude (Ricke et al., 2018). However, challenges persist in terms of moving from conceptual to practical application, such as pinning down parameter specifications, modelling specific mechanisms for impacts, and more fully representing adaptation.

Despite these scientific advances, SCC estimates vary widely in the literature. Technical issues with past and current modelling (e.g., Pezzey, 2019; Pindyck, 2019; EPRI, 2021) and the challenge of comparability across methodologies imply that many estimates are not robust (*high confidence*). Also, as a result, the issue of directional bias of past estimates remains unsettled. Better representation of uncertainty in methods can improve robustness, while detailed methodology assessment and comparison will help define the relative biases of methods (*high confidence*).

Application to decision making

The literature has also assessed the application of aggregate economic impact cost and SCC estimates (Rose and Bistline, 2016; Rose et al., 2017; Kaufman et al., 2020) and identified conceptual and technical issues that need to be considered when using results to inform policy decisions. These issues include: accounting for endogenous marginal benefits and socioeconomic conditions in evaluating policies with non-incremental global emissions implications; consistency in assumptions and treatment of uncertainty across benefit and cost calculations; fully accounting for the streams of both mitigation costs and benefits over time; avoiding inefficiently valuing or pricing emissions more than once across policies and jurisdictions; and accounting for emissions leakage to capture net climate implications. Furthermore, concerns about the robustness of estimates have led some to recommend considering alternatives, such as using marginal mitigation cost estimates based on modelling of policy goals instead of the SCC (e.g., Rose, 2012; Pezzey, 2019; Kaufman et al., 2020), although this comes with its own set of assumptions and technical challenges.

AR6 provides new evidence that relates to the location of the transition from undetectable to moderate risk. At the time of SR15, observations were suggesting that MISI might already be taking place in some parts of the WAIS, while AR5 supported assessment of an additional MISI contribution to SLR of several additional tenths of a metre over the next two centuries. Since SR15, new observations (WGI AR6 Section 9.4.2.1, Fox-Kemper et al., 2021) support the assessment of enhanced grounding line retreat and subsequent mass loss through basal melt in various parts of Antarctica, and year 2100 sea level projections for the RCP8.5 scenario have increased by 10–12 cm owing to ice dynamics. However, the onset of MISI is driven by ocean warming in specific locations (ice cavities beneath floating ice shelves), and the relation between these ocean temperatures and global mean temperature is indirect and ambiguous. In addition, MISI implies a self-sustaining instability in the absence of further forcing. Because forcing is still increasing, it cannot be unambiguously assessed whether MISI is driving the observed retreat of grounding lines in the WAIS, or whether this retreat is a purely forced response (and would stop if the warming stops) or is just a manifestation of natural variability in upwelling of warmer waters on the Antarctic continental shelves and, as a result, is just a temporary effect. Consistent with SROCC, AR6 states with *medium confidence* that sustained mass losses of several major glaciers in the Amundsen Sea Embayment (ASE) are compatible with the onset of MISI, but that whether unstable WAIS retreat has already begun or is imminent remains a critical uncertainty.

Whether associated with MISI or not, WGI AR6 (Fox-Kemper et al., 2021) now assesses with *very high confidence* that mass loss from both the Antarctic (whether associated with MISI or not) and Greenland Ice Sheets, is more than seven times higher over the period 2010–2016 than over the period 1992–1999 for Greenland and four times higher for the same time intervals for Antarctica. Given their multi-century commitments to global SLR, this reinforces the assessment of estimating the boundary between undetectable and moderate risks for ice sheets to lie between 0.7°C (the level of global warming in the 1990s when melting began to accelerate) and 1°C (as in SR15), with a median of 0.9°C.

In the Amazon Forest, increases in tree mortality and a decline in the carbon sink are already reported (Brienen et al., 2015; Hubau et al., 2020), and old-growth Amazon Rainforest may have become a net carbon source for the period 2010–2019 (Qin et al., 2021). Estimates which include land use emissions indicate the region may have become a net carbon source (Gatti et al., 2021). Fire activity is an important driver, and both bigger fires (Lizundia-Loiola et al., 2020) and longer fire season (Jolly et al., 2015) have been reported in South America, although this is strongly linked to land use and land use change as well as climate (Kelley et al., 2021), and indeed land use change may be a stronger driver of potential loss of the Amazon Forest than climate change. The risk of climate-change-related loss of the Amazon Forest is assessed already above 'undetectable', but has only emerged over the last few years, when global warming had reached 1°C, and is linked to land use as well as GSAT levels. Chapter 2 has assessed ecosystem carbon loss from tipping points in tropical forest and loss of Arctic permafrost, and finds a transition to moderate risk over the range 0.6–0.9°C (*medium confidence*). Specifically, WGII AR6 Table SM2.5

finds that ‘Primary tropical forest comprised a net source of carbon to the atmosphere, 2001–2019 (emissions 0.6 Gt y^{-1}, net 0.1 Gt y^{-1}) (Harris et al., 2021). Anthropogenic climate change has thawed Arctic permafrost (Guo et al., 2020), carbon emissions 1.7 ± 0.8 Gt y^{-1}, 2003–2017 (Natali et al., 2019)’. This also supports the upper limit for this transition lying at 1°C.

The potential global loss of an entire ecosystem type, coral reefs, is also considered a large-scale singular event. In the 1990s when global warming was around 0.7°C large-scale coral reef bleaching also became apparent (Section 16.2.3.1), also supporting the lower boundary for this transition in respect of coral reefs.

Overall, given the above evidence on ice sheets, Amazon Forest and coral reefs, the transition from undetectable to moderate risk is assessed to occur between 0.7°C and 1°C warming with a median of 0.9°C with *high confidence*.

The transition from moderate to high risk is informed by an assessment of risks at higher levels of warming than present. Nearly all climate models show warmer temperatures around Antarctica in conjunction with rising global mean temperature, and all ice sheet models show sustained mass loss from the WAIS after temperature increase halts (thus implying MISI takes place) at various levels between 1.5°C and 5°C. An increasing fraction of ice sheet models shows additional sustained mass loss from the East Antarctic Ice Sheet (EAIS) for peak warming between 2°C and 4°C, and all ice sheet models show mass loss for peak warming higher than 4°C. Therefore, we assess an increasing link between MISI, WAIS collapse and Antarctic mass loss, for increasing temperature levels (*high confidence*).

There is *high confidence* in the existence of threshold behaviour of the Greenland Ice Sheet in a warmer climate (WGI AR6 Ch 9, Fox-Kemper et al., 2021); however, there is *low agreement* on the nature of the thresholds and the associated tipping points. Similarly, the likelihood for accelerated and irreversible mass loss from Antarctica increases with increasing temperatures, but thresholds cannot yet be unambiguously identified. By the year 2100, sea level projections (AR6 WGI Figure SPM.8 (IPCC, 2021)) now range from 0.57 m (0.37–0.85 m) for the SSP1–1.9 scenario to 1.35 m (1.02–1.89 m) for the SS5–8.5 scenario and become 1.99 m for the latter scenario (1.02–4.83 m) in the case of low-likelihood, high-impact outcomes resulting from ice sheet instability, for which there is *limited evidence*. It should be noted that inclusion of such low-likelihood, high-impact outcomes dominated by not-well-understood processes affecting ice dynamics on the large ice caps of Greenland, and in particular Antarctica, would also enhance the sea level projections for other scenarios, but to a lesser extent for increasingly weaker forcing. No quantitative assessment of their effect in other scenarios than SSP5–8.5 yet exists as such simulations with ice sheet models have not been carried out, or only in a very limited amount.

It should be noted that ice sheets may take many centuries to respond, implying that risk levels increase over time for the same warming level. Therefore, we base judgements about risk transitions related to ice sheets primarily on their implications for 2000-year commitments to SLR from sustained mass loss from both ice sheets as projected by various ice sheet models, reaching 2.3–3.1 m at 1.5°C peak warming and 2–6 m at 2.0°C peak warming (WGI AR6 TS, Box TS.4 Figure 1; Arias et al., 2021). This is an important feature of the approach to this RFC (i.e., it is not primarily focused on implications for the next 100–200 years). In addition, since the AR5, there is new evidence about the Last Interglacial (LIG), when global mean temperature was about 0.5–1.5°C above the pre-industrial era. AR6 assesses that it is *virtually certain* that sea level was higher than today at that time, *likely* by 5–10 m (*medium confidence*) (B.5.4 WGI AR6 SPM,(IPCC, 2021)). Mid-Pliocene temperatures of 2.5°C (about 3 million years ago when global temperatures were 2.5–4°C higher) also provide evidence as an upper limit for the transition to high risk associated with long-term equilibrium SLR of 5–25 m (WGI AR6 SPM B.5.4). Projected SLR for 2300 in an RCP8.5 or SSP5–8.5 scenario (consistent with a peak warming range of 4–6°C, varies between 1.7–6.8 m and 2.2–5.9 m, respectively (WGI AR6 TS Box TS.4, Arias et al., 2021), and when accounting for marine ice cliff instability taking place on Antarctica, these numbers may increase to a range of 9.5–16.2 m (WGI AR6 TS Box TS.4, Arias et al., 2021).

CMIP6 climate models project drying in the Amazon—especially in June–July–August, irrespective of future forcing scenario, but which increases with GSAT/higher scenarios (Lee et al., 2021). For higher GSAT levels, Burton et al. (2021) explore different forcing scenarios and found, regardless of scenario, burned area increases markedly with GSAT. New understanding of the role of vegetation stomata will act to exacerbate this drying (Richardson et al., 2018b). A transition to high risk of savannisation for the Amazon alone was assessed to lie between 1.5°C and 3°C with a median value of 2.0°C. A mean temperature increase of 2°C could reduce Arctic permafrost area ~15% by 2100 (Comyn-Platt et al., 2018). Chapter 2 has assessed ecosystem carbon loss from tipping points in tropical forest and loss of Arctic permafrost, and finds a transition from moderate to high risk over the range 1.5°C to 3°C with a median of 2°C (*medium confidence*, Table SM2.5, Figure 2.11). Its assessment of the transition from high to very high risk is located over the range 3–5°C (*low confidence*, Table SM2.5, Figure 2.11) based on the potential for Amazon Forest dieback between 4°C and 5°C temperature increase above the pre-industrial period (Salazar and Nobre, 2010).

One of the criteria for locating a transition to very high risk is a limited ability to adapt. In natural systems, limiting warming to 1.5°C rather than 2°C would enhance the ability of coastal wetlands to adapt naturally to SLR, since natural sedimentation rates more likely keep up with SLR (SR15, Hoegh-Guldberg 2018). In human systems, there is *medium confidence* that technical limits will be reached for hard protection to SLR beyond 2100 under high-emissions scenarios, with limits associated with socioeconomic and governance issues reached before 2100 (CCP2).

We therefore estimate the boundary between moderate and high risk to lie between 1.5°C and 2.5°C, with a median at 2.0°C, with *medium confidence* based on projections for melting ice sheets and drying in the Amazon. We also estimate the boundary between high and very high risk to lie between 2.5°C and 4°C, but with *low confidence* due to uncertainties in the projections of SLR at higher levels of warming and differences between levels of warming at which very high risks were assessed in different systems.

16.6.4 Summary

The updated RFCs show that transitions between levels of risk are now assessed to occur at lower levels of global warming than in previous assessments (*high confidence*), levels of confidence in assigning transitions have generally increased, evidence on the potential for adaptation to adequately address risks at different warming levels remains limited, and transitions from high to very high levels of risk have been assessed for all five RFCs, compared with just two RFCs in AR5, together showing how literature published since AR5 is informing us on our future climate risks.

- In particular, risks to unique and threatened systems (RFC1) are now assessed to be already at a high level today, as compared with a moderate level in previous assessments, and transition to a very high level is assessed to occur beginning at 1.2°C, passing through a median value of 1.5°C, and completing the transition at 2.0°C warming (*high confidence*).
- Risks associated with extreme weather events (RFC2) are assessed to have begun to transition to a high level already when global warming reached 1°C, with that transition projected to complete for a warming of 1.5°C (*high confidence*). Newly in AR6, a transition between high and very high levels of risk was assessed to lie at 2.0°C warming for RFC2 (range 1.8–2.5°C).
- For risks associated with the distribution of impacts (RFC3), there is now *high confidence* that a transition to moderate risk has already occurred, and the transition to high risk is now projected to occur between 1.5°C and 2.0°C warming with *medium confidence*. Furthermore, a transition from high to very high risk is provided for the first time in this AR6 assessment, between 2.0°C and 3.5°C warming (*medium confidence*).
- Global aggregate impacts (RFC4) are assessed to have begun to transition to a moderate level already when global warming reached 1°C, and are projected to transition to a high level with warming of 1.5–2.5°C (median 2°C) with *medium confidence.* An assessment of a transition to very high risk is provided for the first time in AR6, over the range 2.5–4.5°C with *low confidence*.
- Risks associated with large-scale singular events are assessed to have already completed transitioning to moderate with 1°C warming (*high confidence*), with a transition to high risk between 1.5°C and 2.5°C (median 2°C) (*medium confidence*). An assessment of a transition to very high risk is provided for the first time in AR6, over the range 2.5–4.5°C with *low confidence*.

In summary, risks to unique and threatened systems (RFC1) are higher at recent and projected levels of warming than assessed previously (*very high confidence*); risks associated with extreme weather events (RFC2) are assessed comparably to AR5 and SR15 at recent and low levels of warming, but notably much higher at projected warming above 1.8°C (*medium confidence*); risks associated with distribution of impacts (RFC3) and global aggregate impacts (RFC4) are similar to SR15 and higher than AR5 above 2°C (*medium confidence*); and those associated with large-scale singular events (RFC5) are similar to SR15 and higher at both recent and projected warming than AR5 (*medium confidence*).

Limiting global warming to 1.5°C would ensure risk levels remain moderate for RFC3, RFC4 and RFC5 (*medium confidence*), but risk for RFC2 would have transitioned to a high risk at 1.5°C and RFC1 would be well into the transition to very high risk (*high confidence*). Remaining below 2°C warming (but above 1.5°C) would imply that risk for RFC3 through 5 would be transitioning to high, and risk for RFC1 and RFC2 would be transitioning to very high (*high confidence*). By 2.5°C warming, RFC1 will be in very high risk (*high confidence*) and all other RFCs will have begun their transitions to very high risk (*medium confidence* for RFC2, RFC3 and RFC4, *low confidence* for RFC5). These highest levels of risk are associated with an irreversible component, such that some impacts would persist even were global temperatures to subsequently decline in an 'overshooting' scenario.

Lack of evidence on the potential for adaptation to adequately reduce risk is a critical gap in our ability to assess global risk transitions at the RFC level, but not the only gap. In some cases, such as RFC1, the widespread nature and rapid speed of the escalating risks, in combination with limited ability to adapt, means that transitions to high risk may occur despite medium or even high levels of adaptation. Risks that are largely natural and not widely mediated by human vulnerability are thus less likely to have risk transitions that shift under higher societal adaptation. Risk transitions that are mediated through human systems, such as distribution impacts, for example, are more likely to shift in response to adaptation as impacts are strongly mediated through vulnerability within human systems, but such a shift is difficult to quantify given knowledge gaps in the literature (Section 16.3). However, in some circumstances, expanded global adaptation could slow some of these transitions (*low confidence*); in the case of RFC2, RFC3 and RFC4, the literature suggests that coordinated global adaptation could increase the global temperature at which risks transition from moderate to high, for example the prevention of mortality associated with heat stress within RFC2.

A higher level of adaptation, applied globally and effectively, could have larger benefits for several RFC, either postponing the onset of a high level of risk until a higher level of warming is reached (and allowing time for mitigation efforts) or allowing a system to survive a temporary overshoot of a lower temperature threshold. Adaptations are likely to have significant potential to reduce risks (Magnan et al., 2021), in particular for risks mediated through human systems. However, there is *limited evidence* available to assess the extent to which current or potential adaptations are or would be adequate in reducing climate risks at different levels of warming, and adaptation implications for risk transitions will be highly localised. Pathways and opportunities for risk management and adaptation actions with transformational potential are discussed in Chapter 17, together with enabling factors, governance frameworks, financing, success factors, and monitoring and evaluation discussed in Chapter 18, supporting sustainable system transitions and leading to options for climate resilient development pathways.

Frequently Asked Questions

FAQ 16.1 | What are key risks in relation to climate change?

A few clusters of key risks can be identified which have the potential to become particularly severe and pose significant challenges for adaptation worldwide. These risks, therefore, deserve special attention. They include risks to important resources such as food and water, risks to critical infrastructures, economies, health and peace, as well as risks to threatened ecosystems and coastal areas.

The IPCC defines key risks related to climate change as potentially severe risks that are relevant to the primary goal of the United Nations Framework Convention on Climate Change treaty to avoid 'dangerous human interference with the climate system', and whatever the scale considered (global to local). What constitutes 'dangerous' or 'severe' risks is partly a value judgement and can therefore vary widely across people, communities or countries. However, the severity of risks also depends on criteria like the magnitude, irreversibility, timing, likelihood of the impacts they describe, and the adaptive capacity of the affected systems (species or societies). The Working Group II authors use these criteria in various ways to identify those risks that could become especially large in the future owing to the interaction of physical changes to the climate system with vulnerable populations and ecosystems exposed to them. For example, some natural systems may be at risk of collapsing, as is the case for warm-water coral reefs by mid-century, even if global warming is limited to +1.5°C. For human systems, severe risks can include increasing restriction of water resources that are already being observed; mortality or economic damages that are large compared with historical crises; or impacts on coastal systems from SLR and storms that could make some locations uninhabitable.

More than 120 key risks across sectors and regions have been identified by the chapters of this report, which have then been clustered into a set of 8 overarching risks, called representative key risks, which can occur from global to local scales but are of potential significance for a wide diversity of regions and systems globally. As shown in Figure FAQ16.1.1, the representative key risks include risks to (a) low-lying coastal areas, (b) terrestrial and marine ecosystems, (c) critical infrastructures and networks, (d) living standards, (e) human health, (f) food security, (g) water security and (h) peace and human mobility.

These representative key risks are expected to increase in the coming decades and will depend strongly not only on how much climate change occurs, but also on how the exposure and vulnerability of society changes, as well as on the extent to which adaptation efforts will be effective enough to substantially reduce the magnitude of severe risks. The report finds that risks are highest when high warming combines with development pathways with continued high levels of poverty and inequality, poor health systems, lack of capacity to invest in infrastructure, and other characteristics making societies highly vulnerable. Some regions already have high levels of exposure and vulnerability, such as in many developing countries as well as communities in small islands, Arctic areas and high mountains; in these regions, even low levels of warming will contribute to severe risks in the coming decades. Some risks in industrialised countries could also become severe over the course of this century, for example if climate change affects critical infrastructure such as transport hubs, power plants or financial centres. In some cases, such as coral reef environments and areas already severely affected by intense extreme events (e.g., recent typhoons or wildfires), climate risks are already considered severe.

Box FAQ 16.1 (continued)

Presentation of the 8 representative key risks assessed in this report (and their underlying main key risks)

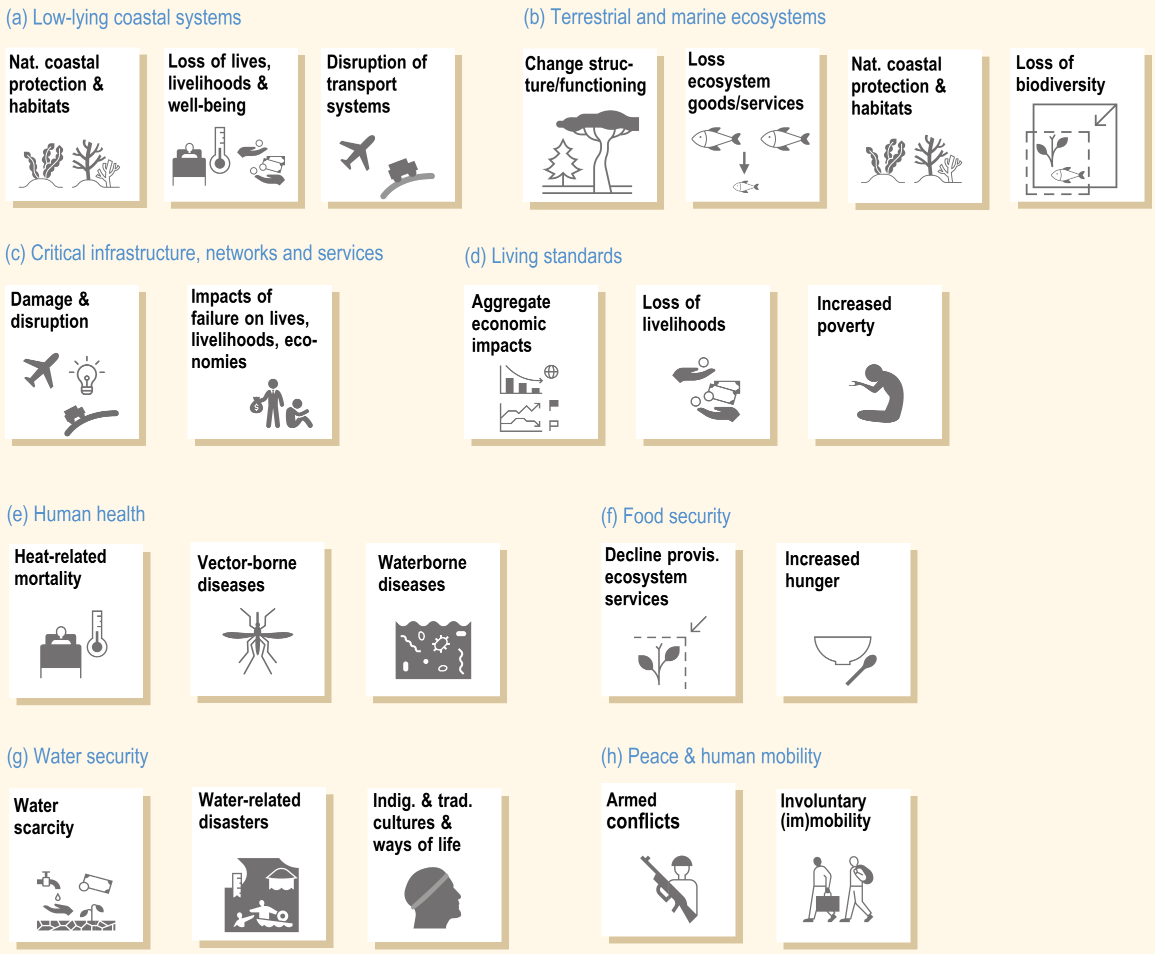

Figure FAQ16.1.1 | Presentation of the eight representative key risks assessed in this report (and their underlying main key risks).

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Frequently Asked Questions

FAQ 16.2 | How does adaptation help to manage key risks and what are its limits?

Adaptation helps to manage key risks by reducing vulnerability or exposure to climate hazards. However, constraining factors make it harder to plan or implement adaptation and result in adaptation limits beyond which risks cannot be prevented. Limits to adaptation are already being experienced, for instance by coastal communities, small-scale farmers and some natural systems.

Adaptation-related responses are actions that are taken with the intention of managing risks by reducing vulnerability or exposure to climate hazards. While mitigation responses aim to reduce greenhouse gas emissions and slow warming, adaptations respond to the impacts and risks that are unavoidable, either due to past emissions or failure to reduce emissions. However, while these responses intend to reduce risks, it is difficult to determine precise levels of risk reduction that can be attributed to adaptation. Changing levels of risk as well as other actions—such as economic development—make it challenging to definitively connect specific levels of risk reduction with adaptation. Although it is not feasible to assess the adequacy of adaptation for risk reduction at global or regional levels, evidence from specific localised adaptation projects do show that adaptation-related responses reduce risk. Moreover, many adaptation measures offer near-term co-benefits related to mitigation and to sustainable development, including enhancing food security and reducing poverty.

Adaptation responses can occur in natural systems without the intervention of humans, such as species shifting their range, time of breeding, or migration behaviour. Humans can also assist adaptation in natural systems through, for example, conservation activities such as species regeneration projects or protecting ecosystem services. Other adaptation-related responses by humans aim to reduce risk by decreasing vulnerability and/or exposure of people to climate hazards. This includes infrastructural projects (e.g., upgrading water systems to improve flood control), technological innovation (e.g., early-warning systems for extreme events), behavioural change (e.g., shift to new crop types or livelihood strategies), cultural shifts (e.g., changing perspectives on urban greenspace, or increased recognition of Indigenous knowledge and local knowledge) and institutional governance (e.g., adaptation planning, funding and legislation).

While adaptation is important to reduce risk, adaptation cannot prevent all climate impacts from occurring. Adaptation has soft and hard limits, points at which adaptive actions are unable to prevent risks. Soft limits can change over time as additional adaptation options become available, while hard limits will not change as there are no additional adaptive actions that are possible. Soft limits occur largely due to constraints—factors that make it harder to plan and implement adaptation, such as lack of financial resources or insufficient human capacity. Across regions and sectors, the most challenging constraints to adaptation are financial and those related to governance, institutions and policy measures. Limited funding and ineffective governance structures make it difficult to plan and implement adaptation-related responses which can lead to insufficient adaptation to prevent risks. Small-scale farmers and coastal communities are already facing soft limits to adaptation as measures that they have put in place are not enough to prevent loss. If constraints that are limiting adaptation are addressed, then additional adaptation can take place and these soft limits can be overcome. Evidence on limits to adaptation is largely focused on terrestrial and aquatic species and ecosystems, coastal communities, water security, agricultural production, and human health and heat.

Adaptation is critical for responding to unavoidable climate risks. Greater warming will mean more and more severe impacts requiring a high level of adaptation which may face greater constraints and reach soft and hard limits. At high levels of warming, it may not be possible to adapt to some severe impacts.

Frequently Asked Questions

FAQ 16.3 | How do climate scientists differentiate between impacts of climate change and changes in natural or human systems that occur for other reasons?

We can already observe many impacts of climate change today. The large body of climatic impact data and research confirms this. To decide whether an observed change in a natural or human system is at least partly an impact of climate change, we systematically compare the observed situation with a theoretical situation without observed levels of climate change. This is detection and attribution research.

Global mean temperature has already risen by more than 1°C, and that also means that the impacts of climate change become more visible. Many natural and human systems are sensitive to weather conditions. Crop yields, river floods and associated damages, ecosystems such as coral reefs, or the extent of wildfires are affected by temperatures and precipitation changes. Other factors also come into play. So, for example, crop yields around the world have increased over the last decades because of increasing fertilizer input, improved management and varieties. How do we detect the effect of climate change itself on these systems, when the other factors are excluded? This question is central for impact attribution. 'Impact of climate change' is defined as the difference between the observed state of the system (e.g., level of crop yields, damage induced by a river flood, coral bleaching) and the state of the system assuming the same observed levels of non-climate-related drivers (e.g., fertilizer input, land use patterns or settlement structures) but no climate change.

So:

'Impact of climate change' is defined as the difference between the observed state of the system and the state of the system assuming the same observed levels of non-climate-related drivers but no climate change. For example, we can compare the level of crop yields, damage induced by a river flood, and coral bleaching with differences in fertilizer input, land use patterns or settlement structures, without climate change and with climate change occurring.

While this definition is quite clear, there certainly is the problem that, in real life, we do not have a 'no climate change world' to compare with. We use model simulations where the influence of climate change can be eliminated to estimate what might have happened without climate change. In a situation where the influence of other non-climate-related drivers is known to be minor (e.g., in very remote locations), the non-climate-change situation can also be approximated by observation from an early period where climate change was still minor. Often, a combination of different approaches increases our confidence in the quantification of the impact of climate change.

Impacts of climate change have been identified in a wide range of natural, human and managed systems. For example, climate change is the major driver of observed widespread shifts in the timing of events in the annual cycle of marine and terrestrial species, and climate change has increased the extent of areas burned by wildfires in certain regions, increased heat-related mortality, and had an impact on the expansion of vector-borne diseases.

In some other cases, research has made considerable progress in identifying the sensitivity of certain processes to weather conditions without yet attributing observed changes to long-term climate change. Two examples of weather sensitivity without attribution are observed crop price fluctuations and waterborne diseases.

Finally, it is important to note that 'attribution to climate change' does not necessarily mean 'attribution to anthropogenic climate change'. Instead, according to the IPCC definition, climate change means any long-term change in the climate system, no matter where it comes from.

Frequently Asked Questions

FAQ 16.4 | What adaptation-related responses to climate change have already been observed, and do they help reduce climate risk?

Adaptation-related responses are the actions taken with the intention of managing risks by reducing vulnerability or exposure to climate hazards. Responses are increasing and expanding across global regions and sectors, although there is still a lot of opportunity for improvement. Examining the adequacy and effectiveness of the responses is important to guide planning, implementation and expansion.

The most frequently reported adaptation-related responses are behavioural changes made by individuals and households in response to drought, flooding and rainfall variability in Africa and Asia. Governments are increasingly undertaking planning, and implementing policy and legislation, including, for example, new zoning regulations and building codes, coordination mechanisms, disaster and emergency planning, or extension services to support farmer uptake of drought tolerant crops. Local governments are particularly active in adaptation-related responses, particularly in protecting infrastructure and services, such as water and sanitation. Across all regions, adaptation-related responses are strongly linked to food security, with poverty alleviation a key strategy in the Global South.

Overall, however, the extent of adaptation-related responses globally is low. On average, responses tend to be local, incremental, fragmented, and consistent with Business-As-Usual practices. There are no global regions or sectors where the overall adaptation-related response has been rapid, widespread, substantial and has overcome or challenged key barriers. The extent of adaptation thus remains low globally, with significant potential for increased scope, depth, speed and the challenging of adaptation limits. Examples of low-extent adaptations include shifts by subsistence farmers in crop variety or timing, household flood barriers to protect houses and gardens, and harvesting of water for home and farm use. In contrast, high-extent adaptation means that responses are widespread and coordinated, involve major shifts from normal practices, are rapid, and challenge existing constraints to adaptation. Examples of high-extent adaptations include planned relocation of populations away from increasingly flood-prone areas, and widely implemented social support to communities to prevent migration or displacement due to climate hazards.

Increasing the extent of adaptation-related responses will require more widespread implementation and coordination, more novel and radical shifts from Business-As-Usual practices, more rapid transitions, and challenging or surmounting limits—key barriers—to adaptation. This might include, for example, best-practice programmes implemented in a few communities being expanded to a larger region or country, accelerated implementation of behaviours or regulatory frameworks, coordination mechanisms to support deep structural reform within and across governments, and strategic planning that challenges fundamental norms and underlying constraints to change.

We have very little information on whether existing adaptation-related responses that have already been implemented are reducing climate risks. There is evidence that risks due to extreme heat and flooding have declined, though it is not clear if these are due to specific adaptation-related responses or general and incremental socioeconomic development. It is difficult to assess the effectiveness of adaptation-related responses, and even more difficult to know whether responses are adequate to adapt to rising climate risk. These remain unknown but important questions in guiding implementation and expansion of adaptation-related responses.

Frequently Asked Questions

FAQ 16.5 | How does climate risk vary with temperature?

Climate risk is a complex issue, and communicating it is fraught with difficulties. Risk generally increases with global warming, though it depends on a combination of many factors such as exposure, vulnerability and response. To present scientific findings succinctly, a risk variation diagram can help visualise the relationship between warming level and risk. The diagram can be useful in communicating the change in risk with warming for different types of risk across sectors and regions, as well as for five categories of global aggregate risk called 'Reasons for Concern'.

A picture speaks a thousand words. The use of images to share ideas and information to convey scientific understanding is an inclusive approach for communicating complex ideas. A risk variation diagram is a simple way to present the risk levels that have been evaluated for any particular system. These diagrams take the form of bar charts where each bar represents a different category of risk. The traffic light colour system is used as a basis for doing the risks, making it universally understandable. These diagrams are known colloquially as 'burning ember' diagrams, and have been a cornerstone of IPCC assessments since the Third Assessment Report, and further developed and updated in subsequent reports. The fact that the diagrams are designed to be simple, intuitive and easily understood with the caption alone has contributed to their longstanding effectiveness. Here, in Figure FAQ16.5.1 below, we provide a simplified figure of this chapter's burning embers for five categories of global aggregate risk, called Reasons for Concern (RFCs), which collectively synthesise how global risk changes with temperature. The diagram shows the levels of concern that scientists have about the consequences of climate change (for a specified risk category and scope), and how this relates to the level of temperature rise.

The dependence of risk associated with the Reasons for Concern (RFC) on the level of climate change

Updated by expert elicitation and reflecting new literature and scientific evidence since AR5 and SR15

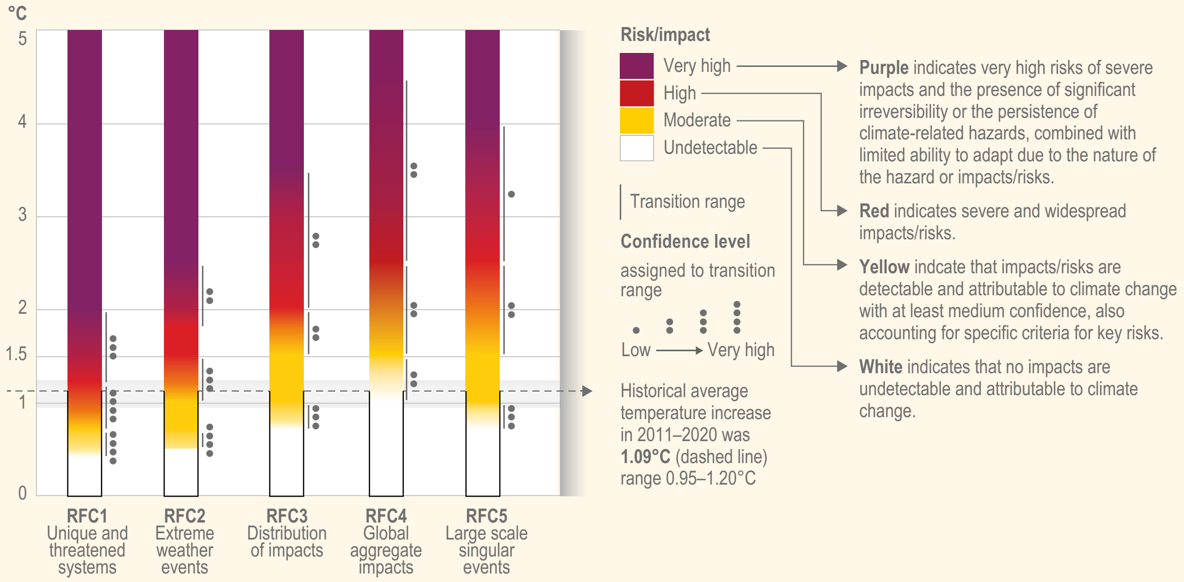

Figure FAQ16.5.1 | Simplified presentation of the five Reasons for Concern burning ember diagrams as assessed in this report (adapted from Figure 16.15). The colours indicate the level of risk accrual with global warming for a low-adaptation scenario. RFC1 Unique and threatened systems: ecological and human systems that have restricted geographic ranges constrained by climate-related conditions and have high endemism or other distinctive properties. Examples include coral reefs, the Arctic and its Indigenous People, mountain glaciers and biodiversity hotspots. RFC2 Extreme weather events: risks/impacts to human health, livelihoods, assets and ecosystems from extreme weather events such as heatwaves, heavy rain, drought and associated wildfires, and coastal flooding. RFC3 Distribution of impacts: risks/impacts that disproportionately affect particular groups owing to uneven distribution of physical climate change hazards, exposure or vulnerability. RFC4 Global aggregate impacts: impacts to socio-ecological systems that can be aggregated globally into a single metric, such as monetary damages, lives affected, species lost or ecosystem degradation at a global scale. RFC5 Large-scale singular events: relatively large, abrupt and sometimes irreversible changes in systems caused by global warming, such as ice sheet disintegration or thermohaline circulation slowing.

In this diagram, the risk variation bars or embers are shown with temperature on the *y*-axis, and the base of the ember corresponds to a baseline temperature. Typically, this baseline temperature is that before global warming

Box FAQ 16.5 (continued)

started (i.e., average temperatures for the pre-industrial period of 1850–1900). This area of the ember appears white, which indicates no to negligible impacts due to climate change. Moving up the ember bar, changing colours show the increase in risk as the Earth warms globally in terms of degrees Celsius—yellow for moderate risk, red for high risk, and purple for very high risk. Definitions of the risk levels are presented in Figure FAQ16.5.1 The risk transitions are informed by the latest literature and scientific evidence, and developed through consultation and development of consensus among experts. The bars depict an averaged assessment across the world, which has the disadvantage of hiding regional variation. For example, some locations or regions could face high risk even when the global risk level is moderate.

When the embers for different risk categories are placed next to each other, it is possible to compare risk levels at different levels of global warming. For example, at 1°C warming all embers appear yellow or white, so it is possible to say that keeping global warming below that particular temperature would help ensure risks remain moderate for all five categories of concern assessed. In contrast, at 2°C warming, risk levels have transitioned to high for all categories assessed, and even reach a very high level of risk in the case of unique and threatened systems.

Frequently Asked Questions

FAQ 16.6 | What is the role of extreme weather events in the risks we face from climate change?

Climate change has often been perceived as a slow and gradual process, but by now it is abundantly clear that many of its impacts arise through shocks, such as extreme weather events. Many places are facing more frequent and intense extremes, and also more surprises. The impact of such shocks is shaped by exposure and vulnerability, where we live, and how we are prepared for and able to cope with shocks and surprises.

The rising risk of extreme events is one of the major RFCs about climate change. It is clear that this risk has already increased today. Many recent disasters already have a fingerprint of climate change.

There are large differences in such risks from country to country, place to place, and person to person. This is of course partly due to differences in hazards such as heatwaves, floods, droughts, storms, storm surges, etc., and the way those hazards are influenced by climate change. However, an even more important aspect is people's exposure and vulnerability: do these hazards occur in places where people live and work, and how badly do they affect people's lives and livelihoods? Some groups are especially vulnerable, for instance elderly in the case of heatwaves, or people with disabilities in the case of floods. In general, poor and marginalised people tend to be much more affected than rich people, partly because they have fewer reserves and support systems that help them to prepare for, cope with and recover from a shock. On the other hand, absolute economic losses are generally higher in richer places, simply because more assets are at risk there.

Many problems caused by extreme weather do not just appear because of one weather extreme, but due to a combination of several events. For instance, dryness may increase the risk of a subsequent heatwave. But the increased risk may also cascade through human systems, for instance when several consecutive disasters erode people's savings, or when a heatwave reduces the ability of power plants to produce electricity, which subsequently affects availability of electricity to turn on air conditioning to cope with the heat. Many shocks also have impacts beyond the place where they occur, for instance when a failed harvest affects food prices elsewhere. Climate risks can also be aggravated by other shocks, such as in the case of coronavirus disease 2019 (COVID-19), which not only had a direct health impact, but also affected livelihoods around the world and left many people much more vulnerable to weather extremes.

Understanding the risks we face can help in planning for the future. This may be a combination of short-term preparation, such as early-warning systems, and longer-term strategies to reduce vulnerability, for instance through urban planning, as well as reducing greenhouse gases to avoid longer-term increases in risk. Many interventions to increase people's resilience are effective in the face of a range of shocks. For instance, social safety nets can help mitigate the impact of a drought on farmers' livelihoods, but also of the economic impacts of COVID-19.

Climate-related shocks are threats to society, but they can also offer opportunities for learning and change. Recent disasters can motivate action during a short window of opportunity when awareness of the risks is higher and policy attention is focused on solutions to adapt and reduce risk. However, those windows tend to be short, and attention is often directed at the event that was recently experienced, rather than resilience in the face of a wider range of risks.