Chapters and Cross-Chapter Papers

1

Point of Departure and Key Concepts

Coordinating Lead Authors: Rawshan Ara Begum (Malaysia/Australia/Bangladesh) and Robert J. Lempert (USA)

Lead Authors: Elham Ali (Egypt), Tor Arve Benjaminsen (Norway), Thomas Bernauer (Switzerland), Wolfgang Cramer (France/Germany), Xuefeng Cui (China), Katharine Mach (USA), Gustavo Nagy (Uruguay), Nils Christian Stenseth (Norway), Raman Sukumar (India), and Philippus Wester (Nepal/the Netherlands)

Contributing Authors: Maarten van Aalst (Netherlands), Gusti Anshari (Indonesia), Richard Betts (UK), Edward R. Carr (USA), Vanesa Castán Broto (UK), Connor J. Cavanagh (Norway), Eva Davidsdottir (Norway), Greg Flato (Canada), Katja Frieler (Germany), Nathan Gillett (Canada/UK), Lorena B. Gonzalez (Mexico), Marjolin Haasnoot (the Netherlands), Jo S Hermansen (Norway), Pandora Hope (Australia), Christian Huggel (Switzerland), Darrell S. Kaufman (USA), Wolfgang Kiessling (Germany), Timothy A. Kohler (USA), Aris Koutroulis (Greece), Sivapuram Venkata Rama Krishna Prabhakar (Japan/India), Judy Lawrence (New Zealand), Timo Leiter (Germany/UK), Martina K. Linnenluecke (Australia), Tabea Lissner (Germany), Leonardo Martinez-Diaz (USA), Md Shahin Mia (Malaysia/Bangladesh), Guy Midgley (South Africa), Jan Minx (Germany), Tero Mustonen (Finland), Johanna Nalau (Australia/Finland), Ben Orlove (USA), Friederike Otto (UK/Germany), Camille Parmesan (France/UK/USA), Karishma V. Patel (USA), Asif Raihan (Bangladesh), Nussaïbah Raja (Mauritius), Lauren Rickards (Australia), Joeri Rogelj (UK/Belgium), Maisa Rojas (Chile), Steven Rose (USA), Lisa Schipper (Sweden/UK), Daniela N. Schmidt (UK/Germany), Sonia I. Seneviratne (Switzerland), Nicholas Philip Simpson (South Africa), Chandni Singh (India), Jo Skeie Hermansen (Norway), Aimee Slangen (the Netherlands), William Solecki (USA), Daithi Stone (New Zealand), Laurent Terray (France), Adelle Thomas (Bahamas), Joe Thwaites (UK), Edmond Totin (Benin), Christopher Trisos (South Africa), Robert Vautard (France), Michael Weisberg (USA), Xuebin Zhang (Canada)

Review Editors: Roberto Sánchez Rodríguez (Mexico) and Michael Sutherland (Trinidad and Tobago/Jamaica)

Chapter Scientist: Karishma V. Patel (USA)

This chapter should be cited as:

Ara Begum, R., R. Lempert, E. Ali, T.A. Benjaminsen, T. Bernauer, W. Cramer, X. Cui, K. Mach, G. Nagy, N.C. Stenseth, R. Sukumar, and P. Wester, 2022: Point of Departure and Key Concepts. In: *Climate Change 2022: Impacts, Adaptation and Vulnerability.* Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, B. Rama (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 121–196, doi:10.1017/9781009325844.003.

Table of Contents

Frequently Asked Questions

Executive Summary

The IPCC Working Group II contribution to the Sixth Assessment Report addresses the challenges of climate action in the context of sustainable development with a particular focus on climate change impacts, adaptation and vulnerability. This chapter frames the point of departure and key concepts building on the IPCC's Fifth Assessment Report (IPCC, 2014a, b), the Special Report on Global Warming of 1.5°C (IPCC, 2018b), the Special Report on the Ocean and Cryosphere in a Changing Climate (SROCC) (IPCC, 2019b), and the Special Report on Climate Change and Land (SRCCL) (IPCC, 2019a); as well as the WGI contributions to the Sixth Assessment Report (IPCC, 2021a) and complements the contribution of the WGIII Sixth Assessment Report, which will be published after this report (IPCC, 2022).

Since IPCC AR5, human influence on the Earth's climate has become unequivocal, increasingly apparent and widespread, reflected in both the growing scientific literature and in the perception and experiences of people worldwide (*high confidence*). Current changes in the climate system and those expected in the future will increasingly have significant and deleterious impacts on human and natural systems. The impacts of climate change and extreme weather events have adversely affected, or caused the loss of ecosystems including terrestrial, freshwater, ocean and coastal ecosystems, including tropical coral reefs; reduced food security; contributed to migration and displacement; damaged livelihoods, health and security of people; and increased inequality. Climate change impacts are concurrent and interact with other significant societal changes that have become more salient since AR5, including a growing and urbanising global population; significant inequality and demands for social justice; rapid technological change; continuing poverty, land and water degradation, biodiversity loss; food insecurity; and a global pandemic. {1.1.1; 1.3; Cross-Working Group Box ATTRIBUTION in Chapter 1}

Since AR5, climate action has grown in salience worldwide across all levels of government as well as among non-governmental organisations, small and large enterprises, and citizens (*high confidence*). At the international level the Paris Agreement and the Sustainable Development Goals (SDGs), along with other targets and frameworks, such as the Sendai Framework for Disaster Risk Reduction, the Convention on Biological Diversity (CBD) Aichi targets, the Addis Ababa Action Agenda for finance and the New Urban Agenda, provide overarching goals and policy context. These agreements also provide policy goals used by this IPCC Report to assess climate action across all levels of society. {1.1.2; 1.4.1; 1.4.3}

IPCC's assessments have grown and changed substantially over the last three decades. Compared to earlier IPCC assessments, this report emphasises a common risk-solution framing across all three Working Groups. This report focuses on solutions for risk reduction and adaptation; provides more integration across the natural and social sciences; applies a more comprehensive risk framework; assesses adaptation directly in the context of sectoral or regional risks; engages with different forms of knowledge, including Indigenous knowledge and local knowledge; and includes an increasing focus on equity and justice. {1.1.4; 1.4.2; Cross-Chapter Box ADAPT in Chapter 1}

Adaptation plays a key role in reducing risks and vulnerability from climate change. Implementing adaptation and mitigation actions together with the SDGs helps to exploit synergies, reduce trade-offs and makes all three more effective. From a risk perspective, limiting atmospheric greenhouse gas (GHG) concentrations reduces climate-related hazards while adaptation and sustainable development reduce exposure and vulnerability to those hazards. Adaptation facilitates development, which is increasingly hindered by impacts and risks from climate change. Development facilitates adaptation by expanding the resources and capacity to reduce climate risks and vulnerability. {1.1.3; 1.5.1; 1.5.3}

The concepts of risk and risk management have become increasingly central to climate change literature, research, practice and decision making (*medium confidence*). Risk, defined as the potential for adverse consequences for human and ecological systems, recognising the diversity of values and objectives associated with such systems, provides a framework for understanding the increasingly severe, interconnected and often irreversible impacts of climate change; how these impacts differentially affect different regions, sectors and populations; how to allocate resources best to manage the resulting risks and how to evaluate the responses that reduce residual risks for current and future generations, economies and ecosystems. {1.2.1; 1.3.1; 1.4.2}

The concepts of adaptation, vulnerability, resilience and risk provide overlapping, alternative entry points for the climate change challenge (*high confidence*). Vulnerability is a component of risk, but also an important focus independently, improving understanding of the differential impacts of climate change on people of different gender, race, wealth, social status and other attributes. Vulnerability also provides an important link between climate adaptation and disaster risk reduction. Resilience, which can refer to either a process or outcome, encompasses not just the concept of maintaining essential function, identity and structure, but also maintaining a capacity for transformation. Such transformations bring forth questions of justice, power and politics. {1.2.1; 1.4.1}

Risks from climate change differ through space and time and cascade across and within regions and systems. The total risk in any location may thus differ from the sum of individual risks if these interactions, as well as risks from responses themselves, are not considered (*high confidence*). The risks of climate change responses include the possibility of mitigation or adaptation responses not achieving their intended objectives or having trade-offs or adverse side effects for other societal objectives. Another core area of complexity in climate risk is the behaviour of systems, which includes multiple stressors unfolding together, cascading or compounding interactions within and across sectors and regions, and nonlinear responses and the potential for surprises. All of this is crucial for effective decision making and decision-support methods. The key risks assessed in this report become important in interaction with the cultures, values, ethics, identities, experiences and knowledge systems of affected communities and societies. {1.3.1}

Increasingly, impacts are detected and attributed to the changing climate. Improved understanding of deep history (palaeoclimate

and biotic responses) suggests that past climate changes have already caused substantial ecological, evolutionary and socioeconomic impacts (*high confidence*). Many recent impacts are not detected, due to a shortage of monitoring and robust attribution analysis (*high confidence*). Detection and attribution assessments inform risk assessment by demonstrating the sensitivity of a system to climate change, and they can inform loss and damage estimates including those involved in potential climate litigation cases. Robust detection and attribution methods now exist and play a significant role in increasing awareness and willingness to act among decision makers and the general population. {1.3.2.1; Cross-Working Group Box ATTRIBUTION in Chapter 1; Cross-Chapter Box PALEO in Chapter 1}

Narratives play an important role in communicating climate risks and motivating solutions. A narrative describes a chronological chain of events, often with a premise and conclusions. In the AR6, as in previous IPCC assessments, climate change scenarios and related narratives (also called storylines) are central in the analysis, synthesis and communication of climate change impacts and of adaptation and mitigation responses. AR6 employs narratives to describe the assumptions, evolution and driving forces for the representative concentration pathways (RCPs) and shared socioeconomic pathways (SSPs) and links these to global warming levels (GWLs) as a complement to RCPs and SSPs for framing impacts (Cross-Chapter Box CLIMATE in Chapter 1). Narratives can also be enablers of transformation by communicating societal goals and the actions needed to achieve them {1.2.2; 1.3.3; 1.5.2}

AR6 highlights adaptation solutions and the extent to which they are successful and adequate at reducing climate risk, increasing resilience and pursuing other climate-related societal goals. For adaptation, a solution is defined as an option which is effective, feasible and conforms to principles of justice. Effectiveness refers to the extent to which an action is anticipated or is observed to reduce climate-related risk. Feasibility refers to the extent to which a measure is considered possible and desirable in a particular context. A successful action is one observed to be effective, feasible and just. Adequacy refers to a set of solutions that together are sufficient to avoid dangerous, intolerable, or severe climate risks. {1.4}

Indigenous knowledge and local knowledge (IK and LK) can provide important understanding for acting effectively on climate risk and can help diversify knowledge that may enrich adaptation policy and practice (*high confidence*). Indigenous Peoples have been faced with adaptation challenges for centuries and have developed strategies for resilience in changing environments that can enrich and strengthen current and future adaptation efforts. Valuing IK and LK is also important for recognition, a key component of climate justice. {1.3.2.3}

AR6 highlights three principles of climate justice: distributive justice, procedural justice and recognition. Distributive justice refers to the allocation of burdens and benefits among individuals, nations and generations. Procedural justice refers to who decides and participates in decision making. Recognition entails basic respect and robust engagement with and fair consideration of diverse cultures and perspectives. This report considers all three principles in the assessment of adaptation options and evaluates the extent to which better outcomes are obtained by choosing just ones. Since potential trade-offs exist among the principles, adaptation assessments will in general involve normative judgements, as well as science-based evidence. {1.4.1.1}

Concepts of justice and measures of well-being are increasingly used to evaluate the extent to which climate change adaptation is equitable and effective (*medium confidence*). AR6 employs evaluation frameworks based on both single and multi-criteria to assess adaptation effectiveness and consistency with principles of justice. Single criteria frameworks aggregate many attributes into a one number or ranking, often quantified using benefit–cost analysis or measures of social welfare. Existing decision processes often favour such single criteria, which also correlate well with many measures of social progress and sustainable development. Multi-criteria frameworks simultaneously report several different biophysical and socioeconomic attributes, which provides more information on potential trade-offs and synergies and can engage with emerging concepts of well-being. {1.4.1.1; 1.4.1.2}

The concepts of enablers, catalysts and the solution space help AR6 assess ways to speed the implementation and expand the range of adaptation solutions. Many potential solutions have not yet been implemented, despite the gap between current and adequate levels of adaptation. Enablers enhance the feasibility of adaptation options and include governance, finance and knowledge**.** Catalysts accelerate and motivate the adaptation decision making process. The concept of solution space—defined as the space within which opportunities and constraints determine why, how, when and who adapts to climate risks—helps this in assessing how human choices and exogenous changes can expand and contract the set of effective, feasible and just solutions. {1.4.2}

Effective governance, adaptation finance and nature-based solutions are important enablers for expanding the solutions space and reducing adaptation gaps (*high confidence*). Actors at many scales and in many sectors are already adapting, and can take additional and more significant adaptation action. These actors include individuals and households, communities, governments at all levels, private sector businesses, non-governmental organisations, religious groups and social movements. Many forms of adaptation (depending on the type of climatic risk and societal context) are likely to be more effective, cost-efficient and potentially also more equitable when organised collectively. Stronger governance and adaptation finance capabilities are usually associated with more ambitious adaptation plans and more effective implementation of such plans. {1.4.2; 1.5.2}

Monitoring and evaluation (M&E) of adaptation refers to a broad range of activities necessary for tracking adaptation progress over time, improving adaptation effectiveness and successful iterative risk management. Monitoring usually refers to continuous information gathering, whereas evaluation denotes more comprehensive assessments of effectiveness and equity, often resulting in recommendations for decision makers. In some literatures, M&E refers solely to efforts undertaken after implementation. In other literatures, M&E refers both to efforts conducted before and after implementation. Since AR5, a growing literature provides initial inventories of adaptation plans and implementation worldwide, but information on effectiveness remains scare (*high confidence*). {*1.4*.3; Cross-Chapter Box ADAPT in Chapter 1}

The concept of limits to adaptation is dynamic in terms of the temporal, spatial and contextual dimensions of climate change risks, impacts and response. Socioeconomic, technological, governance and institutional systems or policies can be changed or transformed in response to the different dimensions of adaptation limits to climate change and extreme events. Adaptation limits can be soft or hard. Soft adaptation limits occur when options may exist but are currently not available to avoid intolerable risks through adaptive actions. Hard adaptation limits occur when no adaptive actions are possible to avoid intolerable risks. The levels of GHG emissions reduction, adaptation and risk management measures are the key factors determining if and when adaptation limits are reached. When a limit (soft) is reached, then intolerable risks and impacts may occur and additional adaptations (incremental or transformational) would be required. Transformational adaptation can allow a system to extend beyond its soft limits and prevent soft limits from becoming hard limits. The loss and damage associated with the future climate change impacts, beyond the limits to adaptation, is an area of increasing focus. However, it is yet to be fully developed in terms of assessment methods, including non-economic values and identifying means to avoid and reduce both economic (loss of asset, infrastructure, land etc.) and non-economic (loss of societal beliefs and values, cultural heritage, biodiversity and ecosystem services) losses and damages. {1.4.4.1; 1.4.4.2}

Key concepts in this report provide a framework for assessing the urgency of climate change adaptation. Adaptation is urgent to the extent that soft adaptation limits are currently being approached or exceeded and that achieving levels of adaptation adequate to address these soft limits requires action at a speed and scale faster than that represented by current trends (*high confidence*). In addition, adaptation is urgent to the extent that any needed expansion of the future solution space requires near-term strengthening and expansion of enablers, such as governance, finance and information. {1.1.3; 1.4.4; 1.5.1}

AR6 highlights the role of transformation in meeting the Paris Agreement, the SDGs and other policy goals. Transformation, and the related term transition, are pluralistic concepts, embracing the idea of major, fundamental changes in society or natural systems as opposed to changes that are minor, marginal or incremental. AR6 has a particular focus on transformational adaptation, which changes the fundamental attributes of a socioeconomic system in anticipation of climate change and its impacts. AR6 describes transitions in five systems: energy, land and ecosystems, urban and infrastructure, industrial and societal. In the past, transformations of such scale have been associated not only with technological and economic changes, but also with shifts in most aspects of society. {1.2.1.3; 1.4.4; 1.5.1}

Future transformation could be deliberate, envisioned and intended by at least some societal actors, who seek to expand the solution space, overcome soft limits to adaptation, reduce residual risk to tolerable levels and achieve societal goals. If such a transformation is not pursued or is not successful and risk remains above intolerable levels, a forced transformation may occur that is less consistent with societal goals. The literature describes incremental and transformational change as linked processes. The transformational adaptation literature suggests shifts from incremental to transformational processes are made possible by knowledge and skills, as well adjustments to vision, agendas and coalitions achieved through monitoring and learning. The socio-ecological and sustainability transitions literature suggests that actors seeking deliberate transformation may take incremental steps that aim to induce societal tipping point behaviour in the near or longer term. Alternative pathways for pursuing deliberate transformations range from a focus on modernisation of sectors such as energy, agriculture and the use of natural resources to proposals for degrowth that intentionally aim to decrease both gross domestic product (GDP) and coupled GHG emissions. {1.2.1.3; 1.4.4; 1.5.1}

Transformation is understood as a collective action challenge among actors with both common and differing values interacting with a mix of competition and cooperation. Significant innovations often begin in niches or protected spaces, sometimes introduced by new entrants or outsiders. The drivers of transformation are multi-dimensional, involving social, cultural, economic, environmental, technical and political processes. The combination of these creates the potential for abrupt and systemic change, the stability of entrenched and interlocked power structures, and the importance of individual beliefs and behaviours. Decision frameworks that consider multiple objectives and multiple scenarios can avoid privileging some views over others and help multiple actors to identify resilient and equitable solutions to complex, deeply uncertain challenges. Nonetheless, common goals and narratives are both enablers of transformation and help align the activities of multiple, loosely co-ordinated actors. {1.5.2}

This report employs the climate resilient development concept to inform co-ordinated implementation of adaptation and mitigation solutions to support sustainable development for all. As a transformation that emerges from the choices of many different actors, climate resilient development follows no single or preferred pathway and no single best combination of adaptation, mitigation and sustainable development strategies. All pathways involve complex trade-offs and synergies among different actions. The climate resilient development concept helps assess the extent to which solutions currently exist to meet societal goals or the extent to which an expanded solution space is required. The concept also helps assess the role of various actors, including governments, citizens, civil society, knowledge institutions, media, investors and businesses as well as the need for arenas of engagement in which they can interact. {1.2.3; 1.5.2; 1.5.3}

1.1 The Current Urgent Moment

1.1.1 A Changing Climate in a Changing World

Numerous additional significant climate-related changes have unfolded worldwide since the publication of the IPCC Fifth Assessment Report (AR5) in 2014 (IPCC, 2014a). Consistent with projections, multiple concurrent changes in the physical climate system have grown more salient, including increasing global temperatures, loss of ice volume, rising sea levels and changes in global precipitation patterns (AR6 WGI Chapter 1, Chen et al., 2021). The changes in the physical climate system, most notably more intensive extreme events, have adversely affected natural and human systems around the world. This has contributed to a loss and degradation of ecosystems, including tropical coral reefs; reduced water and food security; increased damage to infrastructure; additional mortality and morbidity; human migration and displacement; damaged livelihoods; increased mental health issues; and increased inequality. Since AR5, a growing literature attributes change in specific climate variables to observed damages to specific localised human and natural systems in many regions of the world (Figure 1.1, also see Cross-Working Group BOX ATTRIBUTION in Chapter 1).

Concurrently, since AR5, a growing share of people around the world perceive a changing climate, regard these changes as significant and consider climate action to be a matter of high urgency (Wilson and Orlove, 2019; Section 17.4.5). A survey, representing over half the world's population, found that almost two-thirds of people across 50 countries view climate change as an emergency (Flynn et al., 2021), compared to just over half across 23 countries in 2013 (Fagan, 2019). The highest level of support for climate action is among small island developing states (SIDS) (74%), followed by high-income countries (72%), middle-income countries (62%) and, then, least developed countries (58%) (Flynn et al., 2021). Notably, after mid-2018, global media showed a large increase number of mentions of 'global warming', 'climate change' and similar terms (Thackeray et al., 2020). The business community now consistently includes climate change, including 'climate action failure' as a major risk (World Economic Forum, 2021). In late 2019, protests calling for strengthened climate action reached an unprecedented level of over 6000 events in 185 countries, with a reported estimate of 7.6 million participants, largely led by the 'Fridays for Future' youth movement (Chase-Dunn and Almeida, 2020).

Since AR5, governments, businesses and civil society have increasingly responded with planning and actions aimed at reducing current and future risks from climate change (Section 1.1.2, Chapters 16 and 17). Concern with climate change has increasingly motivated actions by governments, the private sector and civil society (Hale et al., 2021; Section 18.4.3). As described in this report, however, current climate policies and actions alone are not sufficient to meet stated policy goals (Section 1.1.3) *(high confidence)*.

This report addresses the challenges of climate action in the context of sustainable development. Climate action takes place in a world already undergoing some of the most rapid and significant societal and environmental change in decades (IPCC, 2018b; Box 1.1). These include species and ecosystems loss due to land and sea use change and pollution (IPBES, 2019a); a growing and urbanising world population (Gerten et al., 2019; van Vliet et al., 2017); technology reshaping the workplace through automation (Schwab, 2017) and information dissemination through social media (Mavrodieva et al., 2019; Pearce et al., 2019); and increasing inequalities due to gender, poverty, age, race and ethnicity (Cross-Chapter Box GENDER in Chapter 18). Economic inequality grows within nations even as it has narrowed among them (UN Department of Economic and Social Affairs, 2020). International polycentric governance and non-state actors play an important role (Beck and Mahony, 2018; Sections 1.4.2 and 17.1.2.1). In 2020 and 2021, a global pandemic dramatically affected the lives of most of the world's population, likely accelerating many of the changes already underway (Cross-Chapter Box COVID in Chapter 7).

The point of departure for this AR6 Working Group II report thus lies in rapid and significant changes in our climate and our world, growing attentiveness to those changes, a gap between current climate action and that needed to address policy goals, and a growing literature that improves understanding and informs potential responses. This chapter defines key concepts and the connections among them useful for comprehending and evaluating these changes, the risks they generate, and options for incremental and transformative solutions that could reduce climate-related risks, impacts and vulnerability.

1.1.2 Policy Context

Since AR5, climate action has grown at all levels of governance as well as among non-governmental organisations, small and large enterprises, and citizens. Two international agreements—the United Nations Framework Convention on Climate Change (UNFCCC) Paris Agreement and the 2030 Agenda for Sustainable Development—jointly provide overarching goals for climate action. The 2015 Paris Agreement frames direct local, national and private sector actions aligned with long-term goals addressing mitigation, adaptation and finance. For mitigation, the agreement calls for 'holding the increase in global average temperature to well below 2°C above pre-industrial levels', 'pursuing efforts to limit the temperature increase to 1.5°C' and 'reaching net zero greenhouse gas (GHG) emissions in the second half of this century' (UNFCCC, 2016). For adaptation, the agreement calls for 'increasing the ability to adapt to the adverse impacts of climate change and foster climate resilience' (UNFCCC, 2016, Article 2), as well as having a dedicated 'global goal on adaptation' (Lesnikowski et al., 2017; Persson, 2019). For finance, the agreement seeks to make 'financial flows consistent with a pathway towards low GHG emissions and climate resilient development'.

The 2030 Agenda for Sustainable Development, adopted in 2015 by UN member states, sets out 17 Sustainable Development Goals (SDGs), frames policies for achieving a more sustainable future and aligns efforts globally to prioritise ending extreme poverty, protecting the planet and promoting more peaceful, prosperous and inclusive societies. SDG 13 ('Climate Action') provides benchmarks to align the Paris Agreement's call to 'strengthen the global response to the threat of climate change, in the context of sustainable development and efforts to eradicate poverty'. Since AR5, several new international conventions have identified climate change adaptation and risk reduction as important global priorities for sustainable development, including the Sendai Framework for Disaster

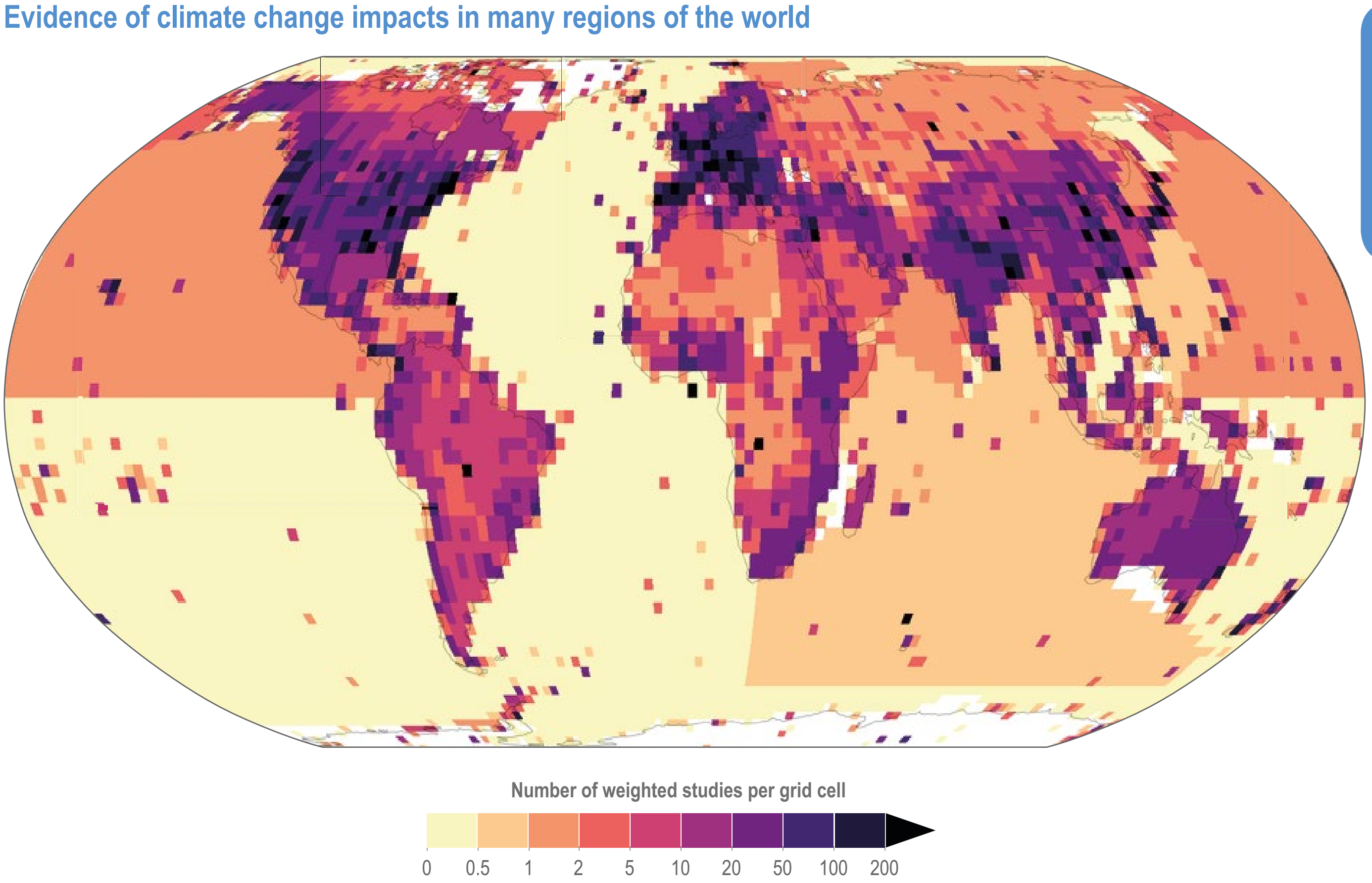


Figure 1.1 | Evidence of climate change impacts in many regions of the world. Global density map shows climate impact evidence, derived by machine-learning from 77,785 studies. Map colouring denotes the number of weighted studies per grid cell for all evidence on climate impacts (N=77,785). Figure adopted from Callaghan et al. (2021).

Risk Reduction (SFDRR) (Tozier de la Poterie and Baudoin, 2015; UNISDR, 2015), the finance-oriented Addis Ababa Action Agenda (UN, 2015) and the New Urban Agenda (UN, 2017). For example, the SFDRR recognises some disasters as 'exacerbated by climate change and increasing in frequency and intensity, significantly [impeding] progress towards sustainable development' (UNISDR, 2015). The Convention on Biological Diversity (CBD) is one of the key international legal instruments for sustainable development for 'the conservation of biological diversity, the sustainable use of its components and the fair and equitable sharing of the benefits arising out of the utilisation of genetic resources' (CBD, 2011). The CBD and its Aichi targets recognises that biodiversity is affected by climate change, with negative consequences for human well-being, but biodiversity, through ecosystem services, contributes to both climate change mitigation and adaptation (CBD, 2010). There is concern that many of the proposed post-2020 biodiversity targets of the CBD may not be met due to climate change impacts (post-2020 biodiversity targets from Chapter 2; Arneth et al., 2020).

At the national level, over 2,315 laws and policies that address climate change now exist in 196 countries and a number of territories as of May 2021 (Grantham Research Institute on Climate Change and the Environment and Sabin Center for Climate Change Law, 2021). Sub-national and non-state actors, including city and state governments and firms and investors, have also increasingly launched climate actions (Hale et al., 2021). Climate change litigation is gaining salience for both governments and corporations as the number of cases filed around the world grew from 834 between 1986 and 2014 to 1,006 since 2015 and growing (Setzer and Higham, 2021).

1.1.3 Adaptation Efforts and Gaps

Adaptation to climate change plays a key role in reducing climate-related risks along with mitigation and sustainable development. From a risk perspective (Section 1.2), emission reductions and carbon removal can both reduce GHG forcing and thus climate-related hazards, while adaptation and sustainable development reduce exposure and vulnerability to those hazards.

Important synergies and trade-offs exist among adaptation and mitigation actions (Section 1.5, Chapter 18). Limiting atmospheric concentrations of GHGs reduces the extent of adaptation needed to keep risk within tolerable levels (Section 1.3, Chapter 16). From a global perspective, understanding adaptation and its limits can inform judgements about the best balance among levels of mitigation and adaptation. Such judgements underlie the mitigation goals of the Paris Agreement. From a more local perspective, there is a wide range of mitigation scenarios (Cross-Chapter Box CLIMATE in Chapter 1),

Box 1.1 | Summary of IPCC AR5 and Special Report findings

The IPCC WGII AR6 builds upon key findings of the IPCC AR5, three subsequent special reports and the simultaneous assessment of the IPCC WGI and WGIII AR6. The findings and assessment approaches adopted across these reports have implications for the point of departure in the WGII AR6. They include the strong recognition of the urgency for climate action, the enhanced focus on risk and the aim to connect the search for near-term climate solutions with longer-term transitions. Headline conclusions of the IPCC AR5 include the following, directly quoted (IPCC, 2014a):

- Human influence on the climate system is clear.
- Recent climate changes have had widespread impacts on human and natural systems.
- Continued emission of greenhouse gases will cause further warming and long-lasting changes in all components of the climate system, increasing the likelihood of severe, pervasive and irreversible impacts for people and ecosystems.
- Adaptation and mitigation are complementary strategies for reducing and managing the risks of climate change.
- Substantial emissions reductions over the next few decades can reduce climate risks in the 21st century and beyond, increase prospects for effective adaptation, reduce the costs and challenges of mitigation in the longer term and contribute to climate-resilient pathways for sustainable development.
- Effective implementation depends on policies and cooperation at all scales and can be enhanced through integrated responses that link adaptation and mitigation with other societal objectives.

Compared to previous IPCC assessments of impacts, adaptation and vulnerability, the IPCC WGII AR5 assessment highlighted new data for attributing observed climate changes and impacts (Cramer et al., 2014; IPCC, 2014c), a more formal approach to risk (IPCC, 2014c; Jones et al., 2014), and an expanded assessment of adaptation (Chambwera et al., 2014; IPCC, 2014c; Klein et al., 2014a; Mimura et al., 2014; Noble et al., 2014).

At the time of the IPCC AR5, very few scientific studies relevant to the impacts of global warming of 1.5°C above pre-industrial levels were available. In 2018, the IPCC concluded a Special Report on the impacts of global warming of 1.5°C levels and related global GHG emission pathways, following an invitation expressed in the Decision text of the Paris Agreement (UNFCCC, 2015a). The report assessed available literature on global warming of 1.5°C and on comparisons between global warming of 1.5°C and 2°C above pre-industrial levels. It also addressed possible pathways for achieving the ambitious goals of the Paris Agreement. Key findings from this report include the following, directly quoted (IPCC, 2018c):

- Global warming is *likely* to reach 1.5°C between 2030 and 2052 if it continues to increase at the current rate.
- Climate-related risks for natural and human systems are higher for global warming of 1.5°C than at present, but lower than at 2°C. Most adaptation needs will be lower for global warming of 1.5°C compared to 2°C.
- In model pathways with no or limited overshoot of 1.5°C, global net anthropogenic CO_2 emissions decline by about 45% from 2010 levels by 2030 (40–60% interquartile range), reaching net zero around 2050 (2045–2055 interquartile range).
- Pathways reflecting current nationally stated mitigation ambitions as submitted under the Paris Agreement would not limit global warming to 1.5°C, even if supplemented by very challenging increases in the scale and ambition of emissions reductions after 2030.

In 2019, a Special Report on the Ocean and Cryosphere in a Changing Climate (SROCC) was published, motivated by the observation that many of the world's people most exposed to risks caused by climate change live in the mountains or near the coast. Key findings include the following, directly quoted (IPCC, 2019c):

- Over the last decades, global warming has led to widespread shrinking of the cryosphere and unabated ocean warming with an uptake of more than 90% of the excess heat in the climate system. Marine heatwaves have doubled in frequency since 1982 and the oceans acidify (*virtually certain*). Global mean sea level is rising, with acceleration in recent decades. Increases in tropical cyclone winds and rainfall exacerbate extreme sea level events and coastal hazards.
- All these trends have impacted ecosystems, food security, water resources, water quality, livelihoods, health and well-being, infrastructure, transportation, tourism and recreation, as well as the culture of human societies, particularly for Indigenous Peoples.
- The Greenland and Antarctic Ice Sheets are projected to lose mass at an increasing rate throughout the 21st century and beyond. Projected ecosystem responses include losses of species habitat and diversity, and degradation of ecosystem functions. Warm-water corals are at high risk already and are projected to transition to very high risk even if global warming is limited to 1.5°C.
- Increased mean and extreme sea level, alongside ocean warming and acidification, are projected to exacerbate risks for human communities in low-lying coastal areas. People with the highest exposure and vulnerability are often those with lowest capacity to respond.

Box 1.1 (continued)

- Services provided by ocean and cryosphere-related ecosystems can be supported by protection, restoration, precautionary ecosystem-based management of renewable resource use, and the reduction of pollution and other stressors.
- Coastal communities face challenging choices in crafting context-specific and integrated responses to sea level rise that balance costs, benefits and trade-offs of available options and that can be adjusted over time.

Also in 2019, IPCC published a Special Report on Climate Change and Land, addressing GHG fluxes in land-based ecosystems, land use and sustainable land management in relation to climate change adaptation and mitigation, desertification, land degradation and food security. Key findings include the following, directly quoted (IPCC, 2019c):

- Human use directly affects more than 70% of the global, ice-free land surface. Land also plays an important role in the climate system. Climate change has adversely impacted food security and terrestrial ecosystems as well as contributed to desertification and land degradation in many regions. Changes in land conditions, either from land use or climate change, affect global and regional climate.
- Pathways with higher demand for food, feed, and water, more resource-intensive consumption and production, and more limited technological improvements in agriculture yields result in higher risks from water scarcity in drylands, land degradation, and food insecurity. Most of the response options assessed contribute positively to sustainable development and other societal goals. Sustainable land management, including sustainable forest management, can prevent and reduce land degradation, maintain land productivity, and sometimes reverse the adverse impacts of climate change on land degradation. It can also contribute to mitigation and adaptation.
- Response options throughout the food system, from production to consumption, including food loss and waste, can be deployed and scaled up to advance adaptation and mitigation. All assessed modelled pathways that limit warming to 1.5°C or well below 2°C require land-based mitigation and land use change.
- The effectiveness of decision-making and governance is enhanced by the involvement of local stakeholders (particularly those most vulnerable to climate change including Indigenous Peoples and local communities, women, and the poor and marginalised) in policies for land-based climate change adaptation and mitigation.
- Near-term action to address climate change adaptation and mitigation, desertification, land degradation and food security can bring social, ecological, economic and development co-benefits.

In 2021, IPCC Working Group 1 published its Sixth Assessment Report on The Physical Science Basis. Key findings from the report include the following, directly quoted from its Summary for Policymakers (SPM) quoted (IPCC, 2019c):

- The scale of recent changes across the climate system as a whole and the present state of many aspects of the climate system are unprecedented over many centuries to many thousands of years.
- Global surface temperature will continue to increase until at least the mid-century under all emissions scenarios considered. Global warming of 1.5°C and 2°C will be exceeded during the 21st century unless deep reductions in carbon dioxide and other greenhouse gas emissions occur in the coming decades.
- Many changes due to past and future greenhouse gas emissions are irreversible for centuries to millennia, especially changes in the ocean, ice sheets and global sea level.
- With further global warming, every region is projected to increasingly experience concurrent and multiple changes in climatic impact-drivers. Changes in several climatic impact-drivers would be more widespread at 2°C compared to 1.5°C global warming and even more widespread and/or pronounced for higher warming levels. Low-likelihood outcomes, such as ice sheet collapse, abrupt ocean circulation changes, some compound extreme events and warming substantially larger than the assessed very likely range of future warming cannot be ruled out and are part of risk assessment.
- From a physical science perspective, limiting human-induced global warming to a specific level requires limiting cumulative CO_2 emissions, reaching at least net zero CO_2 emissions, along with strong reductions in other greenhouse gas emissions. Strong, rapid and sustained reductions in emissions would also limit the warming effect resulting from declining aerosol pollution and would improve air quality.

Other assessment processes also inform the IPCC AR6. For example, a recent joint workshop between the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) and IPCC, the first of its kind, made key observations relevant to the work of IPCC WGII AR6 (Pörtner et al., 2021). In this broad context, the workshop explored diverse facets of the interaction between climate and biodiversity, from current trends to the role and implementation of nature-based solutions and the sustainable development of human society. Key highlights of the workshop include the following, directly quoted from the workshop report:

Box 1.1 (continued)

- Limiting global warming to ensure a habitable climate and protecting biodiversity are mutually supporting goals, and their achievement is essential for sustainably and equitably providing benefits to people.
- Several land- and ocean-based actions to protect, sustainably manage and restore ecosystems have co-benefits for climate mitigation, climate adaptation and biodiversity objectives.
- Measures narrowly focused on climate mitigation and adaptation can have direct and indirect negative impacts on nature and nature's contributions to people.
- Measures narrowly focusing on protection and restoration of biodiversity have generally important knock-on benefits for climate change mitigation, but those benefits may be sub-optimal compared to measures that account for both biodiversity and climate.
- Treating climate, biodiversity and human society as coupled systems is key to successful outcomes from policy interventions.
- Transformative change in governance of socio-ecological systems can help create climate and biodiversity resilient development pathways.

including those which meet or miss the Paris Agreement goals, and overshoot scenarios in which global mean temperature exceed targets for several decades before dropping to desired levels. Such scenarios inform assessments of the level of adaptation that may be required (Section 1.4; Chapter 17).

Adaptation and sustainable development are also interlinked (Section 18.1). Adaptation facilitates development, which is hindered by impacts and risks from climate change. Development facilitates adaptation by expanding the resources and capacity available to manage climate risks. Viewed from a climate justice perspective, some argue that a more just society is more capable of successful adaptation, while others argue that only adaptation that results in a more just society can be judged successful (Section 1.4.1; Chapter 18).

Two concepts—adaptation gaps and limits to adaptation—help frame this report's assessment of the extent to which current adaptation efforts are adequate to meet societal goals. **Adaptation gaps** are defined as 'the difference between actually implemented adaptation and a societally set goal, determined largely by preferences related to tolerated climate change impacts and reflecting resource limitations and competing priorities' (UNEP et al., 2021). Limits to adaptation describe the extent to which no plausible level of adaptation can meet societal goals (Section 1.4.4). Within the limits, adaptation gaps can be closed by increased and more successful adaptation actions. Beyond the limits, only mitigation can close adaptation gaps.

Numerous climate-related impacts already cause severe damage in many places and are projected to increase in the future (Chapter 16). Adaptation can reduce these risks, often significantly, but limits to adaptation have already been reached or are being approached in some sectors and regions (Sections 16.3.1; 16.4). While natural systems worldwide are changing in response to climate change, many are not adapting sufficiently quickly to retain their resilience in the face of current and projected future climate change (Section 16.4). For human systems, numerous lines of evidence suggest that in many regions and sectors current infrastructure, settlement patterns, policies, practices and institutions remain inadequate for current changes in climate conditions (Section 16.2). Inadequate or insufficient adaptation to current conditions is called an adaptation deficit.

In response, adaptation efforts have increased significantly since AR5 (Sections 16.3; 17.2; 17.5.2; Cross-Chapter Box ADAPT in Chapter 1). Assessing the adequacy and effectiveness of these efforts as called for in Article 7 of the Paris Agreement remains challenging (Section 1.3.2.2), because much adaptation is not recorded in the literature and because assessment depends on judgements of effectiveness (Section 1.4.1.2), judgements about societal goals including climate justice (Section 1.4.1.1), and expectations about future GHG concentration pathways and other socioeconomic conditions (Section 16.5, Cross-Chapter Box DEEP in Chapter 17).

Knowledge about adaptation has significantly expanded since AR5 (Cross-Chapter Box ADAPT in Chapter 1). While understanding regarding the extent of adaptation gaps remains limited, the available evidence suggests significant adaptation gaps exist (*high confidence*). Many current adaptation efforts constitute adaptation planning, rather than implementation (Section 16.3). Most current implementation efforts represent incremental as opposed to transformational adaptation despite the proximity to adaptation limits (Sections 17.2; 17.5.2). Some current adaptation efforts are considered maladaptive because they increase some climate-related risks even if they reduce others (Sections 1.4.2.4; 17.5; Chapter 16). Gaps exist in key enablers of adaptation, such as finance (Cross-Chapter Box FINANCE in Chapter 17). Given the long time scales involved with many adaptation actions and the potential to significantly reduce longer-term costs with near-term actions, closing many adaptation gaps requires actions over the next few years by governments, business, civil society and individuals at a scale and speed significantly faster than that represented by current trends.

1.1.4 What is New in the History of Interdisciplinary Climate Change Assessment

Interdisciplinary climate change assessment, which has played a prominent role in science–society interactions on the climate issue since 1988, has advanced in important ways since AR5 (Mitchell et al., 2006; Mach and Field, 2017; Oppenheimer et al., 2019). Building on a substantially expanded scientific and technical literature (Burkett et al., 2014; Minx et al., 2017), this AR6 report emphasises at least three broad themes.

First, this AR6 assessment has an increased focus on risk- and solutions-frameworks. The risk framing can move beyond the limits of single best estimates or most-likely outcomes and include high-consequence outcomes for which probabilities are low or in some cases unknown (Jones et al., 2014; Mach and Field, 2017). In this report, the risk framing for the first time spans all three Working Groups, includes risks from the responses to climate change, considers dynamic and cascading consequences (Section 1.3.1.1), describes with more geographic detail risks to people and ecosystems, and assesses such risks over a range of scenarios (Chapter 16). The focus on solutions encompasses the interconnections among climate responses, sustainable development, and transformation, and the implications for governance across scales within the public and private sectors (Section 17.5.2; Chapter 18). The assessment therefore includes climate-related decision making and risk management, climate resilient development pathways, implementation and evaluation of adaptation, and also limits to adaptation, and loss and damage (Cross-Chapter Box LOSS in Chapter 17; Section 1.4.4). Specific focal areas reflect contexts increasingly important for the implementation of responses, such as cities (Chapter 6).

Second, emphases on social justice and different forms of expertise have emerged (Sections 1.4.1.1; 17.5.2). As climate change impacts and implemented responses increasingly occur, there is heightened awareness of the ways that climate responses interact with issues of justice and social progress. In this report, there is expanded attention to inequity in climate vulnerability and responses, the role of power and participation in processes of implementation, unequal and differential impacts, and climate justice. The historic focus on scientific literature has also been increasingly accompanied by attention to and incorporation of Indigenous knowledge (IK), local knowledge (LK) and associated scholars (Section 1.3.2.3; Chapter 12).

Third, AR6 has a more extensive focus on the role of transformation in meeting societal goals (Section 1.5).

To support these three themes, this report assesses literature with an increasing diversity of topics and geographical areas covered. The diversity is encompassed through sectoral and regional chapters (Chapters 2–15), as well as cross-chapter papers and boxes. The literature also increasingly evaluates the lived experiences of climate change—the physical changes underway, the impacts for people and ecosystems, the perceptions of the risks, and adaptation and mitigation responses planned and implemented. In particular, scientific capabilities to attribute individual extreme weather and climate events to GHG emissions have gone from hypothetical to standard and routine over the last three decades, and societal perceptions of these events and their impacts for people and ecosystems are now being studied as well (Figure 1.1; Cross-Working Group Box ATTRIBUTION in Chapter 1; see synthesis in Chapter 16).

Finally, climate change assessment has become increasingly integrative across multiple disciplines within the natural and social sciences. This report's chapters combine experts across Working Groups and disciplines, such as natural and social sciences, engineering, humanities, law, and business administration. In this assessment cycle, the special reports (Allen et al., 2018; IPCC, 2019a; IPCC, 2019b) all emphasise such integration, and the chapter teams in the present report integrate disciplinary perspectives and also science–policy interactions inherent in climate change impacts, adaptation and vulnerability. There has been increasing real-time assessment of the assessment process itself, including interpersonal dynamics and how they shape key findings (Oppenheimer et al., 2019). Additionally, best practices are being adopted from applied decision and policy analysis, decision support and co-production, in order to increase assessment relevance and usability for decision making (Hall et al., 2019; Mach et al., 2019). Methods of integration in this report include systematic review, meta-analysis, multi-criteria integration and expert elicitation (see synthesis in Chapter 16). The emphasis on knowledge for action has also included the role of public communication, stories and narratives within assessment and associated outreach (Section 1.2.2).

1.2 Different Entry Points for Understanding Climate Change Impacts, Adaptation and Vulnerability

This section introduces key concepts used in this report and the connections between them that present different entry points for understanding climate change impacts, adaptation, and vulnerability.

1.2.1 Overlapping, Complementary Entry Points

Many actors from different research and practice communities engage with understanding and responding to climate risk. Not surprisingly, there thus exist alternative, overlapping and complementary entry points to the discussion widely used throughout the literature and this report.

The concepts of risk and risk management have in recent years been central to climate change research and practice related to impacts, adaptation, and vulnerability. The concepts provide a framework for understanding climate change and its increasingly severe, interconnected and irreversible impacts. They support the implementation of solutions that reduce adverse consequences, pursue opportunities and enable beneficial outcomes for people, economies and nature (IPCC, 2014c; IPCC, 2018c). All three AR6 Working Groups now apply a common risk framework (IPCC, 2020).

Additional concepts—adaptation, vulnerability, exposure, resilience and transformation—also provide important framings for the climate change challenge.

Figure 1.2 displays the connections among many of the key concepts used in this report. This chapter, the Summary for Policymakers, Technical Summary and sectoral and regional chapters are organised around the concepts of risks (Section 1.3), solutions (Section 1.4) and transformation (Section 1.5).

Key concepts that contribute to an understanding of risk include its components hazards, exposure, and vulnerability (Section 1.2.1.1); the recognition that risks may be complex and cascading (Section 1.3.1.2); and the reasons for concern framework used to summarise the most

Connecting key concepts in this report

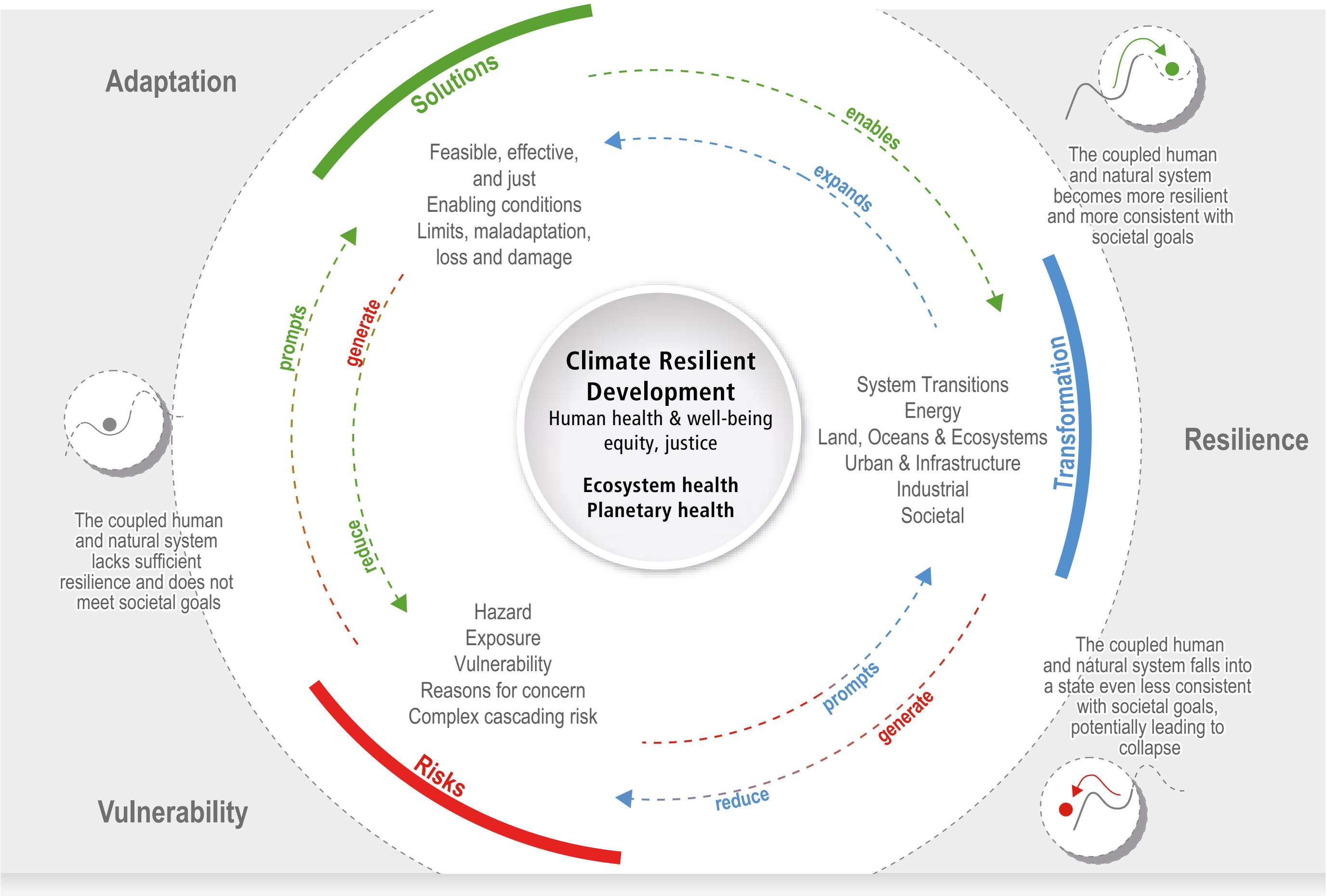


Figure 1.2 | Connecting key concepts in this report. The current coupled human and natural system is insufficiently resilient and does not meet societal goals of equity, well-being and ecosystem health. Meeting the objectives of the Paris Agreement, Sustainable Development Goals and other policy statements requires the system to move to a new and more resilient state. Key concepts used in this report help illuminate our current situation and potential solutions. These key concepts are usefully organised around the concepts of risk, solutions and transformation. Risk can prompt solutions and transformation. Both solutions and transformation seek to reduce some risks but may also generate others. Solutions can enable transformation, and transformation can expand the set of feasible solutions.

policy-relevant risks (Section 1.3.1.1). Key concepts that contribute to an understanding of feasible, effective, and just solutions (1.4.1) include the enablers of governance, finance and knowledge (Section 1.4.2); Transformation is supported by systems transitions in energy, land, infrastructure, industry and society (Section 1.5.1), which if successful can contribute to climate resilient development (Section 1.5).

The centre of Figure 1.2 shows societal goals of equity, health, well-being and climate justice as articulated by the Paris Agreement, SDGs, and other policies and plans (Section 1.4.1). The limits to adaptation (Section 1.4.4), potential for maladaptation (Sections 1.4.2; 17.5.2) and loss and damage (Section 1.4.4.2) present barriers to reaching these goals.

The concept of vulnerability can provide a unique window into the effects of climate change on different communities, individuals and ecosystems, in particular as human systems are affected by race, gender, wealth inequalities and other attributes (Section 1.2.1.2). The concept of adaptation can provide a unique window into the process of adjustment to climate change by human and natural systems (Section 1.2.1.3). Resilience (Section 1.3.1.4) is a broad concept, encompassing both outcomes and processes, an ability to maintain essential function and an ability to transform.

The ball and cup diagrams (Holling, 1973) in Figure 1.2 indicate that the current coupled human and natural system is not resilient, nor does it meet societal goals of equity, well-being and ecosystem health. Some types of transformation may prove inevitable (Section 1.5.1), either a deliberate transformation that results in a more resilient state consistent with societal goals or a forced transformation to a system state inconsistent with the goals.

1.2.1.1 Risk Framing

Risk in this report is defined as the potential for adverse consequences for human or ecological systems, recognising the diversity of values and objectives associated with such systems. In the context of climate change impacts, risks result from dynamic interactions between climate-related hazards with the exposure and vulnerability of the affected human or ecological system. In the context of climate change responses, risks result from the potential for such responses not achieving the intended objective(s), or from potential trade-offs or negative side effects (see Annex II: Glossary). **Risk management** is defined as plans, actions, strategies or policies to reduce the likelihood and/or magnitude of adverse potential consequences, based on assessed or perceived risks (see Annex II: Glossary).

Risk framing is increasingly used to assess climate change impacts on human and natural systems (Sections 1.2.4.1; 16.1; 17.3; Cross-Chapter Box CLIMATE in Chapter 1; IPCC, 2012; Mach and Field, 2017; O'Neill et al., 2017; Connelly et al., 2018; see also Oppenheimer et al., 2014). A risk framing reflects key dimensions of the climate challenge. These features include the changing likelihoods of many different outcomes (including adverse consequences and beneficial opportunities), uncertainties that will persist, and different and contested values, priorities and goals (Jones and Preston, 2011; Mach et al., 2016). The IPCC AR6 and associated special reports apply a broad definition of risk. WGI Cross-Chapter Box 1.3. WGI uses the Climatic Impact Driver terminology, rather than hazard, to neutrally assess changing climatic conditions that are relevant to human and natural systems, leaving the determination of positive/negative consequences and resulting impacts and risks for WGII assessment (WGI Section 12.3). In most cases, throughout this WGII report, the term 'risk' refers to the risks of climate change impacts. The full assessment, however, incorporates all relevant risks from climate change impacts and responses.

The broad definition of risk involves quantitative and integrative understandings of risk (Oppenheimer et al., 2014; Mach and Field, 2017; see also Section 17.3). Risk is sometimes defined as the probability of a consequence, multiplied by the magnitude of that consequence, acknowledging both the diversity of possible consequences and the relevance of values. Yet it also applies in circumstances where probabilities cannot be fully quantified (e.g., Adger et al., 2013). For example, in some cases the probability and magnitude of consequences may be more uncertain, dependent on complex dimensions of the climate (e.g., a cyclone, high tide, and heatwave co-occurring) or the vulnerability of different communities (e.g., the ways in which social networks and community cohesion support the most vulnerable individuals during disasters) (Ford et al., 2018). The determinants of risk vary dynamically through space and time (Jurgilevich et al., 2017; Viner et al., 2020). They interact, compound, and cascade (Dawson, 2015; Adger et al., 2018; see also Section 16.1.2).

Risk framing supports connections with solutions (Jones and Preston, 2011; Mach et al., 2016; Adger et al., 2018). First, risk framing connects the present with the future. (Papathoma-Kohle et al., 2016). For instance, whether wildfire or drought, recent experiences have demonstrated limits to current response capacities relevant to future preparedness (e.g., evacuation of large communities on tight time frames or water management simultaneously responsive to intensifying drought and flooding). Second, risk framing emphasises that uncertainties and complex interactions are integral to decision making (Jones et al., 2014; Dawson, 2015). The uncertainties include high-impact, low-probability outcomes and deep uncertainties for which core processes are not understood and meaningful probabilities cannot be applied (Adler et al., 2016; see also Section 17.2.1; Cross-Chapter Box DEEP in Chapter 17; Chapter 7 in SRCCL, IPCC, 2019a; Cross-Chapter Box 5 in SROCC, IPCC, 2019b). In these circumstances, risk assessment can occur through tools used for risk management across contexts, such as insurance, business, social protection, security and policy planning, and decision making can be iterative and support dynamic adaptive pathways through time (Jones and Preston, 2011; Watkiss et al., 2015; Aven, 2016; see also Section 17.3.2)

Iterative risk management (Vervoort and Gupta, 2018) emphasises that anticipating and responding to climate change does not consist of a single set of judgements at a single point in time, but rather an 'ongoing cycle of assessment, action, reassessment, learning and response (USGCRP, 2018). It is consistent with most approaches applied for implementing adaptation (Jones and Preston, 2011; Jones et al., 2014). For instance, the Paris Agreement is organised as a polycentric process (see Section 1.4) of iterative risk management in which national governments pledge to take specific actions. Those actions are monitored and assessed, and nations asked to update their pledges in light of that assessment.

1.2.1.2 Vulnerability

Vulnerability is a component of risk, but also an important focus independently. Vulnerability in this report is defined as the propensity or predisposition to be adversely affected. It encompasses a variety of concepts and elements, including sensitivity or susceptibility to harm and lack of capacity to cope and adapt (see Annex II: Glossary). Over the past several decades, approaches to analysing and assessing vulnerability have evolved. An early emphasis on top-down, biophysical evaluation of vulnerability included—and often started with—exposure to climate hazards in assessing vulnerability. From this starting point, attention to bottom-up, social and contextual determinants of vulnerability, which often differ, has emerged, although this approach is incompletely applied or integrated across contexts (Bergstrand et al., 2015; Rufat et al., 2015; Spielman et al., 2020; Taberna et al., 2020). Vulnerability is now widely understood to differ within communities and across societies, also changing through time (Kienberger et al., 2013; Jurgilevich et al., 2017; see also Chapter 16). In the WGII AR6, assessment of the vulnerability of people and ecosystems encompasses the differing approaches that exist within the literature, both critiquing and harmonising them based on available evidence. In this context, **exposure** is defined as the presence of people; livelihoods; species or ecosystems; environmental functions, services, and resources; infrastructure; or economic, social, or cultural assets in places and settings that could be adversely affected (Annex II: Glossary). Potentially affected places and settings can be defined geographically, as well as more dynamically, for example through transmission or interconnections through markets or flows of people.

Vulnerability is also a link between the climate risk and disaster risk communities, recognising complementarities and differences between these communities. **Disaster risk management** is the set of processes that improve understanding of disaster risk, foster disaster risk reduction and transfer, and promote continuous improvement in disaster preparedness, response and recovery practices, increasing human security, well-being and sustainable development (see Annex II: Glossary). Climate risk and disaster risk are increasingly addressed together, bridging the climate change adaptation and disaster risk reduction communities (e.g., IPCC, 2012; UNDRR, 2019, especially Chapter 13 in that report). Building on the scientific literature and adaptation and risk reduction practice, the IPCC Special Report on Extremes resulted in several major IPCC advances that continue through the present report, including emphasis on risk and climate-related extremes (e.g., Burton et al., 2012; Lavell et al., 2012) and re-conceptualisation of vulnerability to encompass both social and biophysical orientations (i.e., bridging contextual/bottom-up and climate-driven/top-down approaches) (Polsky et al., 2007; Cardona et al., 2012). Linking disaster risk reduction and climate change adaptation can also be an important basis for discussion in climate negotiations on the allocation of funds needed for tackling climate change, especially in developing countries and SIDS (Begum et al., 2014). The integration of disaster risk management and climate change adaptation in the IPCC AR6 is seen, for example, in the assessment of key risks within and across sectors and regions, along with global-scale reasons for concern, which is attuned to extreme events and disasters (Oppenheimer et al., 2014; see also Chapter 16). Additionally, the assessment of adaptation has prioritised these interconnections (e.g., Mimura et al., 2014), as have literature and practice especially in the context of sustainable development (e.g., Schipper et al., 2016).

1.2.1.3 Adaptation

Adaptation in this report is defined, in human systems, as the process of adjustment to actual or expected climate and its effects, in order to moderate harm or exploit beneficial opportunities. In natural systems, adaptation is the process of adjustment to actual climate and its effects; human intervention may facilitate adjustment to expected climate and its effects (see Annex II: Glossary). Adaptation planning in human systems generally entails a process of iterative risk management. Different types of adaptation have been distinguished, including anticipatory versus reactive, autonomous versus planned and incremental versus transformational adaptation (Chapters 16–18; IPCC WGII glossaries for the TAR, AR4, AR5, and AR6 (Annex II)). Adaptation is often seen as having five general stages: (a) awareness, (b) assessment, (c) planning, (d) implementation and (e) M&E (Moser and Boykoff, 2013; Jones et al., 2014; Mimura et al., 2014; Noble et al., 2014; see also Section 17.4). Government, non-government and private sector actors have adopted a wide variety of specific approaches to adaptation that, to varying degrees, address these five general stages. Adaptation in natural systems includes ‘autonomous’ adjustments through ecological and evolutionary processes. It also involves the use of nature through ecosystem-based adaptation. The role of species, biodiversity and ecosystems in such adaptation options can range from the rehabilitation or restoration of ecosystems (e.g., wetlands or mangroves) to hybrid combinations of ‘green and grey’ infrastructure (e.g., horizontal levees) (Chapters 2 and 3; IPBES, 2018).

The IPCC assessment of adaptation has evolved through time. The WGII AR4 included one chapter dedicated to adaptation, the WGII AR5 expanded to four and the WGII AR6 mainstreams adaptation comprehensively throughout the report. Adaptation science is rapidly evolving, including evaluation of adaptation effectiveness, feasibility, implementation and maladaptation, although major knowledge gaps persist in modelling and analysis (Cross-Chapter Box ADAPT in Chapter 1; Chapter 16; Section 1.4; Holman et al., 2019). The WGII AR6 emphasises assessment of observed adaptation-related responses to climate change, governance and decision making in adaptation, and the role of adaptation in reducing key risks and global-scale reasons for concern, as well as limits to such adaptation (e.g., Chapters 16 and 17). The assessment approach includes adaptation needs, options, planning and implementation across sectors and regions, as well as adaptation opportunities, constraints and also limits (Eisenack et al., 2014; Klein et al., 2014b; Oberlack and Eisenack, 2014; Lehmann et al., 2015; Roggero, 2015; Herrmann and Guenther, 2017; Oberlack, 2017; Sieber et al., 2018; Moser et al., 2019b; Capela Lourenço et al., 2019; Thaler et al., 2019; Russel et al., 2020; see also Chapters 16 and 17).

Since AR5, more adaptation has progressed (IPCC, 2014a; Lesnikowski et al., 2016; see also Sections 16.2.5 and 17.2) and the focus of activity has expanded to include social, institutional and governance dimensions beyond engineered and technical options and to decision processes beyond technocratic, linear framings (IPCC, 2014a; see also Chapter 17). Adaptation includes increasing attention to implementation, M&E and learning through time, not just planning processes (Section 17.3 and 17.5.1). On the one hand, an important advance has been recognition of generalised capacities, such as resources and knowledge, necessary for the feasibility of effective adaptation. Adaptation thereby strongly overlaps with risk management and with the building of resilience and sustainable development (Chapters 17 and 18).

1.2.1.4 Resilience, Including Connections with Development Pathways and Transformation

Resilience in this report is defined as the capacity of social, economic and environmental systems to cope with a hazardous event or trend or disturbance, responding or reorganising in ways that maintain their essential function, identity and structure, while also maintaining the capacity for adaptation, learning and transformation (see Annex II: Glossary). Resilience is an entry point commonly used, although under a wide spectrum of meanings (Reghezza-Zitt et al., 2012; Flood and Schechtman, 2014; Aldunce et al., 2015; Tanner et al., 2015; Fisichelli et al., 2016; Meerow et al., 2016; Moser et al., 2019a). Resilience as a system trait overlaps with concepts of vulnerability, adaptive capacity, and thereby risk. Resilience as a strategy overlaps with risk management, adaptation and also transformation (Woodruff et al., 2018; Moser et al., 2019a). Implemented adaptation is often organised around resilience as bouncing back and returning to a previous state after a disturbance (Fisichelli et al., 2016).

In much of the literature, resilience encompasses not just maintaining essential function, identity and structure, but also maintaining a capacity for adaptation, learning and transformation. Since the earliest framings of resilience around stability and persistence, ecology and allied fields have come to recognise that while systems are often persistent in the face of disturbance, disturbance also creates opportunity for transformation and the emergence of new pathways (Section 1.5.2; Folke, 2006; Allen and Holling, 2010; Folke et al., 2010; Gelcich et al., 2010; Stockholm Resilience Center, 2015; Doppelt, 2017). Across this literature, disturbance is framed as outside the system in question, for which the time frames and spatial scales of disturbances, impacts and responses are central to outcomes (Béné et al., 2011; Brown, 2014; Hamborg et al., 2020). Endogenous processes of transformation are presented as emergent, characterised by thresholds and, as a result, very difficult to anticipate (Scheffer et al., 2001; Walker and Meyers, 2004; Suding and Hobbs, 2009; Scheffer et al., 2012; Hughes et al., 2013; Scheffer et al., 2015). In the last 5 years (2016–2020), the concept of resilience has gained prominence as a core theme in the climate change adaptation literature (Nalau and Verrall, 2021).

Often, development and adaptation communities of practice default to persistence and stability in their use of resilience (Cote and Nightingale, 2012; MacKinnon and Derickson, 2013). Such a framing aligns resilience with a long-standing but increasingly questioned belief that sustainable development can be achieved through incremental adjustments in behaviour and advances in technology that allow for the persistence of existing socioeconomic and socio-ecological arrangements (Klauer, 1999; Banerjee, 2003; Redclift, 2005; UN Inter-agency Task Force on Financing for Development 2019; Chapter 18, Section 1.5). However, the literature increasingly suggests that the achievement of sustainable development will require transformative change in socio-ecological systems at scales ranging from the community to the globe. The concept of climate resilient development, initially introduced in AR5 and now a key focus in this report (see Chapter 18), engages with such transformations and the associated questions of justice, power and politics as shaped by internal, endogenous social factors and their interactions with other drivers of change (Eriksen et al., 2015; Nightingale, 2015b; Carr, 2019; Nightingale et al., 2019; see also Chapter 18).

1.2.2 Narratives, Storylines, Scenarios and Pathways

The concepts of narratives, storylines, scenarios and pathways play an important role in this report. While distinct concepts, they are inter-related and sometimes confused.

A **narrative** is a story with a chronological order or, when cast in the form of an argument, with premises and conclusions (Roe, 1991; Adger et al., 2001). Narratives enable people to envision what various potential futures may mean for environments and livelihoods, and in this way facilitate the development of scenarios for the future (Miller et al., 2015). Narratives can also play a key role in enabling collective action (Section 1.5) by helping disparate groups co-create a common vision of a desirable future and achieve a common understanding of actions needed to move towards that future (Linnér and Wibeck, 2019; Muiderman et al., 2020).

A narrative contains a storyline in addition to a set of actors (Elliott, 2005). A **storyline** is a series of events including their causal connections within a narrative. The IPCC and climate change literature more broadly often use the terms storylines and narratives interchangeably (O'Neill et al., 2017; see also WGI Cross-Chapter Box 6 in Chapter 1; Sections 1.4.4; 10.5.3). A **scenario storyline** refers to a narrative description of a scenario including its main characteristics, relationships between driving forces and how these factors evolve (AR6 WGI Section 1.4.4.2, Chen et al., 2021). Storylines are used to assess risks related to low-likelihood, but high-impact events (Sutton, 2018). In this use of the terms, narratives and storylines do not include specific actors. There is also a critical literature on the use of narratives and storylines based on projected scenarios, which points out the conservative character of these concepts whose performative effect tends to preserve the status quo and the current socioeconomic relationships. (Malm and Hornborg, 2014; Chollet and Felli, 2015; Lövbrand et al., 2015; Demortain, 2019; Theys and Cornu, 2019).

Standard research communication may fail to engage policymakers, media and the public at large (WGI AR6 Section 1.2.4, Chen et al., 2021). Rather, policies and decision making tend to be based on narratives and storylines (Roe, 1994; Roe, 2017). Although mathematical models and narratives are often presumed to be antithetical, in practice they may be complementary and work together (Morgan and Wise, 2017). Communicating research insights through storylines and narratives may have a better chance of transmitting key messages. AR6 employs these communication tools in many places, for instance storylines for constructing and communicating regional climate information or climate services (WGI AR6 Chapter 10, Doblas-Reyes et al., 2021; WGI AR6 Chapter 12, Ranasinghe et al., 2021) or 'low likelihood high warming storylines' (Chapter 4). To better communicate deep uncertainty in sea level rise projections, WGI uses storylines to describe the physical events that would have to unfold to generate its high-end estimates (Cross-Chapter Box DEEP in Chapter 17).

Scenarios are defined in IPCC reports as plausible descriptions of how the future may develop, based on a coherent and internally consistent set of assumptions about key driving forces (e.g., rate of technological

Cross-Chapter Box CLIMATE | Climate Reference Periods, Global Warming Levels and Common Climate Dimensions

Authors: Steven Rose (USA), Richard Betts (UK), Philippus Wester (Nepal/the Netherlands), Aris Koutroulis (Greece)

This Cross-Chapter Box sets out common climate dimensions to contextualise and facilitate AR6 WGII analyses, presentation, synthesis and communication of assessed, observed and projected climate change impacts across WGII chapters and cross-chapter papers. 'Common climate dimensions' are defined as common global warming levels (GWLs), time periods and levels of other variables, as needed by WGII authors for consistent communications. The set of climate variable ranges given below was derived from the AR6 WGI report and supporting resources, and helps to contextualise and inform the projection of potential future climate impacts and key risks. The information enables the mapping of climate variable levels to climate projections and vice versa, with ranges of results provided to characterise the physical uncertainties relevant to assessing climate impacts risk.

Cross-Chapter Box CLIMATE1 (continued)

AR6 WGI Reference Periods, Climate Projections and Global Warming Levels

AR6 WGI adopts a common set of reference years and time periods to assess observed and projected climate change, namely the pre-industrial period, the current 'modern' period and future reference time periods. The IPCC Glossary (2021b) defines the pre-industrial period as 'the multi-century period prior to the onset of large-scale industrial activity around 1750. The reference period 1850–1900 is used to approximate pre-industrial global mean surface temperature (GMST).' The 'modern' period is defined as 1995 to 2014 in AR6, while three future reference periods are used for presenting climate change projections, namely near term (2021–2040), mid-term (2041–2060) and long term (2081–2100), in both the AR6 WGI and WGII reports. Importantly, the historical rate of warming assessed by WGI in AR6 is different to that assessed in AR5 and Special Report on Global Warming of 1.5°C (SR1.5, IPCC, 2018b), due to methodological updates (see WGI Cross-Chapter Box 2.3 in Chapter 2 for details (Gulev, 2021)). This means that the 'modern' period is assessed as slightly warmer compared to 1850–1900 than it would have been with AR5-era methods. This also has implications for the projected timing of reaching policy-relevant levels of global warming, which need to be understood.

To explore and investigate climate futures, climate change projections are developed using sets of different input projections. These consist of sets of projections of GHG emissions, aerosols or aerosol precursor emissions, land use change, and concentrations designed to facilitate evaluation of a large climate space and enable climate modelling experiments. For AR5 (and the Coupled Model Intercomparison Project (CMIP) 5 climate model experiments), the input projections were referred to as representative concentration pathways (RCPs). For AR6 (and the CMIP6 climate model experiments), new sets of inputs are used and referred to as SSP scenarios, where SSP refers to socioeconomic assumptions called the shared socioeconomic pathways (SSPs).

The RCPs are a set of four trajectories that span a large radiative forcing range, defined as increased energy input at surface level in Watts per square metre, ranging from 2.6 W m^{-2} (RCP2.6) to 8.5 W m^{-2} (RCP8.5) by the end of the 21st century, with RCP4.5 and RCP6.0 as intermediate scenarios, and RCP2.6 a peak and decline scenario reaching 3 W m^{-2} before 2100. A range of emissions scenarios compatible with each specific RCP was also assessed in AR5 (Ciais et al., 2013).

A core set of five SSP scenarios, namely SSP1-1.9, SSP1-2.6, SSP2-4.5, SSP3-7.0 and SSP5-8.5, was selected in the AR6 WGI report to fill certain gaps identified in the RCPs (see WGI Cross-Chapter Box 1.4 in Chapter 1 (Chen et al., 2021)). The first number in the label is the particular set of socioeconomic assumptions driving the emissions and other climate forcing inputs taken up by climate models and the second number is the radiative forcing level reached in 2100. WG1 Cross-Chapter Box 1.4 in Chapter 1 provides a comparison of this core set of SSP scenarios with scenarios used in previous reports, with SSP1–1.9 a low overshoot scenario consistent with limiting global average warming to 1.5°C, and SSP1-2.6 a scenario consistent with limiting warming to 2°C.

Also of importance to the impact literature and the WGII report are SSP-RCP combinations, that is, studies that employ climate outcomes based on RCPs and socio-economic assumptions based on SSPs. SSPs can be paired with a range of different RCPs because SSPs can be combined with mitigation policy assumptions to produce a range of emissions pathways. In addition to the SSPs, there are many other emissions pathways and societies consistent with any global mean temperature outcome. These represent uncertainty and broad ranges of possibilities that affect climate change exposure and vulnerability (Rose and and M. Scott, 2020; Rose and Scott, 2018). Furthermore, there are large uncertainties in translating emissions scenarios into concentration pathways due to uncertainties in climate-carbon cycle feedbacks (Jones et al., 2013; Booth et al., 2017).

The plausibility of emissions levels as high as the emissions scenario conventionally associated with the RCP8.5 and SSP5-8.5 concentration pathways has been called into question since AR5, as has the emissions pathway feasibility of the low scenarios (Hausfather and Peters, 2020; Rose and and Scott, 2020). However, these views are contested (Schwalm et al., 2020, for RCP8.5) It is important to realise that emissions scenarios and concentration pathways are not the same thing and higher concentration pathways, such as RCP8.5 could arise from lower emissions scenarios if carbon cycle feedbacks are stronger than assumed in the integrated assessment models (IAMs) used to create the standard scenarios (Booth et al., 2017). In the majority of full-complexity Earth System Models, these feedbacks are stronger than in the IAMs (Jones et al., 2013), so the RCP8.5 concentration pathway cannot be ruled out purely through consideration of the economic aspects of emissions scenarios. Nonetheless, the likelihood of a climate outcome, and the overall distribution of climate outcomes, are a function of the emissions scenario's likelihood. Note that the original RCPs were created explicitly to facilitate a broad range of climate modelling experiments, with the expectation that other issues, such as socioeconomic uncertainty, could be subsequently explored (Moss et al., 2010).

Cross-Chapter Box CLIMATE1 (continued)

An important feature of the AR6 cycle is a stronger emphasis on the use of future GWLs to support consistency and comparability across the three IPCC Working Groups' contributions to the AR6 and improve communication. The common range of GWLs relative to the 1850 to 1900 period, termed the 'Tier 1' range by WGI, are 1.5, 2.0, 3.0 and 4.0°C. The use of GWLs assists in the comparison of climate states across climate change scenarios (projections) and in assessing the broader literature, as well as for cross-chapter and cross-working group comparisons. They facilitate the integration of climate projections, impacts, adaptation challenges and mitigation challenges within and across the three Working Groups as there is a close connection between the level of global warming and climate change impacts. Of particular interest is the timing of when the 'Tier 1' GWLs are reached, relative to the period 1850–1900, under the five SSP x–y scenarios, as well as RCP scenarios. For climate change impacts and adaptation responses, linking GWLs to RCP and SSP climate projections using a climate information translation resource is of great relevance for the WGII contribution to AR6.

AR6 WGII Common Climate Dimensions

WGII's common climate dimensions include (a) a common range of GWLs from WGI, (b) common ranges for other climate variables, (c) information for translating climate variable levels to climate projections and vice versa. See Table Cross-Chapter Box CLIMATE.1 for global warming level ranges by time periods for RCP and SSP climate projections, and Table Cross-Chapter Box CLIMATE.2 for information regarding the timing for when GWLs are reached in climate projections. The common GWL range is based on WGI's 'Tier 1' dimensions of integration range: 1.5°C, 2°C, 3°C and 4°C. The first table illustrates the greater levels of projected global warming with higher emissions pathways, as well as the increasing uncertainty in the climate response over time for a given pathway. The second table illustrates significant uncertainty in the timing for passing GWL thresholds which can narrow for a given GWL, the higher the emissions pathway. Finally, given the importance of geographic heterogeneity in projected changes in future climate, Table Cross-Chapter Box CLIMATE.3a and 3b are provided with ranges for select climate variables (temperature, precipitation, ocean) by GWL and continent (or ocean biome). The ranges illustrate spatial heterogeneity in potential physical changes in levels and uncertainty that are relevant to assessing climate impacts risk. There is significantly more spatial heterogeneity than represented in the table that is relevant to local decision makers (see, for instance, WGI Interactive Atlas).

The common climate dimensions can be used as a dimension of integration for impact studies in WGII, for example by providing a common framework for comparison of projected impacts for different studies (Figure Cross-Chapter Box CLIMATE.1). Moreover, GWL bands are needed in WGII to map the diverse temperature levels found across WGII's literature. The GWL's also facilitate integration with WGIII's global emissions projections categorisation by global mean temperature (WGIII Chapter 3).

Table Cross-Chapter Box CLIMATE.1 | GWL ranges by time periods for CMIP5 (RCP) and CMIP6 (SSP) climate projections (20-year averages). Temperature anomalies relative to 1850–1900. Full ranges for CMIP raw results (across all models and ensemble runs) and WGI AR6 assessed *very likely* (5–95%) ranges. *Sources: Hauser et al. (2019); WGI SPM (IPCC, 2021a); Table SPM.1*

	Full ranges									WGI AR6 assessed *very likely* (5–95%) ranges								
Projection	**2021–2040**			**2041–2060**			**2081–2100**			**2021–2040**			**2041–2060**			**2081–2100**		
RCP2.6	1.0	to	2.2	1.0	to	2.3	0.9	to	2.3	n/a			n/a			n/a		
RCP4.5	1.1	to	2.2	1.4	to	2.7	1.8	to	3.3	n/a			n/a			n/a		
RCP6.0	1.0	to	2.0	1.3	to	2.5	2.3	to	3.6	n/a			n/a			n/a		
RCP8.5	1.1	to	2.6	1.7	to	3.7	3.0	to	6.2	n/a			n/a			n/a		
SSP1–1.9	1.0	to	2.4	1.1	to	2.7	1.0	to	2.5	1.2	to	1.7	1.2	to	2.0	1.0	to	1.8
SSP1–2.6	1.0	to	2.4	1.2	to	2.9	1.3	to	3.1	1.2	to	1.8	1.3	to	2.2	1.3	to	2.4
SSP2–4.5	0.9	to	2.5	1.3	to	3.3	1.9	to	4.4	1.2	to	1.8	1.6	to	2.5	2.1	to	3.5
SSP3–7.0	1.0	to	2.6	1.5	to	3.7	2.7	to	6.2	1.2	to	1.8	1.7	to	2.6	2.8	to	4.6
SSP5–8.5	1.0	to	2.7	1.6	to	4.0	3.1	to	7.2	1.3	to	1.9	1.9	to	3.0	3.3	to	5.7

Cross-Chapter Box CLIMATE1 (continued)

Table Cross-Chapter Box CLIMATE.2 | Timing for when 20-year average GWLs are reached in CMIP5 (RCP) and CMIP6 (SSP) climate projections. GWL anomalies relative to 1850–1900. Ranges based on CMIP raw results (all models and ensemble runs), and WGI AR6 assessed results. For each GWL and RCP/SSP, the earliest and latest 20-year window when a 20-year average GWL is reached across the CMIP models and ensemble members is reported, or the *very likely* (5–95%) assessed range is reported. 'n.c.' means the GWL is not reached during the period 2021–2100. *Sources: Hauser et al. (2019); WGI TS Cross-Section Box Table TS.1(Arias et al., 2021)*

	CMIP5 full ranges			
GWL	**RCP2.6**	**RCP4.5**	**RCP6.0**	**RCP8.5**
4°C	n.c.	n.c.	n.c.	2047–2066 to 2080–2099
3°C	n.c.	2054–2073 to 2070–2089	2062–2081 to 2080–2099	2030–2049 to 2077–2096
2°C	2015–2034 to 2079–2098	2014–2033 to 2075–2094	2023–2042 to 2068–2087	2004–2023 to 2048–2067
1.5°C	1998–2017 to 2075–2094	1998–2017 to 2051–2070	2001–2020 to 2050–2069	1990–2009 to 2035–2054

	CMIP6 full ranges				
GWL	**SSP1–1.9**	**SSP1–2.6**	**SSP2–4.5**	**SSP3–7.0**	**SSP5–8.5**
4°C	n.c.	n.c.	2061–2080 to 2081–2100	2046–2065 to 2081–2100	2042–2061 to 2081–2100
3°C	n.c.	2050–2069 to 2068–2087	2034–2053 to 2081–2100	2030–2049 to 2081–2100	2027–2046 to 2079–2098
2°C	2009–2028 to 2063–2082	2008–2027 to 2075–2094	2009–2028 to 2080–2099	2008–2027 to 2060–2079	2008 - 2027 to 2055 - 2074
1.5°C	1997–2016 to 2058–2077	1997–2016 to 2073–2092	1997–2016 to 2051–2070	1997–2016 to 2042–2061	1997 - 2016 to 2038 - 2057

	WGI AR6 assessed *very likely* (5–95%) ranges				
GWL	**SSP1–1.9**	**SSP1–2.6**	**SSP2–4.5**	**SSP3–7.0**	**SSP5–8.5**
4°C	n.c.	n.c.	n.c.	2070–2089 to n.c.	2058–2077 to n.c.
3°C	n.c.	n.c.	2061–2080 to n.c.	2050–2069 to n.c.	2042–2061 to 2074–2093
2°C	n.c.	2031–2050 to n.c.	2028–2047 to 2075–2094	2026–2045 to 2053–2072	2023–2042 to 2044–2063
1.5°C	2013–2032 to n.c.	2012–2031 to n.c.	2012–2031 to 2037–2056	2013–2032 to 2033–2052	2011–2030 to 2029–2048

Cross-Chapter Box CLIMATE1 (continued)

Table Cross-Chapter Box CLIMATE.3a | Projected continental level result ranges for select temperature and precipitation climate change variables by global warming level. Ranges are 5th and 95th percentiles from SSP5–8.5 WGI CMIP6 ensemble results. There is little variation in the 5th and 95th percentile values by GWL across the SSP1–2.6, SSP2–4.5, SSP3–7.0, and SSP5–8.5 projections. ***Source: WGI AR6 Interactive Atlas*** (https://interactive-atlas.ipcc.Chapter/).

Climate variable	Global warming level	All regions			North America			Europe			Asia			Centra-South America			Africa			Australia			Antarctica		
Mean temperature (°C)	**4°C**	12	to	15	8	to	11	5	to	9	12	to	14	24	to	27	26	to	29	24	to	27	–33	to	–27
	3°C	11	to	14	6	to	11	4	to	7	10	to	14	23	to	26	25	to	28	23	to	26	–35	to	–26
	2°C	10	to	13	5	to	9	3	to	6	8	to	12	22	to	25	24	to	27	22	to	25	–36	to	–27
	1.5°C	9	to	12	4	to	8	2	to	5	8	to	12	22	to	24	24	to	26	22	to	24	–36	to	–27
Mean daily minimum temperature (°C)	**4°C**	8	to	11	4	to	8	1	to	6	6	to	11	19	to	24	21	to	25	18	to	23	–38	to	–29
	3°C	6	to	11	2	to	8	0	to	5	4	to	10	19	to	22	19	to	23	17	to	21	–39	to	–30
	2°C	5	to	10	0	to	6	–2	to	4	3	to	9	17	to	21	18	to	22	16	to	20	–40	to	–31
	1.5°C	4	to	9	–1	to	5	–2	to	3	2	to	8	17	to	21	17	to	22	16	to	19	–41	to	–32
Minimum of daily minimum temperatures (°C)	**4°C**	–12	to	–5	–25	to	–15	–22	to	–14	–18	to	–9	11	to	15	10	to	14	5	to	10	–64	to	–48
	3°C	–13	to	–6	–27	to	–15	–24	to	–15	–20	to	–11	10	to	15	8	to	14	4	to	10	–64	to	–50
	2°C	–15	to	–8	–30	to	–18	–27	to	–17	–22	to	–13	9	to	14	7	to	13	3	to	9	–65	to	–51
	1.5°C	–16	to	–9	–32	to	–20	–28	to	–19	–23	to	–14	8	to	14	6	to	12	3	to	9	–66	to	–51
Mean maximum daily temperature (°C)	**4°C**	16	to	19	12	to	15	8	to	11	15	to	18	27	to	32	30	to	35	28	to	33	–31	to	–25
	3°C	15	to	19	11	to	15	7	to	11	14	to	18	27	to	32	30	to	37	27	to	34	–32	to	–25
	2°C	14	to	18	9	to	13	6	to	9	13	to	17	26	to	31	29	to	36	27	to	33	–33	to	–25
	1.5°C	13	to	17	8	to	12	5	to	9	12	to	16	25	to	30	28	to	35	26	to	33	–33	to	–26
Maximum of daily maximum temperatures (°C)	**4°C**	32	to	37	32	to	38	28	to	33	35	to	40	36	to	43	40	to	47	41	to	49	–12	to	–5
	3°C	31	to	39	31	to	38	28	to	34	35	to	41	35	to	44	39	to	51	41	to	54	–12	to	–3
	2°C	30	to	37	30	to	36	26	to	33	33	to	39	34	to	43	38	to	50	39	to	53	–13	to	–4
	1.5°C	29	to	36	29	to	35	25	to	31	32	to	39	33	to	42	38	to	49	39	to	52	–14	to	–5
Number of days with maximum temperature above 35°C—bias adjusted	**4°C**	81	to	106	36	to	50	11	to	22	57	to	77	138	to	194	153	to	210	140	to	168	0	to	0
	3°C	66	to	87	27	to	40	6	to	15	44	to	59	100	to	153	131	to	183	124	to	147	0	to	0
	2°C	52	to	68	19	to	29	4	to	8	33	to	45	61	to	106	116	to	151	102	to	124	0	to	0
	1.5°C	45	to	58	16	to	24	2	to	5	30	to	39	43	to	85	107	to	133	94	to	115	0	to	0
Number of days with maximum temperature above 40°C—bias adjusted	**4°C**	28	to	40	9	to	16	1	to	5	19	to	26	21	to	68	69	to	92	53	to	83	0	to	0
	3°C	20	to	30	5	to	11	1	to	2	14	to	21	9	to	32	56	to	77	41	to	64	0	to	0
	2°C	14	to	21	2	to	6	0	to	1	9	to	15	3	to	13	41	to	57	27	to	45	0	to	0
	1.5°C	11	to	17	2	to	4	0	to	0	8	to	12	1	to	8	35	to	47	22	to	38	0	to	0

Cross-Chapter Box CLIMATE1 (continued)

Climate variable	Global warming level	All regions			North America			Europe			Asia			Centra-South America			Africa			Australia			Antarctica		
Near-surface total precipitation (mm d–1)	**4°C**	2	to	3	2	to	3	2	to	2	2	to	3	4	to	5	2	to	3	1	to	2	1	to	1
	3°C	2	to	3	2	to	3	2	to	2	2	to	3	3	to	5	2	to	3	1	to	2	1	to	1
	2°C	2	to	3	2	to	3	2	to	2	2	to	3	3	to	5	2	to	3	1	to	2	1	to	1
	1.5°C	2	to	3	2	to	3	2	to	2	2	to	3	3	to	5	2	to	3	1	to	2	1	to	1
Maximum 1-day precipitation amount (mm)	**4°C**	35	to	55	40	to	53	27	to	35	36	to	52	47	to	90	29	to	67	43	to	68	9	to	13
	3°C	31	to	52	34	to	50	23	to	33	30	to	50	37	to	88	25	to	66	38	to	69	8	to	12
	2°C	29	to	50	32	to	48	22	to	32	28	to	47	37	to	85	22	to	59	36	to	66	8	to	11
	1.5°C	28	to	48	31	to	47	21	to	31	27	to	45	35	to	84	21	to	58	36	to	64	8	to	11
Maximum 5-day precipitation amount (mm)	**4°C**	79	to	99	75	to	93	53	to	71	81	to	105	118	to	168	68	to	113	81	to	124	20	to	29
	3°C	66	to	99	68	to	87	48	to	68	70	to	101	97	to	165	60	to	118	76	to	129	19	to	27
	2°C	64	to	93	65	to	84	47	to	65	66	to	95	93	to	162	55	to	107	73	to	122	18	to	26
	1.5°C	63	to	91	63	to	83	46	to	64	64	to	93	92	to	160	52	to	105	74	to	119	18	to	25
Consecutive dry days (precipitation < 1 mm)	**4°C**	36	to	80	23	to	31	26	to	38	35	to	68	31	to	88	48	to	146	45	to	109	44	to	99
	3°C	36	to	88	21	to	33	25	to	43	35	to	76	29	to	82	49	to	160	40	to	127	45	to	120
	2°C	37	to	88	21	to	32	24	to	40	36	to	74	29	to	77	49	to	161	38	to	128	45	to	127
	1.5°C	36	to	87	22	to	31	25	to	37	36	to	74	28	to	77	49	to	159	40	to	125	46	to	131

Table Cross-Chapter Box CLIMATE.3b | Projected sea surface temperature change ranges by global warming level and ocean biome (degrees Celsius). Ranges are 5th and 95th percentiles from SSP5–8.5 WGI CMIP6 ensemble results. There is little variation in the 5th and 95th percentile values by GWL across the SSP1–2.6, SSP2–4.5, SSP3–7.0, and SSP5–8.5 projections. *Source: WGI Interactive Atlas (*https://interactive-atlas.ipcc.Chapter/*).*

Global warming level	All ocean biomes			Northern Hemi-sphere—high latitudes			Northern Hemisphere—subtropics			Equatorial			Southern Hemisphere—subtropics			Southern Hem-isphere—high latitudes			Gulf of Mexico			Eastern boundaries			Amazon River			Arabian Sea			Indonesian Flowthrough		
4°C	1.9	to	2.4	2.0	to	3.3	2.2	to	2.8	2.1	to	3.0	1.8	to	2.4	1.3	to	2.0	2.1	to	2.8	2.1	to	2.7	1.7	to	2.5	2.3	to	2.9	1.9	to	2.7
3°C	1.3	to	1.7	1.2	to	2.2	1.4	to	2.4	1.4	to	2.2	1.2	to	1.7	0.7	to	1.4	1.5	to	2.3	1.4	to	2.1	1.2	to	2.0	1.6	to	2.2	1.3	to	1.9
2°C	0.6	to	1.0	0.5	to	1.4	0.7	to	1.4	0.7	to	1.3	0.5	to	1	0.3	to	0.8	0.6	to	1.4	0.6	to	1.3	0.6	to	1.3	0.6	to	1.3	0.5	to	1.2
1.5°C	0.2	to	0.7	0.1	to	0.9	0.2	to	1.0	0.2	to	0.8	0.2	to	0.6	0.1	to	0.5	0.2	to	1.0	0.2	to	0.9	0.2	to	0.9	0.2	to	0.9	0.1	To	0.8

Cross-Chapter Box CLIMATE1 (continued)

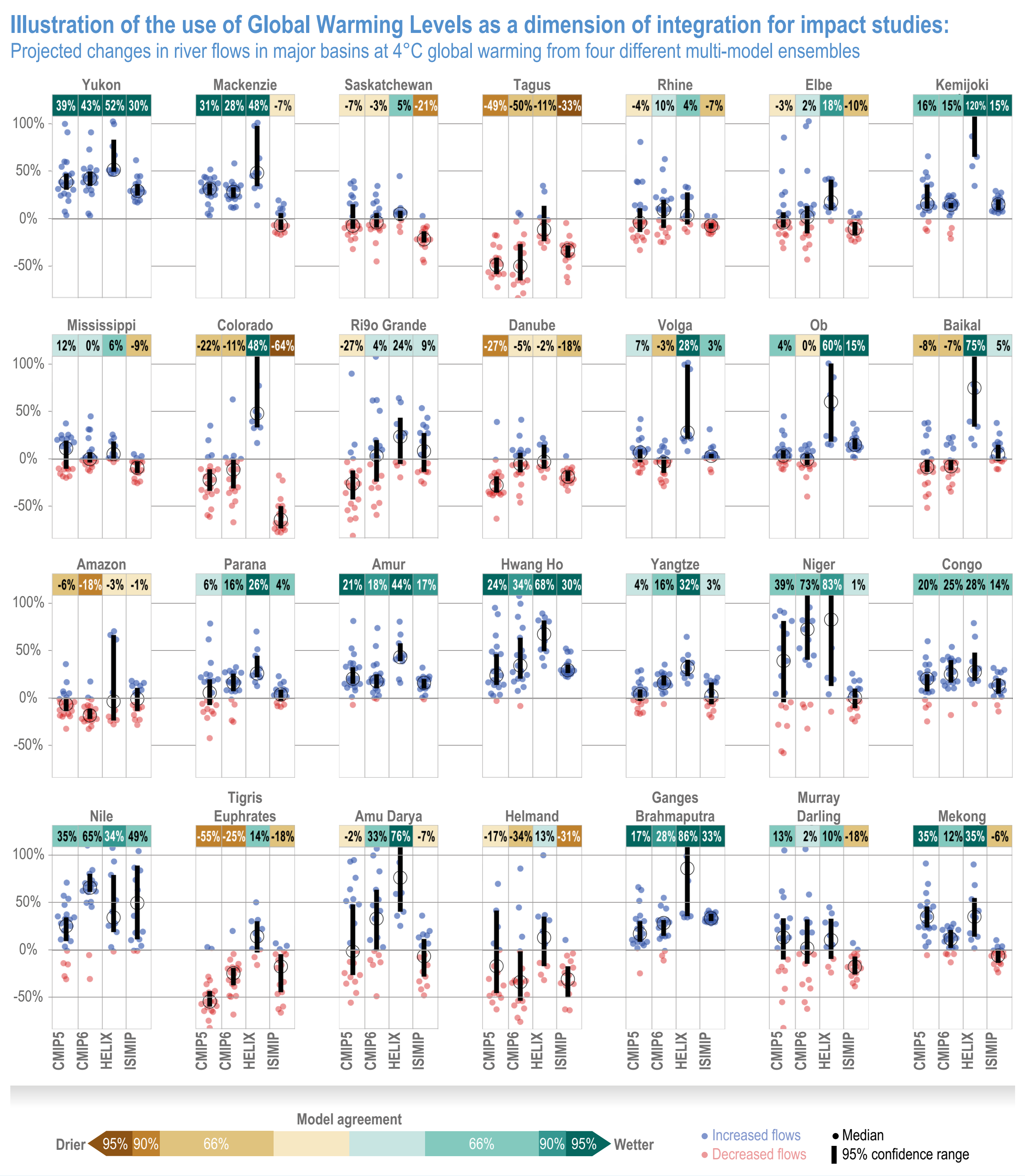


Figure Cross-Chapter Box CLIMATE.1 | Illustration of the use of global warming levels (GWLs) as a dimension of integration for impact studies: projected changes in river flows in major basins at 4°C global warming from four different multi-model ensembles. Results are shown for projected flow changes direct from Earth System Models (ESMs) in CMIP5 and CMIP6, for the Joint UK Land Environment Simulator (JULES) land surface model driven by meteorological outputs of the HadGEM3 and EC-Earth model in the High-End cLimate Impacts and eXtremes (HELIX) ensemble (Betts et al., 2018; Koutroulis et al., 2019), and nine hydrological models driven by a subset of five CMIP5 ESMs in the Inter-Sectoral Impacts Model Intercomparison Project (ISIMIP; Warszawski et al., 2014). Dots show results from individual models, blue for increased flows and red for decreased flows, black circles show the median for each ensemble, and black bars show the 95% confidence range in the median. See Figure 4.11 for further details.

Cross-Chapter Box CLIMATE1 (continued)

To contextualise reported impacts by warming level for the influence of other determinants of risk, where appropriate and feasible (e.g., level of exposure/vulnerability, level of adaptation, time period), common time periods for the past and future can be aligned with WGI's historical and projected time windows. Given differences in available literature, WGII chapters and CCPs (cross-chapter papers) contextualise impacts with respect to exposure, vulnerability and adaptation as appropriate.

Common ranges for other 'climate' variables, such as minimum and maximum temperatures and regional climates, are available based on WGI projections. They are based on feasible combinations with GWLs taken into consideration using the WGI Interactive Atlas. Climate information translation may have been necessary within chapters for mapping the WGII literature and assessments of the common climate dimensions. WGII's climate impacts literature is based primarily on climate projections around AR5 and earlier or assumed temperature levels, though some recent impacts literature uses newer climate projections based on the CMIP6 exercise. Thus, it was important to be able to map climate variable levels to climate projections of different vintages and vice versa and adjust variables, when possible, to a common reference year. WGII chapters and CCPs only provide climate impact information for the common climate dimensions that their literature supports and where there is sufficient evidence.

Interpretation of the update in projected time of reaching 1.5°C global warming from SR1.5 to AR6

In an assessment using multiple lines of evidence, including models, observational constraints and improved understanding of climate sensitivity, WGI project a central estimate of the 20-year average warming crossing the 1.5°C GWL in the early 2030s in all scenarios assessed, except SSP5–8.5 (Lee et al., 2021). This is about 10 years earlier than the midpoint of the likely range (2030–2052) assessed in SR1.5, which assumed continuation of the observed warming rate reported at that time. However, this does not imply that the projected impacts of 1.5°C will be reached 10 years earlier, because roughly half of the 10-year difference is a result of updating the diagnosed historical rate of warming due to methodological advances, new datasets and other improvements (Gulev et al., 2021). The other half of the 10-year difference arises because, for central estimates of climate sensitivity, most scenarios show stronger warming over the near term than was assessed as 'current' in SR1.5 (*medium confidence*).

The revised historical warming rate does not necessarily contribute to a change in timing of estimated impacts. It depends on how impacts are calculated relative to climate. Because the revised historical warming results in a redefinition of the 1.5°C GWL relative to the modern time period (1995–2014) rather than a different level of overall change (Figure Cross-Chapter Box CLIMATE.2 in Chapter 1), impacts assessed relative to the modern time period are unaffected. There are, in effect 'old' and 'new' definitions of the 1.5°C GWL with different levels of impacts, and the impacts assessed for the 'old' 1.5°C GWL now apply to a different level of global warming. However, the timing of impacts assessed relative to pre-industrial (e.g., aggregate economic impact estimates), are affected and we are closer to impact levels associated with 1.5°C and 2°C.

To illustrate with a worked example: in SR1.5, the historical warming between 1850–1900 and the modern period of 2006–2015 was assessed as 0.87°C, implying that the 1.5°C GWL would be accompanied by impacts associated with 0.63°C warming from the modern period. However, AR6 WGI (Gulev et al., 2021) revised the assessment of warming between 1850–1900 and 2006–2015 to 0.94°C, implying that the 1.5°C GWL would be accompanied by a slightly lower level of impacts associated with only 0.56°C warming from the modern period. So, while the redefined 1.5°C GWL would be reached earlier, it would also be accompanied by a lower level of impacts (Figure Cross-Chapter Box CLIMATE.2 in Chapter 1). The impacts associated with the 'old' 1.5°C GWL would now be seen at 1.57°C global warming relative to 1850–1900, reached at the time of the 'old' 1.5°C GWL, if the same future level of warming were to be used as in SR1.5.

However, in addition to this redefinition of the historical warming rate, the assessed future warming in AR6 is also slightly faster than the continuation of reported recent warming used in SR1.5. This means that both the 'old' and 'new' 1.5°C GWLs are projected to be reached earlier than they would have been using the SR1.5 method. This and the revised historical warming diagnosis contribute approximately equally to the assessment of 1.5°C global warming being reached about 10 years earlier than projected in SR1.5.

Central estimates of impacts associated with a specifically defined 1.5°C GWL could therefore be considered to be projected to be reached approximately 5 years earlier than implied by SR1.5. However, uncertainties in regional climate responses at a given GWL are large (Cross-Chapter Box CLIMATE in Chapter 1, Table CLIMATE.3a) and natural climate variability occurs in parallel with ongoing warming, so the potential for impacts higher than central estimates could be a more urgent consideration for risk assessments and adaptation planning than the earlier projected timing of reaching 1.5°C (*high confidence*). It should also be noted that individual years may exceed 1.5°C above 1850–1900 sooner, but this is not the same as exceedance of the 1.5°C GWL which refers to the 20-year mean.

Cross-Chapter Box CLIMATE1 (continued)

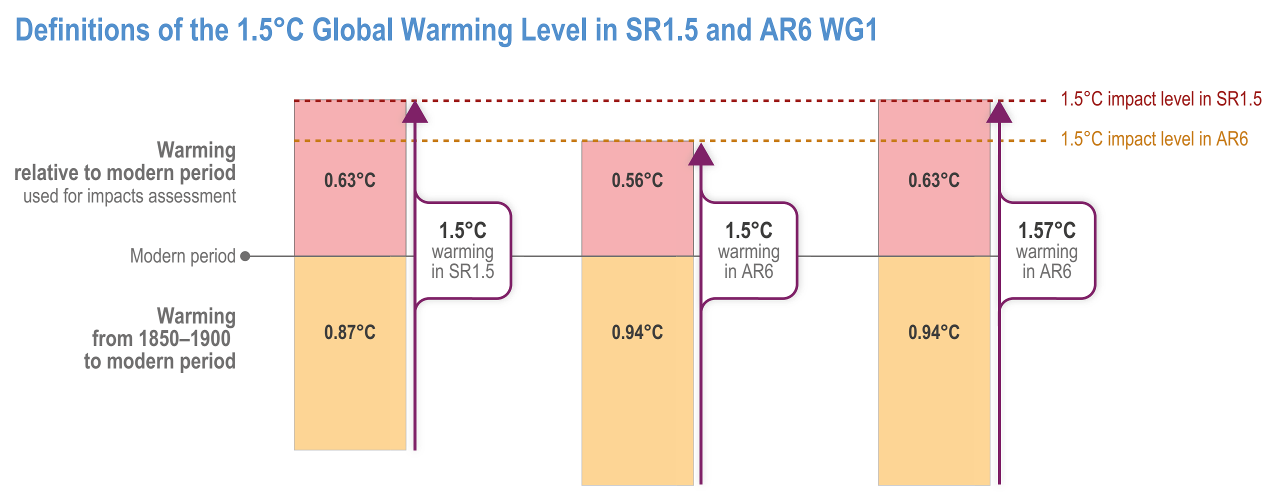


Figure Cross-Chapter Box CLIMATE.2 | Definitions of the 1.5°C global warming level (GWL) in SR1.5 (IPCC, 2018b) and AR6 WGI (IPCC, 2021a). GWLs are defined relative to 1850–1900 but impacts at the GWL are typically assessed in association with warming relative to a modern period 1995–2014, which in SR1.5 was 2006–2015. Revised assessment of the historical warming between 1850–1900 and the modern period (0.87°C in SR1.5 to 0.94°C in AR6) has the effect of slightly reducing the warming between the modern period and the 1.5°C GWL (0.63°C in SR1.5 to 0.56°C in AR6), and the impacts at the GWL previously defined as 1.5°C in SR1.5 now occur at 1.57°C global warming with the AR6 definition. Warming values are central estimates. Heights of the bars are not to scale.

change, prices) and relationships (Annex II: Glossary). Scenarios are neither predictions nor forecasts but rather 'foresights', which imply envisioning challenging futures (Vervoort and Gupta, 2018). Scenarios are used to provide a view of the potential consequences and implications of developments and actions in a 'what-if' mode of exploring the future (AR6 WGIII Section 1.5.1; AR6 WGI Section 1.6.1, Chen et al., 2021). They may be presented as numerical or mental models. Climate change scenarios are generated by climate modellers to highlight possible alternative GHG emission pathways and are used to develop and integrate projections of emissions and their climate change impacts and for analysing and contrasting climate policy choices. Cross-Chapter Box CLIMATE in Chapter 1 describes scenarios used in this report.

Pathways are one element of a larger scenario (O'Neill et al., 2017), focusing on just one element of a larger system of drivers, emissions or concentrations. Scenarios provide one means to represent deep uncertainty when there is disagreement or uncertainty about conceptual models (Cross-Chapter Box DEEP in Chapter 17; IPCC, 2019b). In addition, scenarios provide several important functions in decision support. A lack of strong association with probabilities enables scenarios to promote buy-in from parties to a decision who hold different expectations about the future, helping them to expand the range of futures and options they consider. The process of generating scenarios can serve as the focus of participatory stakeholder exercises and processes, and scenarios can also be used to support risk management by stress-testing alternative policies and identifying robust and adaptive policies under conditions of deep uncertainty (Cross-Chapter Box DEEP in Chapter 17).

1.3 Understanding and Evaluating Climate Risks

Understanding of climate change has advanced in important ways that shape the AR6 assessment. This section describes advances in the understanding of the complex nature of climate change risks, the deep integration of social sciences, and increased utilisation of IK and LK. These multi-faceted dimensions of understanding climate change and evaluating risks are introduced here.

1.3.1 Nature of Climate Risk

Since AR5, understanding of the nature of climate risk has advanced substantially. AR6 assesses the serious, complex and cascading climate risks unfolding across sectors and regions. These risks are shaped by many societal factors including cultural norms and social practice, socioeconomic development, underlying physical and social vulnerability, and societal responses themselves (Section 1.2.1.1). Throughout, there is increased attention to the important role of different forms of knowledge, especially IK and LK, in the understanding and the management of the changing climate.

1.3.1.1 The Nature of Climate Risk as Assessed in this Report

Greater understanding of climate-related risks is emerging; however, there are important shortcomings in the information for some regions and sectors, and for developing versus developed countries. These risks assume significance in interaction with the cultures, values, ethics, identities, experiences, and knowledge systems of affected communities and societies, as well as their governance, finances, capabilities and

Different interactions can decrease or increase climate-related risks

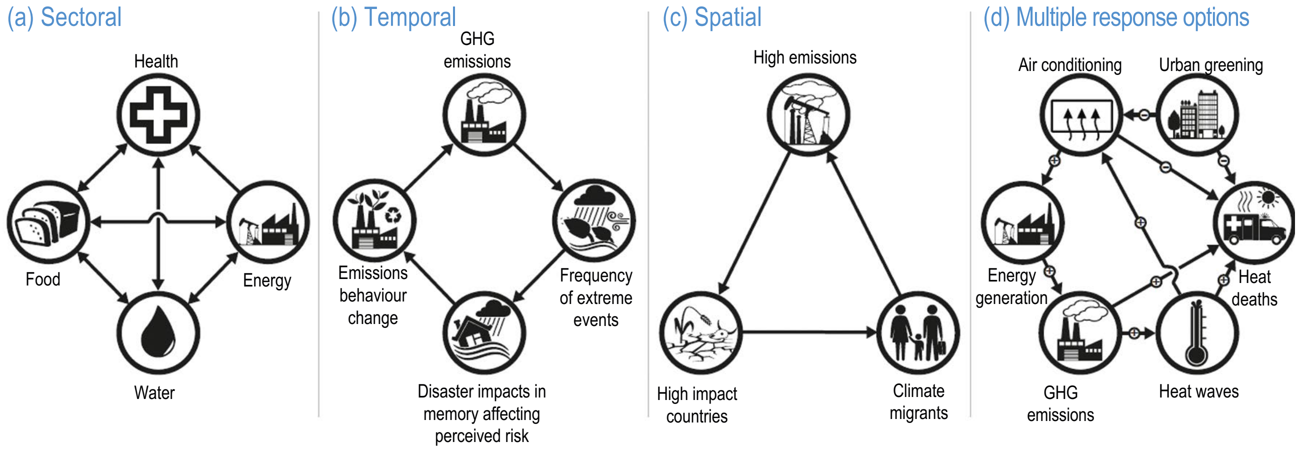


Figure 1.3 | Different interactions can decrease or increase climate-related risks. Key examples include interactions **(a)** among sectors, **(b)** through time, **(c)** across regions, or **(d)** between impacts and responses. The specific interactions indicated within each panel of this figure are illustrative, not comprehensive or indicative of relative importance. Source: (Simpson et. al. 2021)

resources. The key risk assessment in the IPCC AR5 informed the long-term temperature goal in the 2015 Paris Agreement—limiting the increase in global mean temperature to well below 2°C and pursuing efforts towards limiting warming to 1.5°C (Oppenheimer et al., 2014; Pachauri et al., 2014). The IPCC Special Report on Global Warming of 1.5°C, responding to an invitation by UNFCCC, used new scientific information to provide a specific risk assessment associated with the ambitious warming levels targeted by the Paris Agreement (Hoegh-Guldberg et al., 2019). The Special Reports on Oceans and Land further advanced the methods of transparent risk assessment (Zommers et al., 2020). The current assessment expands significantly from the previous reports, aiming to inform and advance understanding of the following core themes: (a) the ways changes in vulnerability and exposure modulate risks of climate change impacts and risk complexity in addition to warming; (b) the knowledge basis relevant to continued refinement of temperature goals; (c) the effectiveness of adaptation solutions; (d) the management of risks at higher levels of warming, should ambitious climate change mitigation be unsuccessful, including limits to adaptation; and (e) the benefits of climate change mitigation and emissions reductions (Section 16.1).

This report evaluates key risks—potentially severe risks—meriting society's full attention globally and regionally across sectors, in order to inform judgements about dangerous anthropogenic interference with the climate system (Oppenheimer et al., 2014; Mach et al., 2016; see also Sections 16.1.2; 16.4; WGI Section 1.2.4.1). As described detail in Chapter 16, evaluation of key risks is based on expert judgement applied to all relevant lines of evidence, with a focus on the role of societal values in determining the importance of a risk. Specific criteria considered relate to the magnitude of adverse consequences, including the potential for irreversibility, thresholds, or cascading effects; the likelihood of adverse consequences; the timing of the risk; and the ability to respond to the risk (Section 16.5.1).

The key risk assessment conveys increasing urgency given the growing visibility of climate change impacts in the current world (Sections 1.1; 16.1). Representative key risks emerging across sectors and regions include risks to coastal socio-ecological systems and terrestrial and ocean ecosystems; risks associated with critical infrastructure, networks and services; risks to living standards and human health; risks to food and water security; and risks to peace and migration (Section 16.5). Compared to the AR5, the emphasis on human dimensions of key climate-related risks has continued and increased, for instance, the potentially severe impacts for cultural heritage (IPCC, 2014c; Pachauri et al., 2014; see also Section 16.4). These human dimensions are essential for understanding vulnerability, impacts and risks central to ensuring human well-being, human security, sustainable development and poverty reduction in a changing climate.

To encompass the nature of climate risk, IPCC assessment since the Third Assessment Report has used five overarching domains, named 'reasons for concern', to assess increasing risk for societies and ecosystems under climate change (IPCC, 2014b; O'Neill et al., 2017; see also Section 16.5; WGI Section 1.2.4.1). The reasons for concern approach has enabled evidence to be combined with expert judgement, in order to provide a holistic assessment across multiple lines of evidence (O'Neill et al., 2017). The approach also respects the uncertainties inherent to climate risk and highlights the ways in which values are relevant in connecting scientific knowledge to societal decision making and risk management. The different reasons for concern underscore that there is no single metric that can reflect all dimensions of climate-related risk and the diversity of consequences for lives and livelihoods, health and well-being, economic and sociocultural assets, infrastructure and ecosystems (Mach and Field, 2017; see also Section 1.4.1.2).

The AR6 Reasons for Concern framework enables integration across key risks and representative key risks, including how risks vary with the

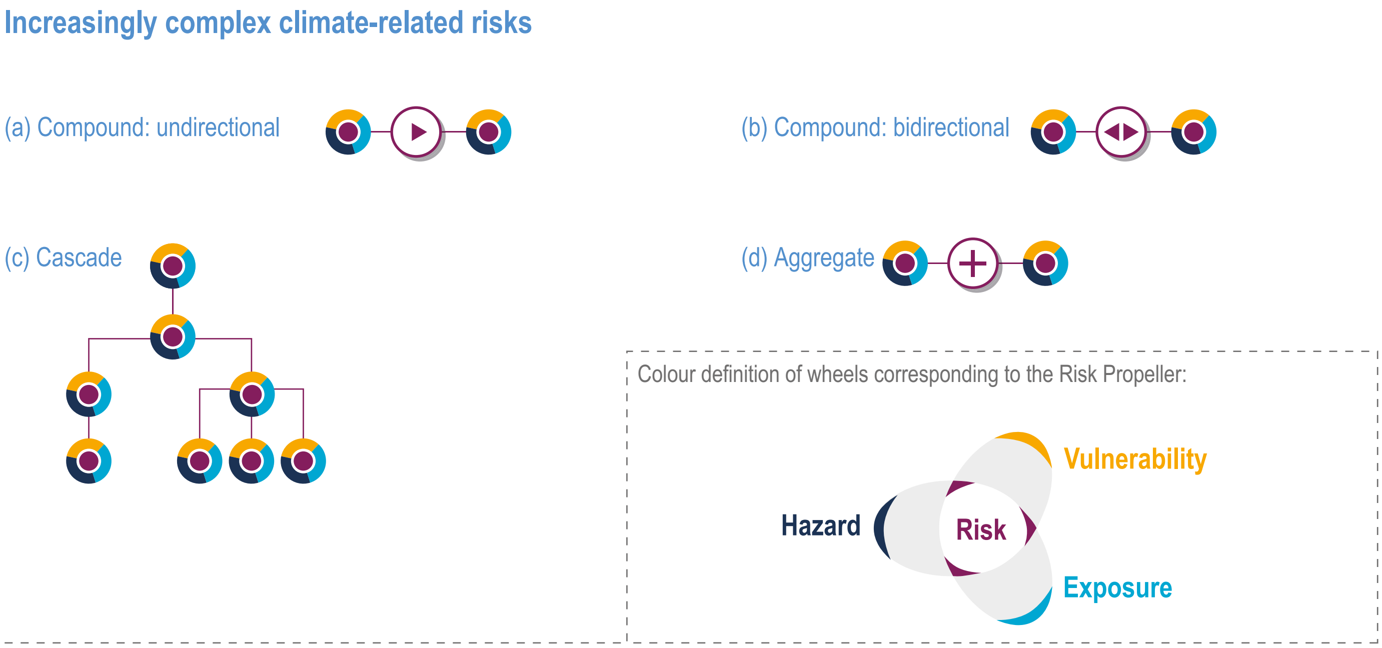


Figure 1.4 | Increasingly complex climate-related risks. Risk results from interactions among the determinants of risk—hazard, vulnerability, and exposure, shaped by responses—which can interact in complex ways. Different risks and responses can compound in single **a**) or multiple **b**) directions, cascade (e.g., with one event triggering another; **c**), and aggregate (e.g., with independent determinants of risks co-occurring; **d**). This complex nature of risk is central in the AR6 assessment. Figure adapted from Simpson et al. (2021).

magnitude of global warming, socioeconomic development pathways and levels of adaptation (Section 16.6). Risk levels are determined through a formal elicitation approach for both representative key risks and reasons for concern, following the authors' assessment of the literature. The reasons for concern consider *unique and threatened systems* (RFC1), such as coral reefs or Arctic Sea ice systems that have especially high vulnerability and low capacity to adapt. They also include the role of *extreme weather events* (RFC2), such as heat waves, heavy rain, drought, coastal flooding or wildfires. The reasons for concern address both the *distributional* and the *aggregate impacts* of climate change (RFC3, RFC4), including the unfairness factor for populations that have contributed little in terms of historic emissions but that are disproportionately vulnerable to the impacts of a changing climate. The final reason for concern relates to *large-scale singular events*, nonlinearities and tipping points (RFC5), including ice sheet collapse and ecosystem regime shifts.

1.3.1.2 The Complexities of Climate Risk

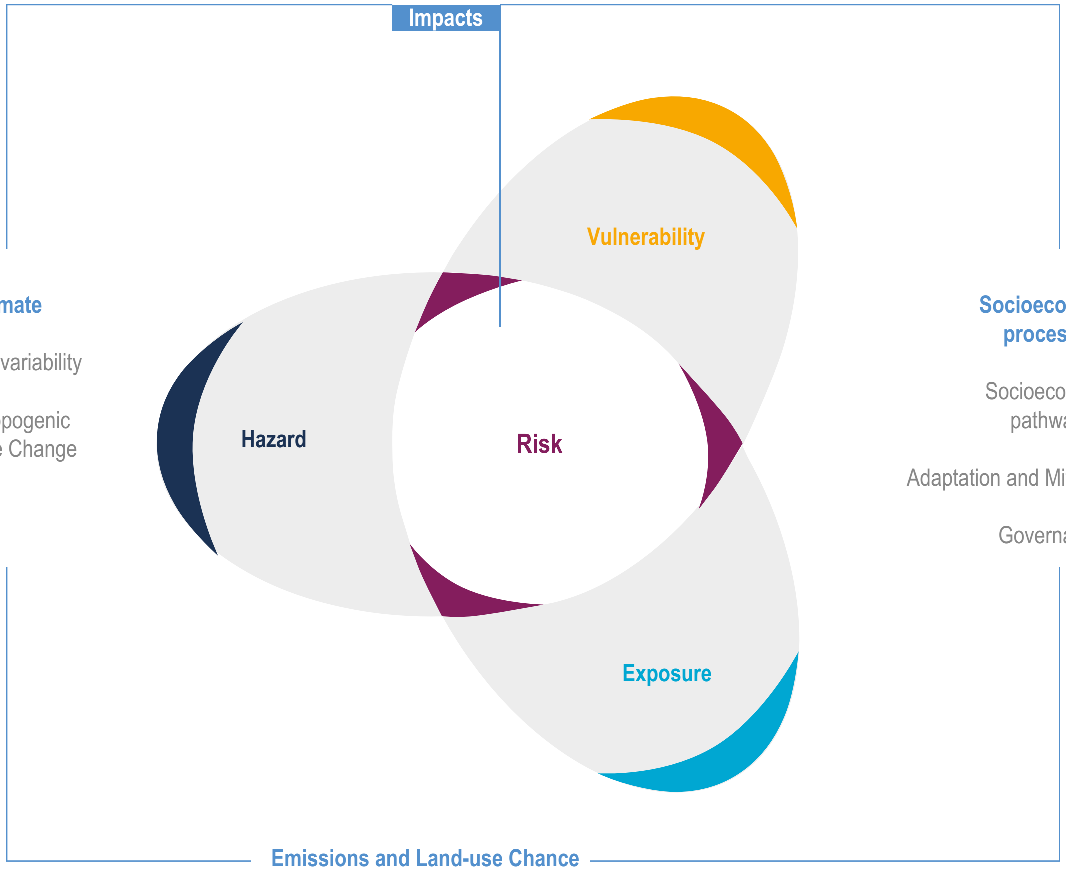
The AR6 assessment incorporates the inherently complex nature of climate risk, vulnerability, exposure and impacts, which include feedbacks, cascades, non-linear behaviour and the potential for surprise (Figures 1.3; 1.4). Many different overlapping and complementary terms and methods are used to evaluate and understand complex climate risk relevant to this report, such as aggregated, compounding or cascading risks, all of which are considered here as relevant to complex climate risk (Pescaroli and Alexander, 2018; Simpson et. al. 2021).

The dynamic nature of risk and its determinants is one important dimension of complexity. The risk of climate change impacts can be usefully understood as resulting from dynamic interactions among climate-related hazards, the exposure and vulnerability of affected human and ecological systems, and also responses (see Section 1.2.1; AR6 Glossary, IPCC, 2021b; WGI AR6 Cross-Chapter Box 2 in Chapter 1, Chen et al., 2021; Oppenheimer et al., 2014). The determinants of risk all can vary and change through space and time in response to socioeconomic development and decision making (Figures 1.4; 1.5; Section 16.1). Hazards are affected by current and future changes in climate, including altered climate variability and shifts in frequency and intensity of extreme events (WGI AR6 Chapter 12, Ranasinghe et al., 2021). Such hazards can be sudden, for example, a heat wave or heavy rain event, or slower onset, for example, land loss, degradation and erosion linked to multiple climate hazards compounding. The severity of climate change impacts will depend strongly on vulnerability, which is also dynamic and includes the sensitivity and adaptive capacity of affected human and ecological systems (McDowell et al., 2016; Jurgilevich et al., 2017; Ford et al., 2018; Viner et al., 2020). As a result, risks vary at fine scale across communities and societies and also among people within societies, depending, for example, on intersecting inequalities and context-specific factors such as culture, gender, religion, ability and disability, or ethnicity (Kuruppu, 2009; Jones and Boyd, 2011; Carr and Thompson, 2014; also Section 16.1.4). The dynamic social distribution of impacts is the subject of increasing attention within climate assessment and responses, including the role of adaptation, iterative risk management and climate resilient sustainable development (Section 16.1).

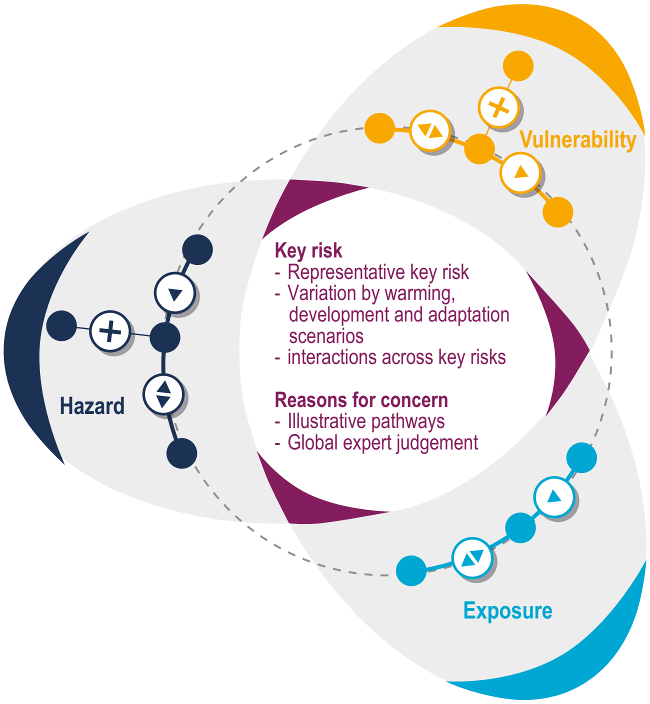
Another core area of complexity in climate risk is the behaviour of complex systems, which includes multiple stressors unfolding together, cascading or compounding interactions, and non-linear responses and the potential for surprises (Kopp et al., 2017; Clarke et al., 2018; Yokohata et al., 2019). Risks and responses, including their determinants, can all interact dynamically in shaping the complexity of climate risk (Figure 1.4). The combined effects of multiple stressors or compound hazards and risks are unlikely to be assessed through

Risk in IPCC assessment through time

(a) The AR5 risk graphic



(b) AR6 additions: response risk and complexity



(c) Future directions: response risks related to adaptation and mitigation

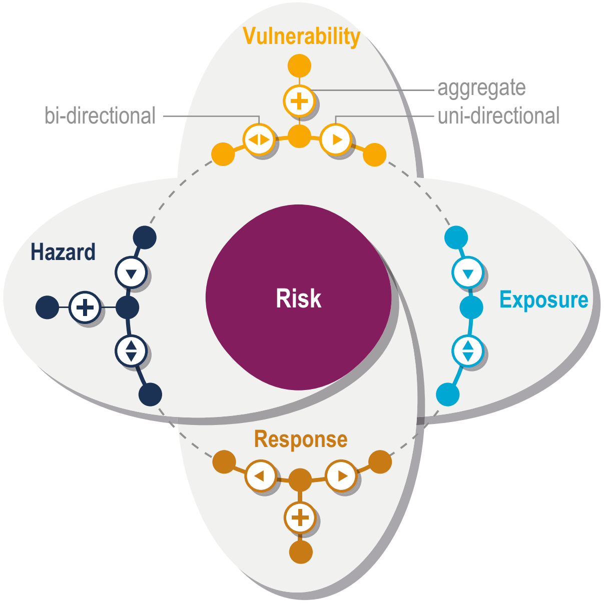


Figure 1.5 | Risk in IPCC assessment through time. (a) An explicit risk framing emerged in the IPCC Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation (SREX) and WGII AR5 (IPCC, 2014a, b). **(b)** In the current assessment, the role of responses in modulating the determinants of risk is a new emphasis (the 'wings' of the hazard, vulnerability, and exposure 'propellers' represents the ways in which responses modulate each of these risk determinants). **(c)** As the risk assessment spans Working Groups, the differential role of risk determinants for risk related to impacts, adaptation, and vulnerability versus risk related to mitigation becomes an increasingly important feature of climate risk assessment as well as management.

simple addition of the independent effects and instead require system approaches to understanding risk. While some components may cancel each other out, others may nonlinearly increase risk. Nonlinearities can result from abrupt climate changes, tipping points or thresholds in responses, alternative stable states, low-probability/high-consequence outcomes or events that cannot be predicted based on current understanding (WGI Section 1.4.4.3).

The nature of climate risk also involves risks from responses themselves (Figure 1.5c). The risks of climate change responses include the possibility of responses not achieving their intended objectives or having trade-offs or adverse side effects for other societal objectives (Annex II: Glossary; Section 16.1). In particular, human responses may create novel hazards and unexpected side effects and entail opportunity costs and path dependencies (Boonstra, 2016). Such feedback loops can unfold at local and global scales, including large-scale interactions among climate, ecological and human systems with human behaviour and decision making affecting such interactions. Response risks can originate from uncertainty in implementation, maladaptation, action effectiveness, technology development or adoption, or transitions in systems (see Sections 1.4 and 1.5). Typical risks may be related to regulation, litigation, competition, sociopolitics or reputation. Interactions across responses can importantly involve co-benefits for other objectives, such as for human health and well-being which may be improved from both reduced air pollution (e.g., AR6 WGI Chapter 6, Szope et al., 2021; WGIII, IPCC, 2022) and enhanced adaptation to climate change. The nature of risk also entails residual impacts that will occur even with ambitious societal responses, given limits to adaptation at sectoral and regional levels (Section 1.4, 16.1, 16.4). In some cases, the losses will be irreversible.

Due to these complexities, the challenge of assessing risks of climate change is not well bounded, will be framed differently by individuals and groups, involves large and deep uncertainties, and will have unclear solutions and pathways to solutions (Rittel and Webber, 1973; Renn, 2008; see also Sections 1.5.2; 17.2.1). Challenges also include the degree to which time is running out, there is no central authority, those seeking the solutions are also causing the problem, and the present is favoured over the future (Sun and Yang, 2016; see also Section 17.2.1). Both the needs for and the limits to adaptation responses fundamentally depend on progress achieved in reducing GHG emissions and limiting the magnitude of climate change that occurs, interlinked with socioeconomic development trajectories and the many social and political factors shaping climate risks and responses.

1.3.2 Assessing, Evaluating, and Understanding Climate Impacts and Risks

Multiple, diverse sources of information underlie our understanding of climate risks and response, including climate change science, diverse social sciences and IK and LK.

1.3.2.1 Detection and Attribution of Climate Change and its Impacts

Anthropogenic climate change is unequivocal and ongoing. The detection of specific changes in the climate and their diverse impacts on people and nature is advancing, with robust attribution of climate change to GHG emissions as well as to other contributing factors (e.g., socioeconomic development, land use change). In the AR6, advances include an increasing ability to link individual extreme weather and climate events to emissions of GHGs, increasing identification of impacts for societies and economies and strong linkages in the attribution methods across Working Groups (Cross-Working Group Box: ATTRIBUTION in Chapter 1).

Impacts occurring today can be put into context through understanding of long-term changes on Earth, introduced in Cross-Chapter Box PALEO in Chapter 1. Climate has always varied and changed in the past, and this change often caused substantial ecological, evolutionary and socioeconomic impacts. Adaptation of ecosystems and societies occurred through responses as diverse as migration to mass extinction. Humankind is at the verge of leaving the Holocene climatic envelope, in which all human achievement since the advent of agriculture has occurred. In some systems, the changes and losses will be irreversible.

1.3.2.2 Perceiving Climate Risk and Human Response

Since AR5, social science literature on how individuals and societies perceive and respond to climate risk has advanced dramatically (Renn, 2008; Jones et al., 2014; Taylor et al., 2014; Neaves and Royer, 2017; Van Valkengoed and Steg, 2019). The literature is increasingly integrating and advancing long-standing scholarship on environmental and social governance, human dimensions of environmental change, risk perception and communication, and enabling conditions for effective policymaking. These emergent literatures on climate risk, human action and solution are reflected in three broad areas of analysis: (a) root drivers (i.e., role of cultural norms and social practice, social structures and economic development status that shape physical and social vulnerability; (b) context-specific barriers and enablers (i.e., governance structures, institutional structure and function, risk perceptions, access to financing and knowledge availability and needs) and (c) the solution-proximate decision space (i.e., climate urgency and catalysing conditions, risk communication strategies, M&E strategies) (see Solecki et al., 2017; Jorgenson et al., 2019).

These three areas are deeply embedded in the social sciences and reflect fundamental questions of how and why humans and their institutions act and respond (Chapter 17). In the past two decades, these basic issues have been applied to research of climate change, dynamic risk and adaptation. Underlying this analysis, particularly of root drivers, barriers and enablers, are assertions regarding the foundational properties of individual and collective behaviour (i.e., self-interest, optimisation, rationality, bounded rationality), how they are structured and how these properties can be revealed. This literature draws on several academic disciplines, including anthropology, economics, geography, political science, psychology, sociology and urban studies. Climate change social science research is often interdisciplinary or transdisciplinary and hence utilises a variety of methods to derive new knowledge (Orlove et al., 2020).

In contrast to previous assessments, AR6 is increasingly focused on the needs for and challenges of assessing the societal response to climate change. The accurate tabulation of adaptation, a key question for examining the solution space, is difficult (Chapter 16; Cross-Chapter Box ADAPT in Chapter 1), since many forms of adaptation activity are under-represented in the peer-reviewed and grey literature. Moreover, the related question of assessing the effectiveness of adaptation, that is, the extent to which it reduces risk, is also difficult. Estimating risk reduction often involves counterfactuals, for instance, quantifying the damage a flood would have caused had a community not adapted prior to a storm or projecting the damage averted by today's adaptation in some future storm (see Cross-Chapter Box PROGRESS in Chapter 17). Many socioeconomic drivers affect risk, so attribution for any observed or projected changes must be allocated among those that are due to adaptation and those due to economic development, cultural changes and other types of policies and trends. For instance, many measures of sustainable development overlap with those for adaptive capacity and both can reduce climate risk while also yielding benefits irrespective of future climate regimes (UNEP, 2018). There are also many different goals for adaptation both among and within different jurisdictions, so that adaptation efforts deemed effective by some individuals may not be deemed effective by others (Dilling et al., 2019).

1.3.2.3 Indigenous Knowledge and Local Knowledge

While scientific knowledge is vital, IK and LK are also necessary for understanding and acting effectively on climate risk (IPCC, 2014a; IPCC, 2019b, SROCC Chapter 1; see also Section 2.4). **Indigenous knowledge** refers to the understandings, skills and philosophies developed by societies with long histories of interaction with their natural surroundings (IPCC, 2019a). **Local knowledge** is defined as the understandings and skills developed by individuals and populations, specific to the places where they live (IPCC, 2019a). These definitions relate to the debates on the world's cultural diversity (UNESCO, 2018a), which are increasingly connected to climate change debates (UNESCO, 2018b). However, there is agreement that, in the same way that there is not a unique definition of Indigenous Peoples because it depends on self-determination (see below), there is not a single definition of neither IK and LK. Therefore, contextualisation is greatly needed. IK and LK will shape perceptions which are vital to managing climate risk in day-to-day activities and longer-term actions.

Such experience-based and practical knowledge is obtained over generations through observing and working directly within various environments. Knowledge may be place based and rooted in local cultures, especially when it reflects the beliefs of long-settled communities who have strong ties to their natural environments (Orlove et al., 2010). Other times, knowledge may be embedded in institutions or oral traditions that mobilise them across contexts, for example, as migrant populations bring their knowledge across different regions, and have global relevance. Scientific insights often confirm IK and LK (Ignatowski and Rosales, 2013), but IK and LK also provides specific, alternative ways to understand environmental change. This includes tacit and embodied aspects of knowledge (Mellegård and Boonstra,

2020) that may be crucial to foster local action and that are not easily captured in scientific knowledge (including cultural indicators, scales and interconnectedness between ecosystems). Multiple knowledge systems (i.e. IK, LK, disciplinary knowledge, technical expertise) may coevolve in iterative and interactive processes whereby they influence each other. However, at the same time, they may have specific characteristics so that they cannot be reduced to each other or subsumed by each other, and they all have relevance to understanding the interactions between society and climate (Bremer et al., 2019).

Cross-Working Group Box ATTRIBUTION | Attribution in the IPCC Sixth Assessment Report

Authors: Pandora Hope (Australia), Wolfgang Cramer (France/Germany), Maarten van Aalst (Netherlands), Greg Flato (Canada), Katja Frieler (Germany), Nathan Gillett (Canada/UK), Christian Huggel (Switzerland), Jan Minx (Germany), Friederike Otto (UK /Germany), Camille Parmesan (France/ UK /USA), Joeri Rogelj (UK /Belgium), Maisa Rojas (Chile), Sonia I. Seneviratne (Switzerland), Aimee Slangen (the Netherlands), Daithi Stone (New Zealand), Laurent Terray (France), Robert Vautard (France), Xuebin Zhang (Canada)

Introduction

Changes in the climate system are becoming increasingly apparent, as are the climate-related impacts on natural and human systems. Attribution is the process of evaluating the contribution of one or more causal factors to such observed changes or events. Typical questions addressed by the IPCC are, for example: 'To what degree is an observed change in global temperature induced by anthropogenic GHG and aerosol concentration changes or influenced by natural variability?' or 'What is the contribution of climate change to observed changes in crop yields that are also influenced by changes in agricultural management?' Changes in the occurrence and intensity of extreme events can also be attributed, addressing questions such as: 'Have human GHG emissions increased the likelihood or intensity of an observed heat wave?'

This Cross-Working Group Box briefly describes why attribution studies are important. It also describes some new developments in the methods used and provides recommendations for interpretation.

Attribution studies serve to evaluate and communicate linkages associated with climate change, for example: between the human-induced increase in GHG concentrations and the observed increase in air temperature or extreme weather events (WGI Chapters 3, 10 and 11); or between observed changes in climate and changing species distributions and food production (e.g., Verschuur et al., 2021; WGII Chapter 2 and others, summarised in Chapter 16) or between climate change mitigation policies and atmospheric GHG concentrations (WGI Chapter 5; WGIII Chapter 14). As such, they support numerous statements made by the IPCC (IPCC, 2013; IPCC, 2014c; WGI Section 1.3, Appendix 1A).

Attribution assessments can also serve to monitor mitigation and assess the efficacy of applied climate protection policies (e.g., Nauels et al., 2019; Banerjee et al., 2020; WGI Section 4.6.3), inform and constrain projections (Gillett et al., 2021; Ribes et al., 2021; WGI Section 4.2.3) or inform loss and damages estimates and potential climate litigation cases by estimating the costs of climate change (Huggel et al., 2015; Marjanac et al., 2017; Frame et al., 2020). These findings can thus inform mitigation decisions, as well as risk management and adaptation planning (e.g., Climate & Development Knowledge Network, 2017).

Steps towards an attribution assessment

The unambiguous framing of what is being attributed to what is a crucial first step for an assessment (Easterling et al., 2016; Hansen et al., 2016; Stone et al., 2021), followed by the identification of the possible and plausible drivers of change and the development of a hypothesis or theory for the linkage (see Figure ATTRIBUTION.1 in Chapter 1). The next step is to clearly define the indicators of the observed change or event and note the quality of the observations. There has been significant progress in the compilation of fragmented and distributed observational data, broadening and deepening the data basis for attribution research (Poloczanska et al., 2013; Ray et al., 2015; Cohen et al., 2018; WGI Section 1.5). The quality of the observational record of drivers should also be considered (e.g., volcanic eruptions: WGI Section 2.2.2). Impacted systems also change in the absence of climate change. This baseline and its associated modifiers such as agricultural developments or population growth need to be considered, alongside the exposure and vulnerability of people depending on these systems.

There are many attribution approaches, and several methods are detailed below. In physical and biological systems, attribution often builds on the understanding of the mechanisms behind the observed changes and numerical models are used, while in human systems other methods of evidence-building are employed. Confidence in the attribution can be increased if more than one approach is used and the model is evaluated as fit for purpose (Hegerl et al., 2010; Vautard et al., 2019; Otto et al., 2020a; Philip et al., 2020; WGI Section 1.5). Finally, appropriate communication of the attribution assessment and the accompanying confidence in the result is needed (e.g., Lewis et al., 2019).

Cross-Working Group Box (continued)

Attribution methods

Attribution of changes in atmospheric GHG concentrations to anthropogenic activity

AR6 WGI Chapter 5 (Canadell et al., 2021) presents multiple lines of evidence that unequivocally establish the dominant role of human activities in the growth of atmospheric CO_2, including through analysing changes in atmospheric carbon isotope ratios and the atmospheric O_2:N_2 ratio (WGI Section 5.2.1.1, Canadell et al., 2021). Decomposition approaches can be used to attribute emissions underlying those changes to various drivers such as population, energy efficiency, consumption or carbon intensity (Hoekstra and van den Bergh, 2003; Raupach et al., 2007; Rosa and Dietz, 2012). Combined with attribution of their climate outcomes, the attribution of the sources of GHG emissions can inform the attribution of anthropogenic climate change to specific countries or actors (Matthews, 2016; Otto et al., 2017; Skeie et al., 2017; Nauels et al., 2019) and, in turn, inform discussions on fairness and burden sharing (WGIII Chapter 14).

Attribution of observed climate change to anthropogenic forcing

Changes in large-scale climate variables (e.g., global mean temperature) have been reliably attributed to anthropogenic and natural forcings (e.g., Hegerl et al., 2010; Bindoff and et al., 2014; WGI Section 1.3.4). The most established method is to identify the 'fingerprint' of the expected space–time response to a particular climate forcing agent such as the concentration of anthropogenically induced GHGs or aerosols, or natural variation of solar radiation. This technique disentangles the contribution of individual forcing agents to an observed change (e.g., Gillett et al., 2021). New statistical approaches have been applied to better account for internal climate variability and the uncertainties in models and observations (e.g., Naveau et al., 2018; Santer et al., 2019; WGI Section 3.2). There are many other approaches, for example, global mean sea level change has been attributed to anthropogenic climate forcing by attributing the individual contributions from, for example, glacier melt or thermal expansion, while also examining which aspects of the observed change are inconsistent with internal variability (WGI Sections 3.5.2; 9.6.1.4).

Specific regional conditions and responses may simplify or complicate attribution on those scales. For example, some human forcings, such as regional land use change or aerosols, may enhance or reduce regional signals of change (Lejeune et al., 2018; Undorf et al., 2018; Boé et al., 2020; Thiery et al., 2020; see also WGI Sections 10.4.2; 11.1.6; 11.2.2). In general, regional climate variations are larger than the variations in global mean climate, adding additional uncertainty to attribution (e.g., in regional sea level change, WGI Section 9.6.1). These statistical limitations may be reduced by 'process-based attribution', focusing on the physical processes known to influence the response to external forcing and internal variability (WGI Section 10.4.2).

Attribution of weather and climate events to anthropogenic forcing

New methods have emerged since AR5 to attribute the change in likelihood or characteristics of weather or climate events or classes of events to underlying drivers (National Academies of Sciences, 2016; Stott et al., 2016; Jézéquel et al., 2018; Wehner et al., 2019; Wang et al., 2020; WGI Sections 10.4.1; 11.2.2). Typically, historical changes, simulated under observed forcings, are compared to a counterfactual climate simulated in the absence of anthropogenic forcing. Another approach examines facets of the weather and thermodynamic status of an event through process-based attribution (Hauser et al., 2016; Shepherd et al., 2018; Grose et al., 2020; WGI Section 10.4.1; WGI Chapter 11). Events where attributable human influences have been found include hot and cold temperature extremes (including some with widespread impacts), heavy precipitation, and certain types of droughts and tropical cyclones (e.g., Vogel et al., 2019; Herring et al., 2021; WGI Section 11.9). Event attribution techniques have sometimes been extended to 'end-to-end' assessments from climate forcing to the impacts of events on natural or human systems (Otto et al., 2017; examples in Table 16.1; Section 16.2).

Attribution of observed changes in natural or human systems to climate-related drivers

The attribution of observed changes to climate-related drivers across a diverse set of sectors, regions and systems is part of each chapter in the WGII contribution to the AR6 and is synthesised in WGII Chapter 16 (Section 16.2). The number of attribution studies on climate change impacts has grown substantially since AR5, generally leading to higher confidence levels in attributing the causes of specific impacts. New studies include the attribution of changes in socioeconomic indicators, such as economic damages due to river floods (e.g., Schaller et al., 2016; Sauer et al., 2021), the occurrence of heat-related human mortality (e.g., Vicedo-Cabrera et al., 2018; Sera et al., 2020) or economic inequality (e.g., Diffenbaugh and Burke, 2019).

Cross-Working Group Box (continued)

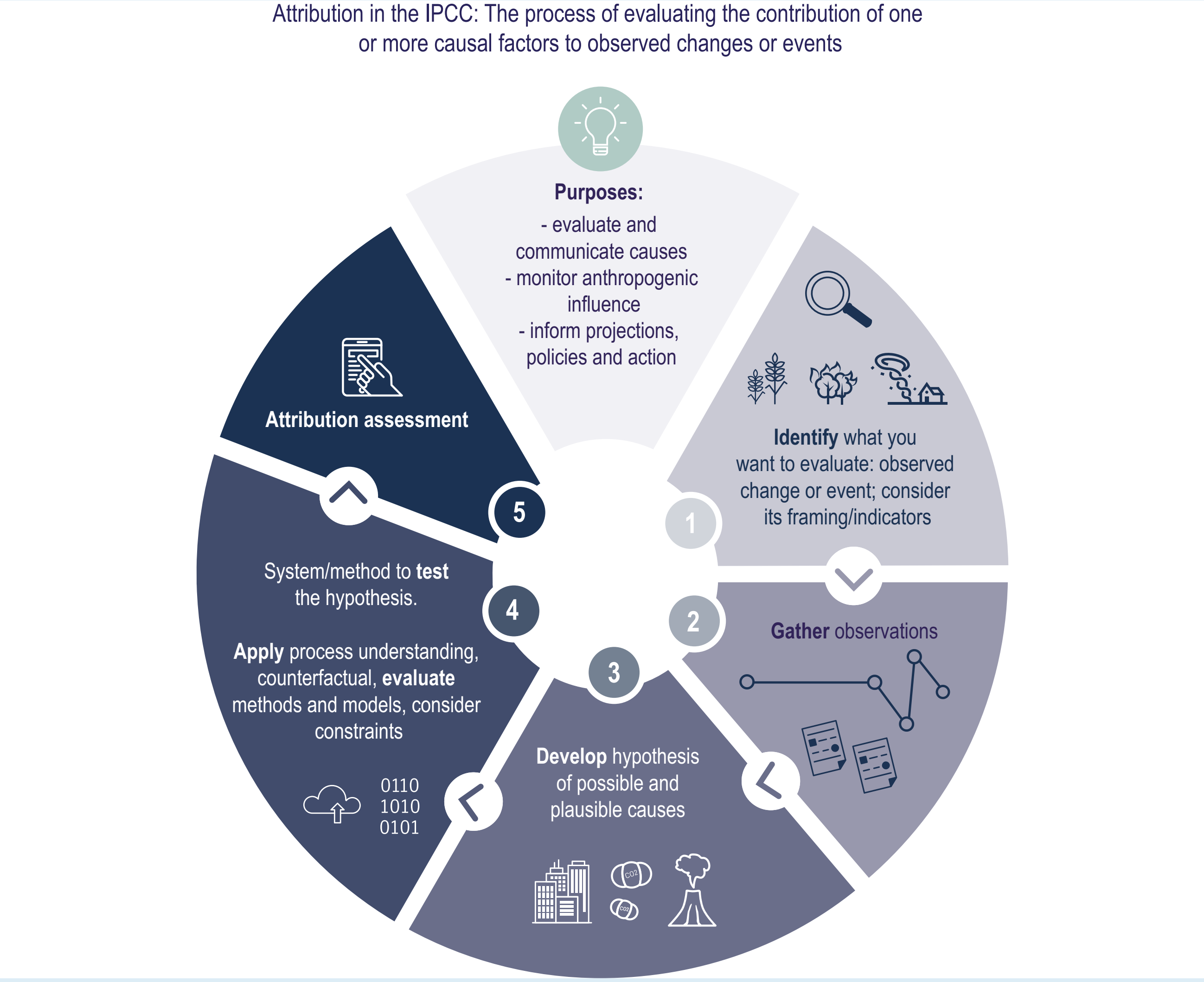


Figure Cross-Working Group Box ATTRIBUTION.1 | Schematic of the steps to develop an attribution assessment, and the purposes of such assessments. Methods and systems used to test the attribution hypothesis or theory include model-based fingerprinting, other model-based methods, evidence-based fingerprinting, process-based approaches, empirical or decomposition methods and the use of multiple lines of evidence. Many of the methods are based on the comparison of the observed state of a system to a hypothetical counterfactual world that does not include the driver of interest to help estimate the causes of the observed response.

Impact attribution covers a diverse set of qualitative and quantitative approaches, building on experimental approaches, observations from remote sensing, long-term *in situ* observations and monitoring efforts, teamed with LK, process understanding and empirical or dynamical modelling (Section 16.2; Stone et al., 2013; Cramer et al., 2014). The attribution of a change in a natural or human system (e.g., wild species, natural ecosystems, crop yields, economic development, infrastructure or human health) to changes in climate-related systems (i.e., climate and ocean acidification, permafrost thawing or sea level rise) requires accounting for other potential drivers of change, such as technological and economic changes in agriculture affecting crop production (Hochman et al., 2017; Butler et al., 2018), changes in human population patterns and vulnerability affecting flood or wildfire induced damages (Huggel et al., 2015; Sauer et al., 2021), or habitat loss driving declines in wild species (IPBES, 2019b). These drivers are accounted for by estimating a baseline condition that would exist in the absence of climate change. The baseline might be stationary and be approximated by observations from the past, or it may change over time and be simulated by statistical or process-based impact models (Section 16.2; Cramer et al., 2014). Assessment of multiple independent lines of evidence, taken together, can provide rigorous attribution when more quantitative approaches are not available (Parmesan et al., 2013). These include palaeodata, physiological and ecological experiments, natural 'experiments' from very long-term datasets indicating consistent responses to the same climate trend/event and 'fingerprints' in species' responses that are uniquely expected from climate change (e.g., poleward range boundaries expanding and equatorial range boundaries contracting in a coherent pattern worldwide, Parmesan and Yohe, 2003). Meta-analyses of species/ecosystem responses, when conducted with wide geographic coverage, also provide a globally coherent signal of climate change at an appropriate scale for attribution to anthropogenic climate change (Parmesan and Yohe, 2003; Parmesan et al., 2013).

Cross-Working Group Box (continued)

Impact attribution does not always involve attribution to anthropogenic climate forcing. However, a growing number of studies include this aspect (e.g., Diffenbaugh and Burke, 2019, for the attribution of economic inequality between countries; Frame et al., 2020, for the attribution of damages induced by Hurricane Harvey; or Schaller et al., 2016, for flood damages).

Cross-Chapter Box PALEO | Vulnerability and Adaptation to Past Climate Changes

Authors: Wolfgang Kiessling (Germany, Chapter 3, Cross-Chapter Paper 1), Timothy A. Kohler (USA, Chapter 14), Wolfgang Cramer (France, Chapter 1, Cross-Chapter Paper 4), Gusti Anshari (Indonesia, Chapter 2), Jo Skeie Hermansen (Norway, CA Chapter 1), Darrell S. Kaufman (USA, WG 1, Chapter 2), Guy Midgley (South Africa, Chapter 16), Nussaïbah Raja (Mauritius, CA Chapter 3), Daniela N. Schmidt (UK/Germany, Chapter 13), Nils Chr. Stenseth (Norway, Chapter 1), Sukumar Raman (India, Chapter 1)

Understanding how Earth's biota have responded to past climate dynamics is essential to understanding current and future climate-related risks, as well as the adaptive capacity and vulnerabilities of ecosystems and the human livelihoods depending on them. Here we assess climate impacts on long geological time scales (Cross-Chapter Box PALEO in Chapter 1, Figure PALEO.1), as well as for the last 70 kyr of *Homo sapiens*' existence (Cross-Chapter Box PALEO in Chapter 1, Figure PALEO.2). Climate responses of natural and human systems are intertwined through the physiological limits of wild animals, livestock, plants and humans, subject to a slow evolutionary dynamic (Pörtner, 2021; Sections 2.6.1; 3.3).

Climate has always changed, often with severe effects on nature, including species loss

Observations provided by the historical, archaeological, and palaeontological records, together with paleoclimatic data, demonstrate that climatic variability has high potential to affect biodiversity and human society (*high confidence*). The evolution of the Earth's biota has been punctuated by global biodiversity crises often triggered by rapid warming (*high confidence*) (Figure PALEO.1; Bond and Grasby, 2017; Benton, 2018; Foster et al., 2018;). These so-called hyperthermal events were marked by rapid warming of >1°C, which coincided with global disturbances of the carbon and water cycles, and by reduced oxygen and pH in seawater (Foster et al., 2018; Clapham and Renne, 2019). Magnitudes of global temperature shifts in hyperthermal events were sometimes greater than those predicted for the current century but extended over longer periods of time. Rates inferred from paleo records that are coarsely resolved are inevitably lower than those from direct observations during recent decades, and caution must be exercised when describing the rate of recent temperature changes as unprecedented (Kemp et al., 2015). Mass extinctions, each with greater than 70% marine species extinctions, occurred when the magnitude of temperature change exceeded 5.2°C (Song et al., 2021), albeit species extinctions occurred at lower magnitudes of warming (*medium confidence*).

Adaptation options to rapid climate change are limited

Responses of biota to rapid climate change have included range shifts (*very high confidence*), phenotypic plasticity (*high confidence*), evolutionary adaptation (*medium confidence*), and species extinctions, including mass extinctions (*very high confidence*). While knowledge about the relative roles of these processes in promoting survival during times of climate change is still limited (Nogués-Bravo et al., 2018), they have influenced the evolutionary trajectories of species and entire ecosystems (*high confidence*), and also the course of human history (*medium confidence*). The combined ecological and evolutionary responses to ancient rapid warming events ranged from extinction of 81% of marine animal species and 70% of terrestrial tetrapod species on land at the end of the Permian period (~ 252 million years ago, Ma) (Smith and Botha, 2005; Stanley, 2016) to low rates of species extinctions but biome- and range shifts on land and in the ocean at the Palaeocene-Eocene Thermal Maximum (PETM, ~ 56 Ma) (Figure PALEO.1; Ivany et al., 2018; Fraser and Lyons, 2020; Huurdeman et al., 2021). Temperature and deoxygenation were key drivers of past biotic responses in the oceans (Gibbs et al., 2016; Penn et al., 2018; Section 3.3) (*high confidence*), whereas on land the interplay between temperature and precipitation is less well established in ancient hyperthermals (Frank et al., 2021) (*medium confidence*). Climate-driven extinction risk increased by up to 40% when a short-term climate change added to a long-term trend in the same direction, for example when a long-term warming trend was followed by rapid warming (Mathes et al., 2021).

Cross-Chapter Box PALEO (continued)

Organismic traits associated with extinctions during ancient climate changes help identify present-day vulnerabilities and conservation priorities (Barnosky et al., 2017; Calosi et al., 2019; Reddin et al., 2020; Chapters 2; 3; Cross-Chapter Paper 1). Marine invertebrates and fishes are at greater extinction risk in response to warming than terrestrial ones because of reduced availability of thermal refugia in the sea (Pinsky et al., 2019) (*high confidence*). Terrestrial plants showed reduced extinction during past rapid warming compared to animals (*high confidence*), although they readily adjusted their ranges and reorganised vegetation types (Yu et al., 2015; Lindström, 2016; Heimhofer et al., 2018; Slater et al., 2019; Huurdeman et al., 2021).

Population range shifts including migrations are common adaptations to climate changes across multiple time scales and ecological systems in the past and in response to current warming (*high confidence*). Poleward expansions and retractions (Reddin et al., 2018; Williams et al., 2018; Fordham et al., 2020) as well as migration upslope and downslope in response to warming and cooling were common adaptations (Ortega-Rosas et al., 2008; Iglesias et al., 2018;). During warming periods, diversity loss was common near the equator (*medium confidence*)(Kiessling et al., 2012; Kröger, 2017; Yasuhara et al., 2020), while diversity gains and forest expansion occurred in high latitudes (Brovkin et al., 2021). Comparison of contemporary shells and skeletons with historical collections in museums (Barnes et al., 2011) and the analysis of skeletons of long-lived organisms (Cantin et al., 2010) indicate significant climate-induced change in organismic growth rates today (*high agreement, medium confidence*).

Humankind has responded to regional climate variability within a narrow Holocene climatic envelope

Early human evolution (beginning ~2.1 Ma) occurred in a highly variable climate characterised by glacial-interglacial cycles. This variability may have favoured key hominin adaptations such as bipedality, increased brain size, complex sociality, and more diverse tools (Potts, 1998; Potts et al., 2020) (*medium confidence*), but extinctions of five species of *Homo* have also been attributed partly to climate change (Raia et al., 2020) (*low confidence*). The 'out-of-Africa' dispersal of anatomically modern humans may have been driven by climate variability (Timmermann and Friedrich, 2016; Tierney et al., 2017) (*medium confidence, low agreement*). Most late Pleistocene megafaunal extinctions are attributed to direct and indirect human impacts (Sandom et al., 2014), although some were likely accelerated by climate change (Wan and Zhang, 2017; Westaway et al., 2017; Carotenuto et al., 2018; Saltré et al., 2019) (*low confidence*).

The emergence of agriculture (~10.2 ka) in southwest Asia was associated with stable (within ±1°C global mean annual on multi-century time scale; WGI Chapter 2) warm and moist conditions (Richerson et al., 2001; Rohling et al., 2019; Palmisano et al., 2021). Variability in resource availability and agricultural production, entrained by climatic variability, is implicated in the disruption and decline of numerous past human societies (*medium confidence*) (d'Alpoim Guedes and Bocinsky, 2018; Cookson et al., 2019; Jones, 2019; Park et al., 2019). These crises are partially caused by regional climate anomalies including Holocene 'Rapid Climate Change Events' (Rohling et al., 2019) not visible in the globally averaged conditions shown in Figure PALAEO.2. Such anomalies affected human population size (Clark et al., 2019; Kuil et al., 2019; Riris and Arroyo-Kalin, 2019), health (Campbell and Ludlow, 2020) and social stability/conflict (Büntgen et al., 2011; Kohler et al., 2014), and triggered migrations (D'Andrea et al., 2011; Schwindt et al., 2016; Chiotis, 2018; Pei et al., 2018) or retarded them (Betti et al., 2020; FAQ 14.2). Populations have also been impacted by sea level change in coastal areas (Turney and Brown, 2007; Cross-Chapter Box SLR in Chapter 3).

Evidence for widespread droughts ~4.2 ka, lasting for several centuries in some regions, has been tentatively linked to declines of the Akkadian Empire (Weiss, 2017; Carolin et al., 2019), the Indus Valley (Giosan et al., 2018; Sengupta et al., 2020), and the Egyptian Old Kingdom and Yangtze River Valley (Ran and Chen, 2019). Deteriorating climates often exacerbate accumulating weaknesses in social systems to which population growth and urban expansion contribute (Knapp and Manning, 2016; Lawrence et al., 2021; Scheffer et al., 2021). The rather narrow climatic niche favoured by human societies over the last 6000 years is poised to move on the Earth's surface at speeds unprecedented in this time span (IPCC, 2021a), with consequences for human well-being and migration that could be profound under high-emission scenarios (Xu et al., 2020). This will overturn the long-lasting stability of interactions between humans and domesticated plants and animals as well as challenge the habitability for humans in several world regions (Horton et al., 2021) (*medium confidence*).

Cross-Chapter Box PALEO (continued)

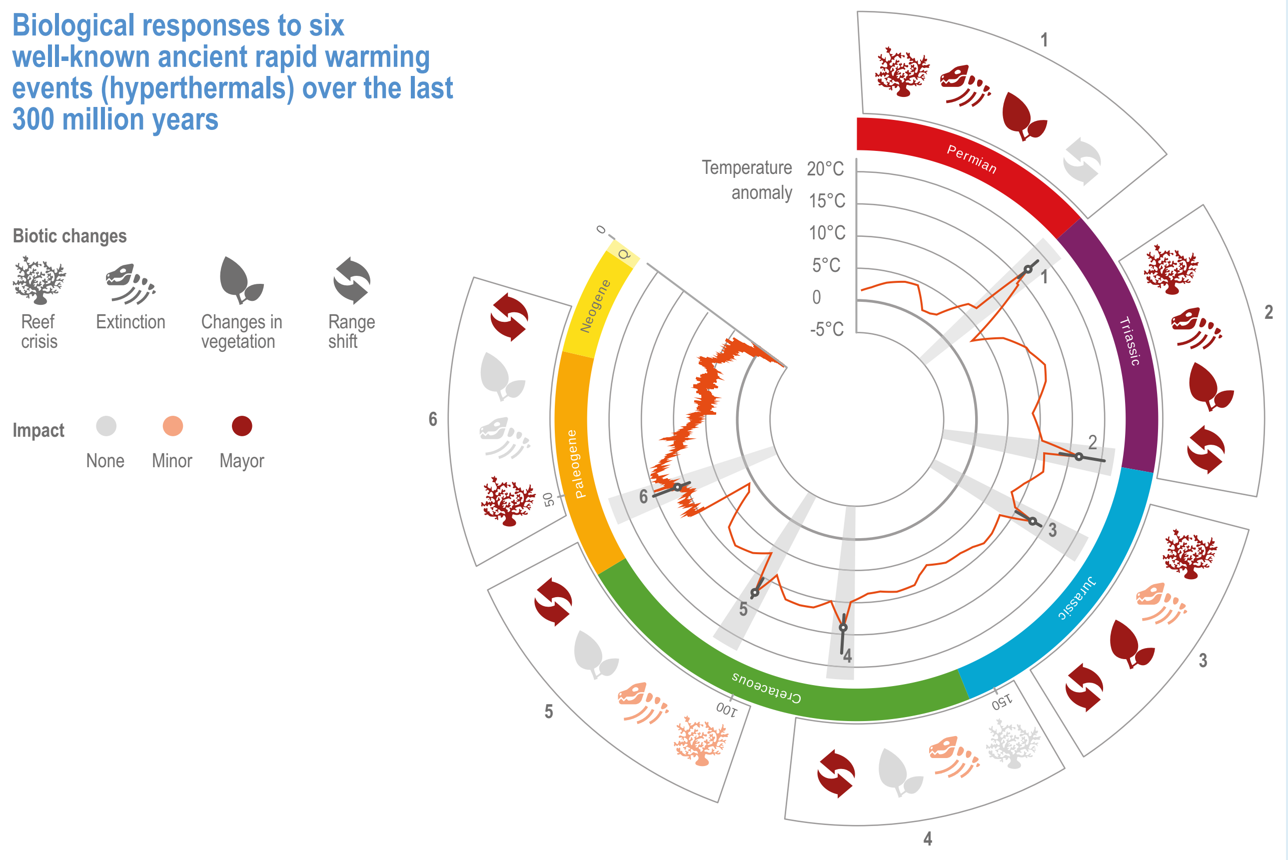


Figure Cross-Chapter Box PALEO.1 | Biological responses to six well-known ancient rapid warming events (hyperthermals) over the last 300 million years. Temperature anomalies (mean temperature difference to pre-industrial 1850–1900, solid orange curve) derived from climate modelling (300–66 Ma) (Haywood et al., 2019) and deep-sea proxy data (66–0.1 Ma) (Hansen et al., 2013). Temperature peaks underneath the grey bars indicate well-known hyperthermals with temperature anomalies derived from temperature-sensitive proxy data (Foster et al., 2018). Error bars indicate uncertainties in peak warming events (ranges in the literature). Insets show observed impacts to the biosphere. Q, Quaternary.

Climate change destroys unique natural archives and important cultural heritage sites

Climate change not only impacts past ecosystems and societies but also the remains they have left. The progressive loss of archaeological and historical sites and natural archives of paleo environmental data (WGI Chapter 2) constitutes often-overlooked impacts of climate change (Cross-Chapter Box SLR in Chapter 3; Anderson et al., 2017; Hollesen et al., 2018; Climate Change Cultural Heritage Working Group International, 2019). These archives include peat bogs and coastal archives lost to sea level rise, droughts and fires, degradation through permafrost thaw, and dissolution. The ancient cultural diversity documented by such sites is an important resource for future adaptation (Rockman and Hritz, 2020; Burke et al., 2021). Since many of these sites constitute anchors for IK, their loss is not just data lost to science, it also interrupts intergenerational transmission of knowledge (Green et al., 2009).

Cross-Chapter Box PALEO (continued)

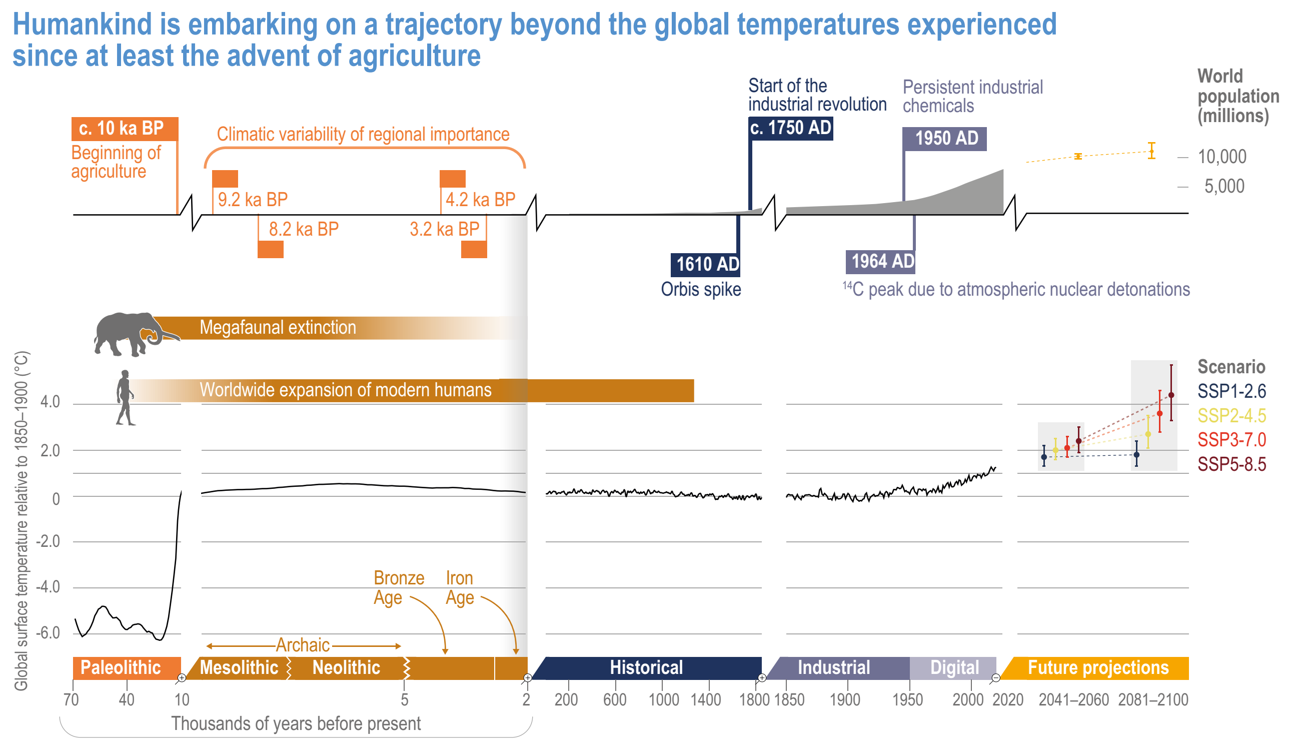


Figure Cross-Chapter Box PALEO.2 | Humankind is embarking on a trajectory beyond the global temperatures experienced since at least the advent of agriculture. Global surface temperature change for the last 70,000 years (relative to 1850–1900; data from WGI Chapter 2) alongside projections (with 5–95% range; WGI Chapter 4) and major events in human societies. Global climatic parameters do not always capture regional variability of importance to specific societies. The 'Orbis Spike' represents a pronounced dip in atmospheric CO_2 from the Law Dome ice core (Antarctica) (MacFarling Meure et al., 2006) marking the globalisation in biota and trade of the Columbian Exchange and population declines and afforestation in the Americas. This, and the 1964 ^{14}C peak, have been suggested as possible markers for the onset of the Anthropocene (Lewis and Maslin, 2015). Population trends from United Nations (2019).

Moreover, IK and LK may be particularly relevant to ensuring that climate action does not cause further harm, and also addresses historical injustices committed against Indigenous Peoples and other marginalised social groups, recognising them as active agents of their own change (Nursey-Bray et al., 2019). There are between 370 and 500 million people in at least 90 countries belonging to about 5,000 different ethnic groups that are classified as 'Indigenous' (Sangha et al., 2019). Although there is no single, universal definition of Indigenous Peoples, core criterion within both the ILO Convention on Indigenous and Tribal Peoples (1989) and the UN Declaration on the Rights of Indigenous Peoples (UN, 2007) include: (a) self-determination and (b) the recognition that Indigenous Peoples as distinct social and cultural groups that retain collective ancestral ties to the lands they inhabited or to the lands from which they have been displaced. Indigenous Peoples attribute cultural and spiritual values to land, environmental features and landscapes (ILO, 2013; ILO, 2019). Indigenous Peoples suffer disproportionally. For example, they are three times more likely to live in extreme poverty than non-Indigenous Peoples; they are also more likely to suffer discrimination and violence (UN, 2020). At the same time, Indigenous Peoples have long led climate change and environmental protection agendas.

Indigenous Peoples have been faced with adaptation challenges for centuries and have developed coping strategies in changing environments (Coates, 2004). Along with other local groups, they hold relevant knowledge about the environment and environmental change, the impact of those changes on ecosystems and livelihoods, and possible effective adaptive responses (see Cross-Chapter Box INDIG in Chapter 18). Therefore, the participation of Indigenous Peoples in climate change decisions and the inclusion of Indigenous knowledge in the IPCC assessment process should be of high priority (following recommendations in UNESCO, 2018b, and UN, 2020). Furthermore, the participation of scientifically trained climate specialists with indigenous backgrounds is valuable to the work of IPCC because the assessment must reflect a diverse range of views and expertise (for examples of IK, see Cross-Chapter Box INDIG in Chapter 18). Article 31 of the UN Declaration on the Rights of Indigenous Peoples (2007) supports the inclusion of IK and LK in the IPCC assessment process, calling for the use of IK and LK to be protected and validated by Indigenous Peoples themselves and their inclusion as active participants in the assessment (Klenk et al., 2017). Paying special attention to the mechanism whereby some forms of knowledge have been excluded in previous reports—such as the use of technical knowledge or acronyms, or the deployment of discipline-specific validation mechanism—is a first step towards developing an inclusive assessment that reflects a wide range of voices.

The AR4 was the first IPCC report to explicitly discuss the value of IK and LK in adaptation and mitigation processes. AR5 recognised the importance of creating synergies across disciplines in the production of knowledge, acknowledging the importance of 'non-scientific' sources such as IK, which may not follow discipline conventions but nevertheless reflects the outcomes of learning across generations (Burkett et al., 2014). This also explains the importance of including IK and LK and diverse stakeholder interests and values in local decision making processes (Jones et al., 2014). Such processes should be done in partnership with IK and LK knowledge holders and, when possible, be led by them (Inuit Tapiriit Kanatami, 2018). Recent IPCC reports have included distinct sections dedicated to IK and LK (e.g., IPCC, 2019b). The IPCC Special Report on Climate Change and Land (SRCCL) includes a section on 'Local and Indigenous knowledge for addressing land degradation' (2019a) and the IPCC Special Report on Ocean and Cryosphere (SROCC) describes LK as 'what non-Indigenous communities, both rural and urban, use on a daily and lifelong basis,' a type of knowledge which is recognised as 'multi-generational, embedded in community practices and cultures, and adaptive to changing conditions' (2019b). The IPCC Special Report on Global Warming of 1.5°C emphasised the high vulnerability of Indigenous Peoples to climate change. It stated that disadvantaged and vulnerable populations, including Indigenous Peoples and certain local communities, are at disproportionately higher risk of suffering adverse consequences with global warming of 1.5°C and beyond (IPCC, 2018b). The report also assessed evidence in relation to the importance of including IK and LK in adaptation options, explaining their role in early warning systems and arguing that they are part of a range of approaches to catalyse wide-scale values and are consistent with adapting to and limiting global warming to 1.5°C (IPCC, 2018b).

Since AR5, several academic publications have directly addressed the challenges of including IK and LK in climate research (Ford et al., 2016; Yeh, 2016; David-Chavez and Gavin, 2018) and demonstrated its value in building resilience to extreme events related to climate change (Janif et al., 2016; Olazabal et al., 2021). For instance, IK and LK has proved useful in land management methods that reduce wildfire risk (Nepstad et al., 2006; Cook et al., 2012; Welch et al., 2013; Mistry et al., 2016). Since IK is traditionally communicated through storytelling and oral history, there are practical challenges to integrating it into an assessment that prioritises scientific knowledge. There is a need for increased critical engagement towards the co-production of knowledge (Ford et al., 2016). Scholars now recognise the ontological and epistemological differences in approaches, understandings and effects of climate change (Yeh, 2016). One common strategy has been assessing Indigenous observations of climate change alongside scientific data (Klein et al., 2014a) as a means to bridge the gap between scientific inquiry and Indigenous knowledge systems (Fernández-Llamazares et al., 2017). The Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) and the CBD have helped illustrate how to bridge multiple knowledge systems, particularly those conceived from different ontologies. Rather than viewing IK as a single source of knowledge to be compared with scientific data, recent scholarship suggests assessments, such as the IPCC, directly involve Indigenous researchers (Yumagulova et al., 2019) to ensure ethical and equitable engagement with IK. Such partnership with and leadership of Indigenous Peoples on climate research is also consistent with the UN Declaration on the Rights of Indigenous Peoples (e.g., Bawaka Country et al., 2015; Inuit Tapiriit Kanatami, 2018; Cross-Chapter Box INDIG in Chapter 18).

1.3.3 Regional Assessment

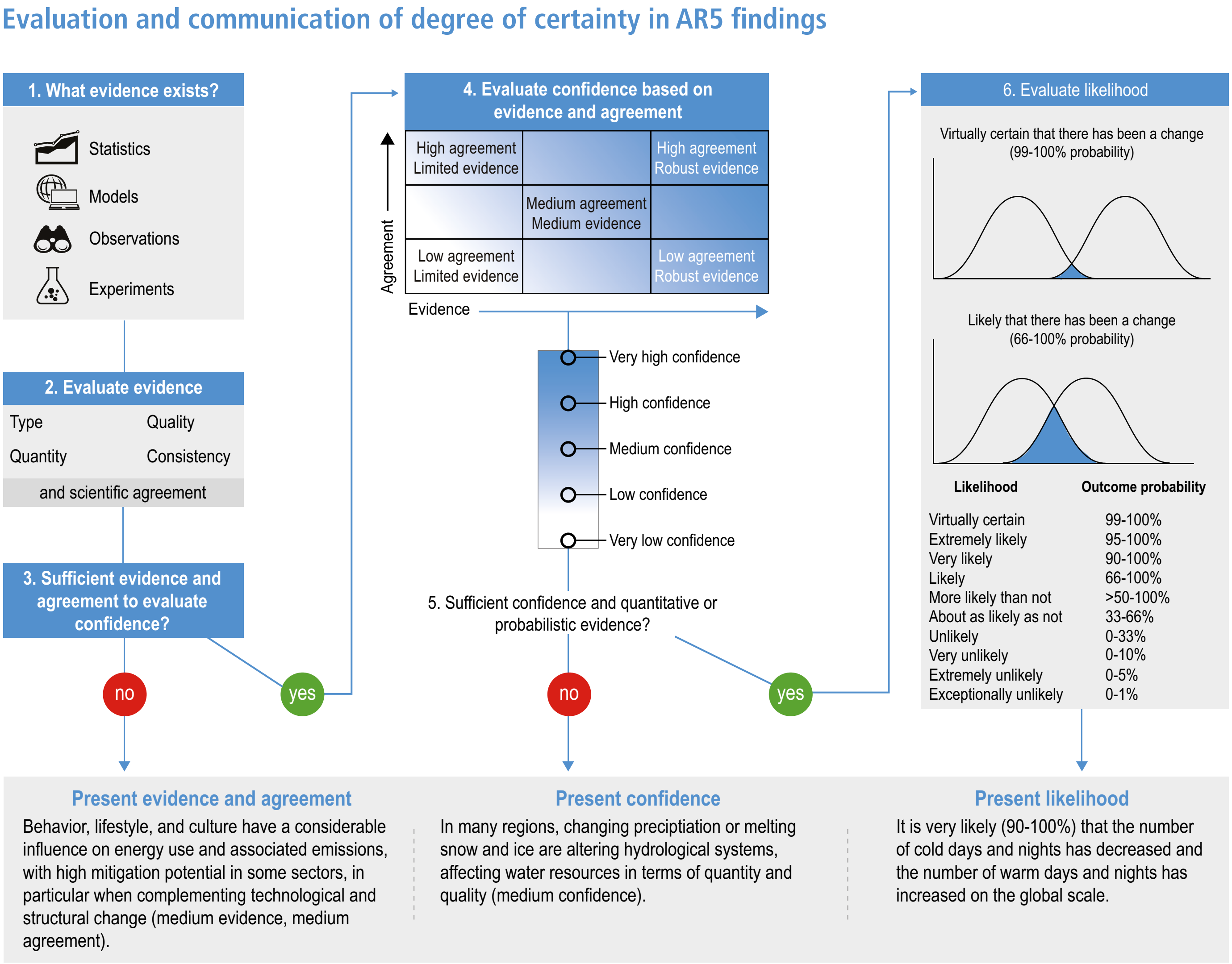
As climate change is a multi-scale phenomenon, from the local to the global, the assessment of climate risks and climate change impacts is strongly spatial, with a focus on regional climate change. The term 'regions' is used in different ways throughout the AR6 assessment as the use of the term varies across disciplines and context.

First, there are chapters dedicated to regional assessment in AR6 WGII (Chapters 9–14 and Cross-Chapter Papers 4 and 6). Within the content of these and other chapters of AR6, the term region is often used to describe continental and sub-continental regions, oceanic regions, hemispheres, or more specific localities within these geographic areas. Building on the continental domains defined in AR5 WGII and to ensure consistency with WGI Chapter 12 (Ranasinghe et al., 2021) and the WGI *Atlas* (Gutiérrez et al., 2021), AR6 WGII uses a continental set of regions, namely Africa, Asia, Australasia, Europe, North America, Central and South America, Small Islands, Polar Regions and the Ocean.

Second, the term regions is used to categorise areas around the globe with common topographical characteristics or biological characteristics. For example, Chapter 2 introduces regions in its discussion of biomes, as in arid, grassland, savanna, tundra, tropical, temperate and boreal forested regions. Chapter 3 adds reference to an area's orientation with bodies of water, using terms such as deltaic, coastal, intercoastal, freshwater and salty. In addition, Cross-Chapter Paper 2 uses a coastal region typology based on physical geomorphology considering elevation, coastal type and topography (see Cross-Chapter Paper 2, p. 5; Barragán and de Andrés, 2015; Kay and and Adler, 2017; Haasnoot et al., 2019a).

Third, CCPs are dedicated to *typological regions*, defined in the Annex II: Glossary as regions that share one or more specific features (known as 'typologies'), such as geographic location (e.g., *coastal*), physical processes (e.g., *monsoons*), biological (e.g., coral reefs, tropical forests, deserts), geological (e.g., mountains) or *anthropogenic* (e.g., megacities), and for which it is useful to consider the common climate features. Typological regions are generally discontinuous (such as monsoon areas, mountains, deserts and megacities) and are specifically used to integrate across similar climatological, geological and human domains.

Understanding climate risks across regions also requires consideration of the capabilities of developing countries and scientists across country contexts in conducting climate assessments. Substantial unevenness of available climate observations, risks assessments and scientific literature across regions and country capacities substantially challenges a globally comprehensive assessment (Connelly et al., 2018).



Likelihood	Outcome probability
Virtually certain	99-100%
Extremely likely	95-100%
Very likely	90-100%
Likely	66-100%
More likely than not	>50-100%
About as likely as not	33-66%
Unlikely	0-33%
Very unlikely	0-10%
Extremely unlikely	0-5%
Exceptionally unlikely	0-1%

Behavior, lifestyle, and culture have a considerable influence on energy use and associated emissions, with high mitigation potential in some sectors, in particular when complementing technological and structural change (medium evidence, medium agreement).

In many regions, changing preciptiation or melting snow and ice are altering hydrological systems, affecting water resources in terms of quantity and quality (medium confidence).

It is very likely (90-100%) that the number of cold days and nights has decreased and the number of warm days and nights has increased on the global scale.

Figure 1.6 | The IPCC AR5 and AR6 framework for applying expert judgement in the evaluation and characterisation of assessment findings. This illustration depicts the process assessment authors apply in evaluating and communicating the current state of knowledge. Guidance for the application of this framework is described in full detail in Mastrandrea et al. (2010). In addition to scientific knowledge, IK and LK is central to understanding and acting effectively on climate risk (Section 1.3.2.3). The diagram in this figure is reproduced from Mach et al. (2017).

1.3.4 Evaluating and Characterising the Degree of Certainty in Assessment Findings

Since 1990, IPCC assessments have included designated terms and other approaches for communicating the expert judgements made by authors (Mastrandrea and Mach, 2011). The goal of such methods has been consistent treatment of uncertainties in assessing and communicating the current state of knowledge. Because terms such as 'probable' or 'likely' hold very different meanings to different people, a standardised approach is essential for enabling consistent interpretation (WGI Section 1.2.3.1). Since its 2001 assessment, IPCC authors have applied common guidance on expert judgement across the Working Groups (Moss and Schneider, 2000; IPCC, 2005). The AR5, iteratively building from past IPCC guidance, was the first report to apply a single framework consistently across the Working Groups and their diverse topics and associated disciplines (Figure 1.3; Mastrandrea et al., 2010; Mastrandrea and Mach, 2011). The outcome was increased comparability of assessment conclusions across the full spectrum of the physical science basis of climate change and resulting impacts, risks and responses (Mach et al., 2017).

This framework for expert judgement is again being applied in the AR6 and associated special reports in the assessment cycle (Mastrandrea et al., 2010; see also WGI Box 1.1). Under the framework, the assessment of scientific understanding and uncertainties begins with evaluation of **evidence** and **agreement**—especially the type, amount, quality and consistency of evidence and the degree of agreement (steps 1–3 in Figure 1.6). Evidence assessed can reflect observations, experimental results, process-based understanding, statistical analyses or model outputs. Evidence is most robust when it consists of multiple lines of consistent, independent and high-quality evidence. The degree of agreement considers the extent of established, competing or speculative explanations for a given topic or phenomenon across the scientific community. Together, this evaluation of evidence and agreement forms a traceable account for each key finding in the assessment. Subsequently, the framework proceeds to evaluation of levels of **confidence**, which integrate evidence and agreement (steps 3–5 in Figure 1.6). Confidence reflects qualitative judgements of the validity of findings. It thereby facilitates, more readily, comparisons across assessment conclusions. Increasing evidence and agreement corresponds to increasing confidence (step 4 in Figure 1.6).

If uncertainties can be quantified, the framework involves a further option of characterising assessment findings with **likelihood** terms or more precise presentations of probability (steps 5–6 in Figure 1.6). The relevant probabilities can pertain to single events or broader outcomes. Probabilistic judgements can be based on statistical or modelling analyses, elicitation of expert views or other quantitative analyses. Where appropriate, authors can present probability more precisely with complete probability distributions or percentile ranges, also considering tails of distributions important for risk management. Usually, likelihood assignments are underpinned by high or very high confidence in the findings.

Confidence is often most applicable in characterising key findings in WGII assessment (Mach et al., 2017). This tendency results from the diverse lines of evidence across disciplines relevant to climate change impacts, adaptation and vulnerability. By contrast, likelihood is more common in WGI assessment.

The guidance to authors additionally identifies other practices and approaches relevant in applying expert judgement and developing assessment findings (Mastrandrea et al., 2010; Mastrandrea and Mach, 2011; Mach and Field, 2017). First, authors are encouraged to carefully consider appropriate generalisation within assessment findings, emphasising insights that are integrative, nuanced and rigorous (IAC, 2010; Mastrandrea et al., 2010; NEAA, 2010). Second, authors are instructed to attend to potential biases, including in group dynamics, such as tendencies towards overconfidence and anchoring or Type I (false positive) error aversion (Mastrandrea et al., 2010; Brysse et al., 2013; Anderegg et al., 2014; Morgan, 2014). Third, particular attention is drawn to the importance of evaluating and communicating ranges of potential outcomes to inform decision making and risk management (Mastrandrea et al., 2010). In some cases, deep uncertainties related to parameters or processes that are unknown or disagreed upon strongly benefit from dedicated methods of assessment and decision support (see Cross-Chapter Box DEEP in Chapter 17). Fourth, the guidance explores the different ways that framings of conclusions can shape their interpretation by readers. Finally, the guidance underscores the importance of reflecting upon all sources of uncertainty, which can include deep, difficult-to-quantify and easy-to-underestimate uncertainties arising from incomplete understanding of relevant processes or competing conceptualisations across the literature (Mastrandrea et al., 2010). A detailed review of literature assessing IPCC uncertainty characterisation methods is provided in WGI 1.2.3.1.

1.4 Societal Responses to Climate Change Risks

AR6 highlights the concept of **solutions**, defined as *effective*, *feasible* and *just* means of reducing climate risk, increasing resilience and pursuing other climate-related societal goals. This section introduces key concepts used in this report to assess the goals associated with adaptation, its process and governance, its implementation, M&E and its limits.

The term ‘solutions’ has various synonyms used across this and previous IPCC reports, including options, measures, actions and responses. All denote policies, technologies, processes, investments or other activities undertaken in reaction to or with the intent of addressing some aspect of climate change (Chapter 17). The term ‘solutions’ has drawbacks, suggesting a finality, that is, the problem is solved. Solving climate change in this sense is not likely for the foreseeable future. In addition, the word ‘solutions’ sometimes denotes a narrow set of responses, such as ‘technical solution’, as opposed to more wide-ranging actions that might be involved in a transition to resilience. Nonetheless, AR6 highlights the term ‘solutions’ because, compared to these other terms, when acted upon or incorporated in policy, it denotes effectiveness and some degree of progress at achieving desired goals.

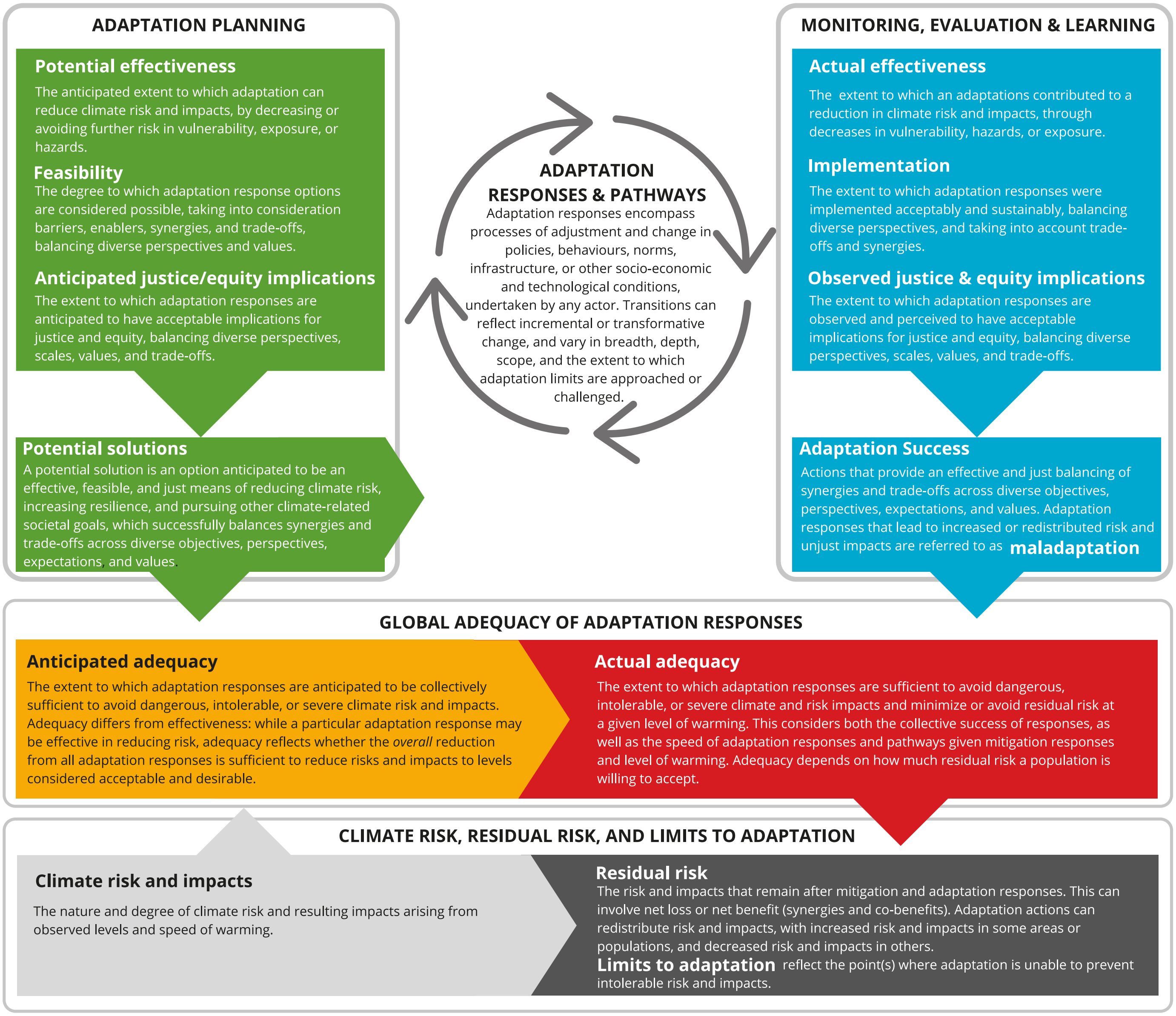
Assessing successful adaptation is, however, difficult (Cross-Chapter Box ADAPT in Chapter 1). WGIII Section 1.6 summarises four broad analytic frameworks—aggregate efficiency, ethics and equity, transition dynamics, and psychology and politics—relevant to mitigation and concludes that failure to integrate understanding across them has been a fundamental reason for inadequate progress to date in reducing GHG emissions. While the four analytic frameworks used in WGIII also all contribute to the understanding of adaptation, an integrated view remains elusive because adaptation differs strongly from mitigation. In particular, the goals of adaptation are harder to define and measure than those for mitigation. The feasibility, effectiveness and success of many adaptation actions depend more strongly on context. A different, often more diffuse, set of actors are involved, and it is often hard to distinguish what activities count as adaptation.

Given these challenges, this report provides an assessment of adaptation solutions based on the attributes **justice**, **feasibility** and **effectiveness**, as shown in Figure 1.7.

A solution is just when its outcomes, the process of implementing the action and the process of choosing the action respects principles of distributive, procedural and recognitional **justice** (Section 1.4.1.1). Any assessment of justice depends on an understanding of potential outcomes of alternative options (Chapter 16), as well as processes of decision making (Chapter 17). Consideration of justice necessarily introduces normative elements into any assessment of what constitutes a solution.

A solution is **effective** to the extent it reduces climate risk. Effectiveness can refer to whether an adaptation-related action reduces risk (Section 1.4.1.2; Chapter 16) or the extent to which an action achieves its intended outcomes within a stated time frame (Chapter 17). Effectiveness can also include measures of economic efficiency, assessment of net

Assessing adaptation solutions and success



ADAPTATION PLANNING

Potential effectiveness
The anticipated extent to which adaptation can reduce climate risk and impacts, by decreasing or avoiding further risk in vulnerability, exposure, or hazards.

Feasibility
The degree to which adaptation response options are considered possible, taking into consideration barriers, enablers, synergies, and trade-offs, balancing diverse perspectives and values.

Anticipated justice/equity implications
The extent to which adaptation responses are anticipated to have acceptable implications for justice and equity, balancing diverse perspectives, scales, values, and trade-offs.

Potential solutions
A potential solution is an option anticipated to be an effective, feasible, and just means of reducing climate risk, increasing resilience, and pursuing other climate-related societal goals, which successfully balances synergies and trade-offs across diverse objectives, perspectives, expectations, and values.

ADAPTATION RESPONSES & PATHWAYS
Adaptation responses encompass processes of adjustment and change in policies, behaviours, norms, infrastructure, or other socio-economic and technological conditions, undertaken by any actor. Transitions can reflect incremental or transformative change, and vary in breadth, depth, scope, and the extent to which adaptation limits are approached or challenged.

MONITORING, EVALUATION & LEARNING

Actual effectiveness
The extent to which an adaptations contributed to a reduction in climate risk and impacts, through decreases in vulnerability, hazards, or exposure.

Implementation
The extent to which adaptation responses were implemented acceptably and sustainably, balancing diverse perspectives, and taking into account trade-offs and synergies.

Observed justice & equity implications
The extent to which adaptation responses are observed and perceived to have acceptable implications for justice and equity, balancing diverse perspectives, scales, values, and trade-offs.

Adaptation Success
Actions that provide an effective and just balancing of synergies and trade-offs across diverse objectives, perspectives, expectations, and values. Adaptation responses that lead to increased or redistributed risk and unjust impacts are referred to as **maladaptation**

GLOBAL ADEQUACY OF ADAPTATION RESPONSES

Anticipated adequacy
The extent to which adaptation responses are anticipated to be collectively sufficient to avoid dangerous, intolerable, or severe climate risk and impacts. Adequacy differs from effectiveness: while a particular adaptation response may be effective in reducing risk, adequacy reflects whether the *overall* reduction from all adaptation responses is sufficient to reduce risks and impacts to levels considered acceptable and desirable.

Actual adequacy
The extent to which adaptation responses are sufficient to avoid dangerous, intolerable, or severe climate and risk impacts and minimize or avoid residual risk at a given level of warming. This considers both the collective success of responses, as well as the speed of adaptation responses and pathways given mitigation responses and level of warming. Adequacy depends on how much residual risk a population is willing to accept.

CLIMATE RISK, RESIDUAL RISK, AND LIMITS TO ADAPTATION

Climate risk and impacts
The nature and degree of climate risk and resulting impacts arising from observed levels and speed of warming.

Residual risk
The risk and impacts that remain after mitigation and adaptation responses. This can involve net loss or net benefit (synergies and co-benefits). Adaptation actions can redistribute risk and impacts, with increased risk and impacts in some areas or populations, and decreased risk and impacts in others.
Limits to adaptation reflect the point(s) where adaptation is unable to prevent intolerable risk and impacts.

Figure 1.7 | Assessing adaptation solutions and success. A solution is defined as an adaptation option which is effective, feasible and conforms to principles of justice. These attributes can be assessed *ex ante* during adaptation planning. During implementation, the overall success of a response can be judged via monitoring and evaluation of these attributes. Adaptation unfolds as an iterative learning process of assessment, implementation, monitoring, adjustment and learning. A set of responses is adequate to the extent that they sufficiently reduce climate risk to levels considered tolerable. Adaptation may not fully avoid residual risks, but the more adequate the response, the less residual risk remains. Adaptation also has limits beyond which it is no longer possible to avoid intolerable risks and impacts.

benefits over costs and the extent to which an action enhances broader and multi-dimensional measures of societal well-being (Section 1.4.1.2). Assessments of effectiveness will often involve uncertainty, which may affect judgements about the comparative effectiveness and justice of alternative options (Chapters 16; 17; Cross-Chapter Box DEEP in Chapter 17). Assessment of effectiveness also involves consideration of maladaptation (Section 1.4.2.4) in which an action, often inadvertently, increases risk or vulnerability for some or all affected individuals or communities.

A solution is **feasible** to the extent it is considered possible and desirable, taking into consideration barriers, enablers, synergies and trade-offs (Section 1.4.2). AR6 assesses the feasibility of a wide range of adaptation options (Cross-Chapter Box FEASIB in Chapter 18), building on the approach of the SR1.5 report, which uses five dimensions of feasibility: geophysical, environmental-ecological, technological, economic, sociocultural, institutional. In addition, feasibility can also refer to a specific set of actions, so that feasibility in any particular situation may depend on specific conditions of governance capacity, financial capacity, public opinion, interest group pressure, and the distribution of political and economic power (Chapter 17). For instance, a particular jurisdiction may find either of two options feasible when implemented alone but might lack the capacity to implement them both at the same time. Feasibility can be a context-dependent and time-varying attribute. Many solutions, for instance those that seek to unlock financing or build public support for certain actions, aim at increasing the feasibility of future adaptation responses (Sections 1.4.2; 1.5).

1.4.1 What is Equitable, Just and Effective Adaptation?

Articulating the goals of adaptation is an important initial step in the decision-making process (Jones et al 2014). Adaptation often involves trade-offs among various options of adaptation, mitigation and sustainable development, as well as judgements based on science, engineering and economics, and questions of distribution and democratic participation (Jafry et al., 2018). Articulating the goals of adaptation at the international, national and local levels thus requires engaging with the concepts of equity, justice and effectiveness (*high confidence*).

1.4.1.1 Equitable Adaptation Informed by Concepts of Justice

Assessing climate action involves ethical considerations that the literature often describes as climate justice. The term ‘climate justice,’ however, has been used in different ways in different contexts and by different communities. Grassroot organisations and activists often focus on unequal global power relations, wealth, and interests within communities, within nations, and along the North–South divide, as well as the historical responsibility for climate change (Chatterton et al., 2013). Some national governments also view climate justice as the right of developing countries to industrialise. Balancing these issues, international climate change negotiations have primarily focused on current capacities and responsibilities for addressing climate change as reflected in the UNFCCC principle of ‘common but differentiated responsibilities’ (Fisher, 2015).

Since principles of justice are substantive normative commitments that have been debated for centuries, it would be unrealistic to expect a universal consensus. Nevertheless, there is broad agreement about the core issues. Just normative principles are ones that result in fair and equitable allocation of goods, vulnerabilities and risks (Caney, 2014; Schlosberg, 2009; Schlosberg, 2013; Jafry et al., 2018)

It is common to distinguish between distributive justice, procedural justice and recognition (Fraser, 1999; Schlosberg, 2003; Schlosberg, 2009; Reckien et al., 2017; Forsyth, 2018; Olazabal et al., 2021). The first refers to the distribution of burdens and benefits; the second to who decides and participates in decision making; while recognition entails basic respect and robust engagement with and fair consideration of diverse values, cultures, perspectives, and worldviews. Recognition is closely linked to distributive and procedural justice (Hourdequin, 2016). Without recognition, actors may not benefit from the two other aspects of justice (*medium confidence*). Recognition thus represents both a normative principle as well as an underlying cause of unjust distribution and lack of democratic participation (Svarstad and Benjaminsen, 2020). However, recognition is still under-represented in climate justice compared to general scholarship and debate on justice principles (Chu and Michael, 2018; Benjaminsen et al., 2021).

Three principles of distributive justice are especially relevant to adaptation: *fairness between individuals*, *fairness between states* and *fairness between generations* (Fleurbaey et al., 2014*)*. Fairness between individuals means that the distribution of goods, vulnerabilities and risks of climate change should not fall on individuals for arbitrary reasons. It would be arbitrary if, say, a family were disproportionately affected by climate-induced drought by chance alone. Similarly, an adaptation action that protects some and creates risks for others is unfair if the final distribution of burdens and benefits is arbitrary.

The second consideration of distributive justice is *international justice*, or fairness between states. An important idea in international climate negotiations has been *common but differentiated responsibilities* (CBDR) and respective capabilities, stated in Principle 7 in the Rio Declaration (1992), as well as by the Kyoto Protocol (1997). The principle reflects the underlying idea that *all* countries must address climate change, but the form of climate action depends on the situation the country finds itself in. Developed countries may find themselves in a position where they can decarbonise more rapidly and ensure financial flows, while the responsibilities of LDCs and SIDS may primarily come in the form of adaptation actions. This means that uneven distribution of wealth and power between (and within) countries is a key driver of climate injustice.

The third consideration of distributive justice relevant to climate adaptation is fairness between generations and the obligation to ensure that future generations are guaranteed at least a minimally decent life (Jonas, 1985; Llavador et al., 2010). For example, youth climate activists and political philosophers have argued that today’s children, as well as generations yet unborn, will be exposed to far greater risks than most living adults so that policymakers should work to avoid shifting all burdens of adaptation to future generations.

Procedural justice addresses the fairness of the processes by which decisions are made and the legitimacy of those making the decisions (Gutmann and Thompson, 2009; Kitcher, 2011). Criteria include transparency, the application of neutral principles among parties, respect for participants’ rights and inclusive participation in decision making, which often takes the form of participatory processes. Article 6 of the Framework Convention creates a binding commitment on parties to promote public participation in addressing climate change. Increased participation by civil society in climate policy discussion, including new forums such as the Local Communities and Indigenous People’s Platform of the UNFCCC work toward this goal (UNFCCC, 2021). Genuine, not merely formal, participation requires communities be well-acquainted with the climate change risks they face and are given a full voice in the process of adaptation planning. Many local communities, especially those most vulnerable to climate change, remain excluded, which is inconsistent with principles of procedural justice. In addition to a normative principle, models of decision making also suggest that diverse, representative decision makers can be expected to make better decisions than more limited groups (Hong and Page, 2004; Landemore, 2013; Singer, 2019).

In AR5 WGIII (IPCC, 2014a) discussions of justice and ethical concepts were combined with discussions of economic principles while the adaptation chapters did not explicitly discuss climate justice. This report moves beyond AR5 by connecting the assessment of policy choices to normative principles and showing how better outcomes are obtained by choosing just ones.

1.4.1.2 Equitable and Effective Adaptation Informed by Concepts and Measures of Well-being

Planning and assessment of effective and just adaptation require appropriate measures of both criteria. This report uses both single and multi-criteria measures. Local and regional decision makers employ benefit–cost analysis to efficiently allocate scarce resources among alternative adaptation efforts and among adaptation and other societal needs. Decision makers at national and global levels can employ measures of social welfare to consider trade-offs and synergies among adaptation, mitigation, and development. Such measures can avoid wasteful allocation of resources and help avoid maladaptation. Such measures also prove useful because well-established approaches exist to evaluate such quantities, and because income is highly correlated with a wide range of indicators of social progress and climate change adaptation capacity (Dasgupta et al., 2018).

Aggregate, monetised economic measures are, however, insufficient to address issues of climate justice fully or to reflect that wide range of worldviews and values that different people bring to questions of climate action and development (Chambwera et al., 2014). While recent work has enriched the consideration of distributive justice in aggregate social welfare functions (Adler, 2012), multi-objective approaches that separately report several biophysical and socioeconomic attributes can prove valuable (Section 17.3.3). Many adaptation measures, in particular those that encompass transformational social changes (Section 1.5), involve complicated trade-offs among multi-dimensional benefits and costs (Adger, 2016). Different people commonly value such trade-offs differently, particularly in heterogeneous societies. Multi-objective measures can thus enhance transparency, fairness, legitimacy and participation by highlighting the different outcomes that different people and communities might find important, making the specific trade-offs more transparent and explicit, and avoiding privileging any particular view on the appropriate trade-offs (Lempert et al., 2018; Siders, 2019b; Siders and Keenan, 2020).

The SDGs and Key Representative Risks (Chapter 16) exemplify such multi-criteria measures. In addition, many communities increasingly measure policy outcomes using multi-objective measures, often organised around the concept of well-being and designed to allocate resources and implement policies to advance social progress (Lee et al., 2015; City of Santa Monica, 2018). Similarly, the Human Development Index (HDI), which derives from the capabilities approach, combines income (as gross national income, GNI, and parity purchasing power, PPP) with an education and a health indicator and integrates human and socioeconomic factors (Herrero et al., 2012; USEPA, 2016; Leal Filho et al., 2018; Nagy et al., 2018; UNDP, 2018). The inequality-adjusted HDI value, or IHDI, can be interpreted as the level of human development when inequality is accounted for (UNDP, 2018).

The multi-criteria concept of well-being has been increasingly employed as a structured framework for measuring social progress in many areas of public policy (Lamb and Steinberger, 2017) including climate and health (Chapter 7) and, to a lesser extent, in other areas of the climate change adaptation literature (Singh et al., 2021). Well-being reflects the ability of a person to pursue and realise the goals that they value (Sen, 1985). The disaster risk management community employs well-being to evaluate mental health impacts in terms of peoples' abilities to cope with trauma and loss because of natural disasters (Berry et al., 2010; MacDonald et al., 2015; Willox et al., 2015). The term appears in the literature with concepts such as human security (Koren and Butler, 2006; Adger, 2010; Pasgaard et al., 2017), subjective well-being or happiness (Sekulova and van den Bergh, 2013; Rehdanz et al., 2015; Fanning and O'Neill, 2019), welfare (Gough, 2015) and living standards or quality of life (Degorska and Degorski, 2018; Rao and Min, 2018).

Recent work has used quantified measures of well-being and multi-objective decision-support tools to balance among equity and efficiency objectives in disaster risk management (Section 1.5.2; Chapter 17; Markhvida et al., 2020). Rather than focus on the economic value of lost assets, the well-being measure evaluates disaster impacts and recovery policies by considering the fraction of consumption lost at the household level for different income cohorts. Not surprisingly, poor households account for twice as much of the disaster losses when evaluated by effects on well-being rather than by asset losses. The most effective policy responses also differ when using well-being and asset loss-based measures. Ciullo et. al. (2020) compare flood control strategies using multi-objective decision criteria that include both benefit–cost and distributional components, show how the favoured strategy can depend on whether one seeks equitable risk or equitable risk reduction, and propose tools that can help embed both ethical and efficiency considerations in adaptation decisions. Widespread use of such approaches could strengthen consideration of climate justice along with efficiency in the evaluation of climate risks and adaptation (Section 1.5.2; Dryzek et al., 2013).

1.4.2 Enabling and Governing Adaptation

Adaptation actions taken by individuals, social groups and organisations in response to climate and environmental stimuli depend, in part, on the options they have (see Chapters 16 and 17). Actions previously taken can reduce the scale of responses needed subsequently, increase the options available, reduce barriers to additional action and increase capacity to respond. Successful adaptation sufficient to meet the goals of the Paris Agreement and SDGs needs to involve actors at many scales and in many sectors, including individuals and households, communities, governments at all levels, private sector businesses, non-governmental organisations, religious groups and social movements. This report highlights the increased range of societal actors engaged in adaptation and the need for multi-level and polycentric governance. The section describes key concepts related to the process of adaptation and assessment of how human choices and exogenous changes can expand and contract the set of available solutions.

1.4.2.1 Adaptation Process and Expanding the Solution Space

Adaptation actions include those taken with the explicit intention of reducing climate risk, as well as actions taken without reference to climate change, for example, building community resilience irrespective of any particular hazard. Adaptation actions can include those aimed at reducing a specific risk or actions aimed at systemic changes, and also include adjustments to current practices or transformational changes. In addition, the success of adaptation in one place or jurisdiction can depend on activities in other places or jurisdictions.

Adaptation actions span a vast range of activities. Successful adaptation generally requires a portfolio of actions, often implemented by multiple actors in different sectors, often in different places and over time (Section 17.2.2). Useful taxonomies include categorising such actions around representative key risks (Figure 17.3), and by human systems and scenarios of adaptation extent for four components of adaptation (depth, scope, speed and limits) (Table 16.2). As shown in Chapter 17, for instance, ecosystem-based adaptation, hardening buildings and physical barriers, and changes to zoning and planned retreat can reduce risks to coastal socio-ecological systems. Restoration and protection of forests, enhancing ecosystem connectivity through corridors and ecosystem-based adaptation can reduce risks to terrestrial and ocean ecosystems. Increased use of grey, green and blue infrastructure and upgrading design standards, city plans and more redundancy in power systems and other networks can reduce risks associated with critical infrastructure. Insurance and diversified or changed livelihoods can reduce risks to living standards and equity. Improved health-care systems, disaster management and early warning can reduce risks to human health. Better management of land, soil and fisheries, and changing diets and reducing food waste can reduce risks to food security. Improved water efficiency and policies to reduce demand can reduce risks to water security.

Previous IPCC reports have described in detail adaptation for individual actors as an iterative risk management process of scoping (identifying risks, vulnerabilities, objectives and decision-making criteria), analysis (identifying options, assessing risks, evaluating trade-offs) and implementation (implementing chosen options, monitoring, and reviewing and learning) (Jones et. al. 2014). This AR6 report expands the focus to consider adaptation processes with multiple actors and a richer temporal dimension in which actions taken at one time can expand or contract the set of feasible, effective and just options available at another time, thereby increasing or decreasing the ability of adaptation to reduce risks (Section 17.1). This AR6 report also expands the focus to include decision processes the implement both adaptation and mitigation (Chapter 18), as well as heightened attention to M&E, which is a key prerequisite for successful iterative risk management and achieving effective and just adaptation outcomes at local to global levels (Sections 1.4.3; 17.5.2). The challenges of implications for adaptation, mitigation and sustainable development outcomes result from decision-making process at different levels (Von Stechow et al., 2015; Bertram et al., 2016). Overcoming these challenges often requires significant learning and innovative ways of linking science, practice and policy at all scales (Shaw and Kristjanson, 2014).

Box 1.2 | Financing as an example of enabler

According to the UNFCCC, adaptation finance includes public, private and alternative sources of finance for supporting adaptation actions, whereby adaptation and resilience are often used interchangeably in this context. Adaptation finance constitutes a crucial enabling condition and shaper of the solution space, depending on other enabling conditions, such as proper planning, implementation and governance, which are also the triggers for investments and finance to flow, ensuring positive adaptation outcomes. Details of adaptation finance can be found in Chapter 17 (Cross-Chapter Box FINANCE in Chapter 17; Section 17.4). The adaptation and resilience options offer multiple benefits, including avoiding risks and losses, economic growth and well-being, as well as social and environmental benefits (Agrawal and Lemos, 2015; Bayleyegn et al., 2018; Global Commission on Adaptation, 2019). Hence, the rate of return on adaptation is large; for example, there is a huge potential of net benefits, that is USD 7.1 trillion while investing USD 1.8 trillion globally in climate resilience and adaptation options, such as early warning systems, climate-resilient infrastructure, improved dryland agriculture crop production, global mangrove protection and building resilience of water resources (Global Commission on Adaptation, 2019). These net benefits resulted primarily from reducing future losses and risk, increasing productivity and innovation, and social and environmental benefits. Despite significant uncertainty and concerns over undue focus on efficiency (monetary), benefit-cost estimates often ignore important issues of non-economic values, effectiveness of risk reduction and climate justice (procedural/distributional).

The current public and private financial flows to adaptation are much smaller than needed (Cross-Chapter Box FINANCE in Chapter 17). Only a small portion of overall adaptation finance needs is likely to be covered by public sector finance. Private sector investment thus needs to play a crucial role. Hence, tracking adaptation finance flows is important for enabling effective planning and prioritisation of investments, assessing whether needs are being met, and ensuring accountability towards funding commitments, such as the USD 100 billion promised to developing countries per year by 2020 under the Paris Agreement (Donner et al., 2016). Since AR5, significant progress has been made in tracking adaptation finance flows through UNFCCC channels, multi-lateral development banks and bilateral finance (Cross-Chapter Box FINANCE in Chapter 17), but large information gaps on adaptation finance via national public finance, commercial lenders, investors, asset managers and insurers, company finance, and individuals and households remain. That these financial flows do not occur suggests misaligned incentives and other governance challenges that could be addressed as part of a response to climate change (Chapter 17). Across regions and sectors, financial constraints have been identified as the most common and important determinants leading to limits to adaptation (Chapter 16).

Box 1.3 | Nature-based solutions

Nature-based solutions (NbS) (Section 2.6; Cross-Chapter Box NATURAL in Chapter 2) provides an example of how innovative ideas can expand the climate solution space (IPCC, 2018b; Seddon et al., 2019). A commonly used definition of NbS is that of The World Conservation Union (IUCN), which defines it as 'actions to protect, sustainably manage, and restore natural or modified ecosystems, that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits' (Cohen-Shacham et al., 2016). In the context of IPCC, it focuses on NbS which deliver climate change adaptation or mitigation benefits. NbS generally benefits biodiversity and supports its role in both climate mitigation and adaptation. While the carbon-sequestering mitigation role of increasing forest and tree cover has dominated much of the earlier discussions, the role of NbS in promoting adaptation of natural ecosystems and human societies to climate change is being increasingly emphasised. The details of different categories of ecosystem services in the ocean or on land, including biodiversity, food provision, other provisioning services (e.g., medicinal and commercial products), and regulating and cultural services are described in Chapters 2 and 3.

Forest restoration would certainly contribute substantially towards climate-proofing and achievement of several SDGs as well as the Paris Agreement. There is increasing evidence that diverse, native tree species plantations are more likely to be resilient to climate change in contrast to fast-growing monocultures, (Hulvey et al., 2013) often of exotic species. At the same time, other natural ecosystems such as savannas, grasslands, peatlands, wetlands and mangroves have considerable value in acting as carbon sinks as well as providing other ecosystem services such as hydrological regulation, coastal protection, maintaining biodiversity and contributing to human livelihoods especially pastoralists and fishermen (Veldman et al., 2015; Conant et al., 2017; Leifeld and Menichetti, 2018; Seddon et al., 2019). Coastal and marine ecosystems including wetlands and mangroves have featured prominently in studies of NbS in climate adaptation and mitigation potential for 'blue carbon' sequestration (Inoue, 2019; Sections 3.6.2.1; 6.3.3; Cross-Chapter Paper 2.3.2.3). Agroecological practices such as agroforestry, intercropping, rotational grazing, organic manuring, and integrating livestock production with cropping etc can also consider as NbS which contribute to both climate mitigation and adaptation (Altieri and Nicholls, 2017; Webb et al., 2017; Bezner Kerr et al., 2019; Leakey, 2020; Box 5.10).

There are concerns about large-scale conversion of non-forest land into forest plantations for the sole purpose of increasing carbon sinks through bioenergy with carbon capture and storage (BECCS) (Heck et al., 2018; Hanssen et al., 2020; Cross-Chapter Box in Chapter 2), which may actually result in negative carbon sink (Jackson et al., 2002; Mureva et al., 2018) and significant loss of overall biodiversity (Abreu et al., 2017). Such large-scale afforestation may also lead to the dispossession of previous users, such as smallholders and pastoralists. Hence, when NbS include forest plantations or other large-scale conversion of land use, there is a risk that they result in maladaptation and malmitigation, including climate injustice (Seddon et al., 2019; Cousins, 2021).

Much of the conceptual framework for NbS has come from initiatives to bring environmental, social and economic dimensions to the same level of importance, particularly in the context of a highly urbanised society (Section 6.3.3; Faivre et al., 2017; Nesshöver et al., 2017). Emphasis has been placed on urban storm water management (Section 2.6.5.2) and heat mitigation using measures, such as sustainable drainage systems, urban forests, parks and green roof-tops, apart from coastal defences using NbS (Section 13.6.2.3) This has triggered much debate on how distinct the concept of NbS is in relation to other similar concepts, such as ecosystem-based adaptation (EbA) approaches (Section 9.11.4.2). There are calls for an assessment framework for proving the 'effectiveness and efficiency' of NbS in providing superior ecosystem and societal benefits (Calliari et al., 2019). Instead, EbA can be treated as a subset of NbS (Chapter 2). However, the time frame of EbA is also an important consideration; thus, grassland and forest restoration would operate at different time scales, while mangrove restoration can promote adaptation only at local to national scales, depending on the extent and nature of coastlines (Taillardat et al., 2018). Given the complex nature of plant and animal species adapting to climate change through dispersal and migration to more suitable habitat, this also means that landscape-scale approaches, as opposed to purely protected areas, are needed to promote adaptation, conserve and sustainably use biodiversity, and sustain livelihoods (Vos et al., 2008; Sukumar et al., 2016).

Two concepts—enabling conditions and catalysing conditions—help frame this report's assessment of factors that over time can help expand the set of available solutions (Section 17.4). Enabling conditions enhance the feasibility of adaptation and mitigation options (AR6 Glossary, IPCC, 2021b). Enablers include finance, technological innovation, strengthening policy instruments, institutional capacity, multi-level governance and changes in human behaviour and lifestyles. Chapter 17 (see also WGIII Figure 1.4) identifies three broad categories of enabling conditions: (Section 17.4): governance, finance and knowledge. Catalysing conditions motivate and accelerate the adaptation decision-making process, leading to more frequent and more substantial adaptation (Chapter 17). While enablers make adaptation more feasible and effective, catalysing conditions provide an impetus for action. These later conditions include a sense of urgency (Section 17.4.5.1), system shocks, such as those from natural disasters, policy entrepreneurs and social movements.

The concept of the **solution space** provides a framework for assessing how the options available for adaptation for any particular community are not constant over time and can depend on the past, current and future choices of many actors. The solution space is defined as the space within which opportunities and constraints determine why, how, when and who adapts to climate risks (Haasnoot et al., 2020). The concept aims to capture the dynamic inter-temporal, spatial and jurisdictional interconnections among adaptation actions. A larger solution space indicates people and organisations with more options for adapting to and reducing their risk from climate change. Both human choices and exogenous changes in human and natural systems affect the future solution space. For instance, changes such as the magnitude and rate of climate change may shrink the space. Economic growth can generate more resources that expand the solution space as can implemented adaptation actions such as pilot projects, awareness raising and changes in laws and regulations.

AR5 used the concept of solution space in its SPM Figure 8 (IPCC, 2014c). Several AR6 chapters, in particular Chapters 13, 14 and 18, use the concept to address challenges salient in AR6. In any assessment of solutions, what is feasible, effective and just depends not only on the potential solution itself but the particular biophysical and societal context in which it might occur (Section 17.5; Wise et al., 2014; Gorddard et al., 2016). Solutions can also be space and time dependent because the biophysical and societal context can change over space and time (Section 18.1.4). In addition, the large gap that exists between current climate action and that needed to meet policy goals suggests that decision makers may not only seek to implement available solutions but seek to actively expand the set of solutions (Chapters 17; 18). Finally, as used in this report, the concept of solution does not fully engage with questions of ‘by whom?’ and ‘for whom?’ In many cases solutions would necessarily be implemented by multiple, independent actors interacting with varying degrees of cooperation and competition (Sections 1.5.2).

1.4.2.2 Governing Adaptation

Governance and governing refer to the structures, processes and actions through which private and public actors interact to address societal goals. This includes formal and informal institutions and the associated norms, rules, laws and procedures for deciding, managing, implementing and monitoring policies and measures at any geographic or political scale, from global to local. Governance systems and the specific societal institutions through which they are organised are crucial to the feasibility and success of climate change adaptation, both in terms of its effectiveness in reducing climate risk and vulnerability, as well as equity (including climate justice), with respect to incremental as well as transformational adaptation. This is why AR6 WGII pays even more attention than previous assessments to governance as an important enabling condition, and to the wide range of new actors beyond governments involved in planning, implementing, monitoring and evaluating adaptation action. The assessments in subsequent chapters of AR6 WGII show that successful and equitable collective adaptation efforts at different levels and scales, based on key principles of iterative risk management, require strong, usually multi-level. governance systems. Multi-level governance refers to the dispersion of governance across multiple levels of jurisdiction and decision making, including global, regional, national and local, as well as trans-regional and trans-national levels (see also WG III Chapter 1). The concept emphasises that modern governance generally consists of, and is more flexible, when there are linkages of governance processes across different scales and levels. Multi-level governance is widely regarded as crucial, particularly for transformational adaptation, defined as ‘adapting to climate change resulting in significant changes in structure or function that go beyond adjusting existing practices including approaches that enable new ways of decision making on adaptation’ (IPCC SR1.5, IPCC, 2018b; see also Section 1.5). The assessment in subsequent chapters also shows that public governance arrangements and institutions support most adaptation for addressing the main climate risks, though the importance of the private sector and community organisations in adaptation is increasing. It also shows that polycentric governance tends to benefit adaptation.

The empirical literature on adaptation governance has advanced strongly since AR5. It shows that stronger general governance capabilities are usually associated with more ambitious adaptation plans and more effective implementation of such plans (UNEP, 2014; Chen et al., 2016; Keskitalo and Preston, 2019b: 24; ND-GAIN, 2019; Oberlack, 2017; Oberlack and Eisenack, 2018; Woodruff and Regan, 2019; UNEP, 2018; UNEP et al., 2021). Governance capabilities are, to a significant degree, but not exclusively, a function of available financial resources and technology. They are also a function of social capital and societal institutions, including well-functioning local, regional and national governments, and collaboration among these governmental actors and non-governmental stakeholders, including civil society and the private sector. The literature also points to governance conditions that are likely to enable transformational adaptation (Maor et al., 2017; see also Sections 1.4.4; 1.5; Chapter 17).

Existing comparative data for adaptive capacity worldwide is at a rather coarse level of temporal and spatial resolution. It can, nonetheless, provide a very general picture of rates of change in adaptive capacity at the national scale, and differences between countries. Further empirical research is needed to identify the most important predictors of variation across countries and time, though the available data suggests that differing national income and education levels play a major role in accounting for differences in adaptive capacity (Andrijevic et al., 2020). Spatially more resolved (sub-national) data is needed because a large body of case study research suggests that there is strong variation within countries, particularly the large ones (e.g., India, China, Brazil, United States) (Chapter 16; see also Nalau and Verrall, 2021 and Cross-Chapter Box ADAPT). Moreover, higher degrees of adaptive capacity do not mean that adaptation action will follow automatically, nor that it will succeed in terms of equity and effectiveness in reducing vulnerability to climate change and enhancing well-being. How differences across and within countries in climate risk exposure translate into adaptation action, contingent on differences in adaptive capacity, can to some extent be inferred from case studies, but this remains to be studied at a larger, comparable and generalisable scale.

Governance capacity constitutes an important enabling condition not only because it facilitates the (efficient) organisation and implementation of adaptation action, but also because it contributes to learning. The latter is central to the process of adaptation as information regarding current and future climate conditions continues to evolve, as does understanding of appropriate response options and the actors involved. In addition, norms, values and practices may change in response to changing conditions (Jones et al., 2014). Much learning by individuals, communities and organisations is unplanned (National Research Council, 2009), as is much current adaptation (Berrang-Ford, 2020), which can reduce near-term costs and administrative complexity, but may prove maladaptive (Section 1.4.2.4). Iterative risk management (Section 1.2.1.1) and related concepts such as risk governance (Renn, 2008) describe a planned learning process of ongoing assessment, action and reassessment. Iterative risk management can be as simple as scheduling future updates of assessments and plans, as with the 5-year updates of the global stocktake after 2023 called for in the Paris Agreement, or encompass more elaborate learning processes, such as dynamic adaptive pathways (Haasnoot et al., 2019b; Cross-Chapter Box DEEP in Chapter 17) which include specific near-term actions, specific trends to monitor and specific contingency actions to take depending on the future conditions observed. While often more effective at meeting goals, such planned learning processes may pose implementation and governance challenges (Metzger et al., 2021)

Mainstreaming adaptation into existing governance structures and associated organisations and their investments, policies and practices can contribute to expanding the solution space and support efforts at transformative adaptation. For instance, urban planning can support adaptation by mainstreaming adaptation into city plans, such as land use planning, procuring resilient infrastructure and transportation, supporting health and social services, promoting community-based adaptation, and protecting and integrating biodiversity and ecosystem services into city planning (Section 17.4.3). Mainstreaming adaptation also shows many shortcomings, such as diminishing the visibility of dedicated, stand-alone adaptation approaches (Persson et al., 2016), unequal distribution of adaptation efforts, diluting responsibilities for implementation (Nalau et al., 2016; Reckien et al., 2019), exhibiting disconnects between planning, investment and implementation, having limited policy coherence (Friend et al., 2014; Bizikova et al., 2015; England et al., 2018; Koch, 2018) and failing to adequately balance overlapping and/or competing policy objectives (Vij et al., 2018).

Finally, governing adaptation in ways that maximise the solution space and facilitate learning can help avoid maladaptation. Maladaptation refers to potentially adverse effects of certain forms of adaptation action, such as increased GHG emissions or increased vulnerability to climate change and diminished welfare of certain parts of a population now or in the future (Anguelovski et al., 2016; Keskitalo and Pettersson, 2016; Veldkamp et al., 2017; Zimmermann et al., 2018; Benzie et al., 2018; IPCC, 2018b; Munia et al., 2018; Nadin and Roberts, 2018; Prabhakar et al., 2018). Maladaptation is an example of response risk, which is increasingly highlighted in both AR6 WGII and

Adaptation assessment prior to implementation and M&E during and after implementation

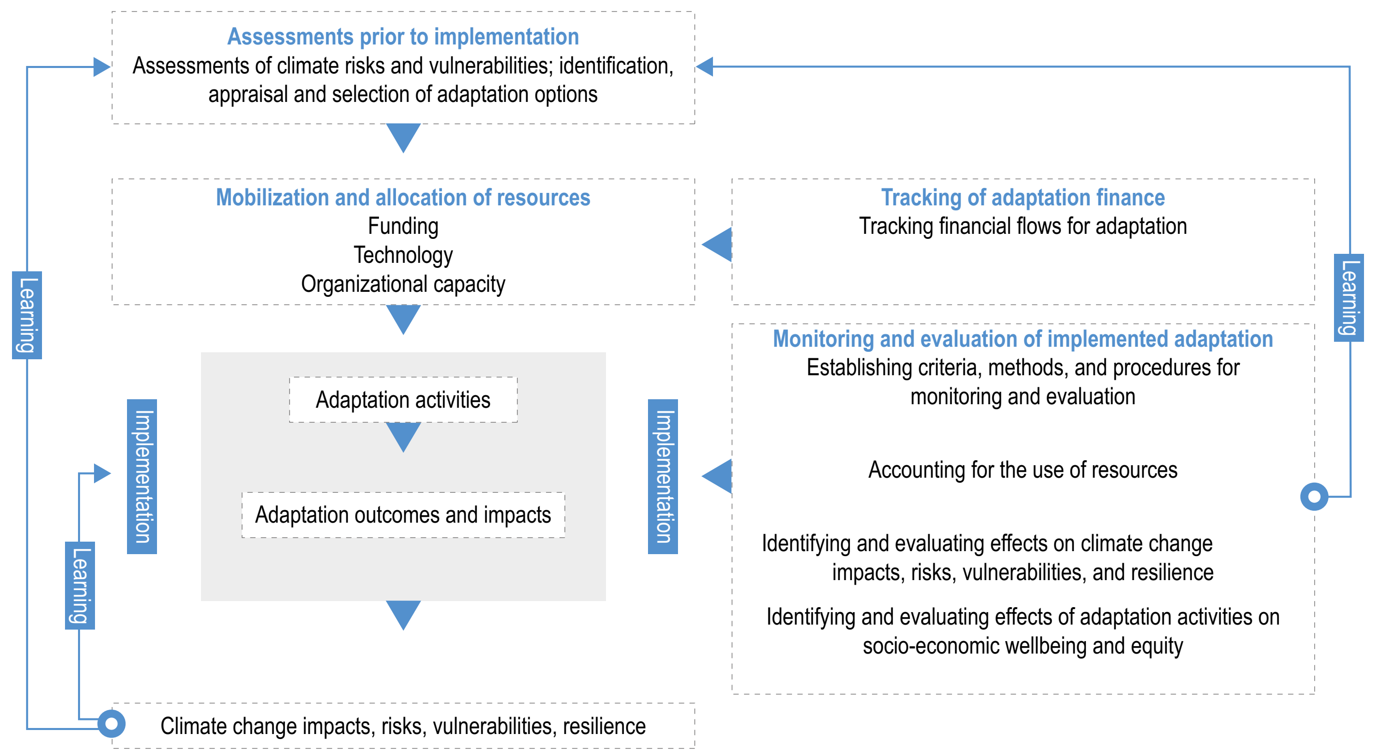


Figure 1.8 | Adaptation assessment prior to implementation and M&E during and after implementation. Both systematic assessment of adaptation needs and options and M&E of implemented adaptation are key to iterative climate risk management and to achieving effective and equitable adaptation. Most assessments to date have referred to aspects prior to implementation. There is much less systematic evidence on adaptation action, and even less evidence on adaptation outcomes and impacts and their implications for climate change impacts, risks, vulnerabilities and resilience. Figure 17.9 provides more detail on M&E.

WGIII (Section 1.3.1.2; see also IPCC Risk Guidance, Reisinger, 2020). One example is that adaptation action may set paths that limit the choices of future generations to adapt. This last characteristic refers to the lock-in effects of improperly designed and costly infrastructures that affect the ability of future generations to amend.

Maladaptation can result from many potential barriers, including administrative, human, financial and technical resource constraints (Hassanali, 2017; Pardoe et al., 2018; Singh et al., 2018); lack of transparency and/or capacity in governance (Friend et al., 2014); unreliable information on climate impacts and the lack of key policy guidelines (Pilato et al., 2018); entrenched institutional, legal and technical obstacles (Gao, 2018) and low literacy, including environmental and scientific literacy (Wright et al., 2014); exclusion of vulnerable groups (Forsyth, 2018); governance fragmentation (that is, a fragmentation of laws, regulations, and policy requirements); and limited cross-sectoral collaboration, meaning that there is limited coordination and that top-down planning approaches are not connected to local dynamics (Archer et al., 2014; Pardoe et al., 2018). This report draws attention to maladaptation challenges recognising that not all adaptation-related responses reduce risks (Chapter 16). Besides, maladaptation is the opposite of successful adaptation, which is associated with reduction of climate risks and vulnerabilities for humans and ecosystems, increased well-being and co-benefits with other sustainable development objectives. (Chapter 17)

1.4.3 Monitoring and Evaluation of Adaptation

M&E encompasses a broad range of activities serving multiple purposes, including tracking progress of adaptation efforts over time, understanding equity and effectiveness of adaptation options and outcomes, and informing ongoing adaptation processes (Section 17.5.2.1). While monitoring and evaluation are often referred to jointly as 'M&E,' monitoring usually refers to continuous information gathering, whereas evaluation denotes more comprehensive assessments of effectiveness and equity, often resulting in recommendations for decision makers (Sections 17.5.1.1; 17.5.1.7). In some literatures M&E refers solely to efforts undertaken after implementation. In other literatures, M&E refers both to efforts conducted before and after implementation. As shown in Figure 1.8, M&E is essential to the process of iterative risk management, both in terms of adaptation assessment prior to implementation and M&E of implemented adaptation measures. AR6 highlights that M&E after implementation is much less common than adaptation assessment prior to implementation (Section 17.5.2.1; Berrang-Ford, 2020).

Tracking adaptation planning and policies: Since AR5, interest in M&E for tracking progress in adaptation has grown substantially at the local, national and global level. The Paris Agreement calls for a global stocktake every 5 years starting in 2023 (Cross-Chapter Box PROGRESS in Chapter 17). It also encourages states to monitor and evaluate their adaptation plans, policies, programmes and actions and provides guidance on communicating information about adaptation to the international community (UNFCCC, 2015b, Article 7.9d; UNFCCC, 2018a, Decision 9/CMA.1; UNFCCC, 2018b, Decision 18/CMA.1).

Since AR5, a large number of case studies on individual local to national level adaptation measures have been published (see Chambwera et al., 2014; Keskitalo and Preston, 2019b), as well as comparative studies across countries over multiple years (Lesnikowski et al., 2016; Biesbroek et al., 2018; Biesbroek and Delaney, 2020). The existing literature now allows for at least preliminary conclusions about where and why we observe adaptation efforts, as described in the sectoral, regional and synthesis chapters of this report.

While case studies provide context-specific insights, global inventories are essential for tracking global progress on adaptation (UNEP, 2018; UNEP et al., 2021; Cross-Chapter Box PROGRESS). Until recently, the dominant approach surveyed National Communications to the UNFCCC to measure the amount of adaptation planning activity worldwide (Gagnon-Lebrun and Agrawala, 2007; Lesnikowski et al., 2016). More recent assessments have focused also on the quality of local and

Cross-Chapter Box ADAPT | Adaptation science

Authors: Johanna Nalau (Australia/Finland), Lauren Rickards (Australia), Tabea Lissner (Germany), Katharine J. Mach (USA), Lisa Schipper (Sweden/UK), Chandni Singh (India), William Solecki (USA), Adelle Thomas (Bahamas) and Edmond Totin (Benin)

High-level statements:

- Adaptation knowledge consists of a diverse set of sources including academic research, applied analysis, and practice and experience with projects and policy on the ground.
- Adaptation science encompasses both research 'on adaptation', documenting and analysing experiences of adaptation, and 'for adaptation', aiming to advance the planning and implementation of adaptation.
- The nature of adaptation research is diversifying and examines different approaches from local case studies to more global, transboundary, comparative and interactive perspectives, although critical conceptual and empirical gaps remain in defining effectiveness in adaptation and measuring adaptation progress.

This cross-chapter box complements the reviews of specific adaptation knowledge, content and progress described throughout WGII by providing a higher-level analysis of the shifting characteristics of and trends in **adaptation research** and its evolution over time.

Cross-Chapter Box ADAPT (continued)

The characteristics and diversity of adaptation knowledge

The knowledge base on adaptation has matured significantly since AR5. Whereas adaptation research was primarily academic during the 1990s and 2000s, it now includes a proliferation of on-the-ground experience of how to adapt to climate change, increasingly documented in reports and papers. Furthermore, academic research on adaptation has diversified significantly. Understanding the characteristics and diversity of this knowledge base is key for it to effectively inform decision making and action on adaptation.

Academic work on adaptation now spans an increasing number of disciplines and countries and is published across diverse academic outlets and disciplines, with 28.5% annual average increase in adaptation specific publications (Nalau and Verrall, 2021). This expands the range of considerations and perspectives within adaptation research and increases the challenge of identifying and synthesising all relevant research on adaptation in reviews or assessments (Berrang-Ford et al., 2015; Webber, 2016; Singh et al., 2020; Sietsma et al., 2021). Also, large bodies of research and knowledge exist that support climate adaptation ideas, theoretical development and practical implementation, but are not explicitly framed as climate change adaptation (Dupuis and Biesbroek, 2013; Biesbroek et al., 2018; Keskitalo and Preston, 2019a). Therefore, debates still emerge about what actually counts as 'adaptation' (Dupuis and Biesbroek, 2013), and what knowledge is being assessed and measured for this purpose.

IPCC assessment reports combine two complementary approaches to adaptation research: that which is 'on' or 'about' adaptation and that which is 'for adaptation'. Both are needed because research 'on adaptation' helpfully investigates the phenomenon and processes of adaptation (e.g., via analyses of others' adaptation practices and efforts), while research 'for adaptation' generates knowledge that can enable the planning and implementation of adaptation (e.g., action research as part of an adaptive capacity-building process) (Swart et al., 2014).

One of the contributions of research 'on adaptation' is to track and debate the broader trends, core characteristics and overall assumptions embedded in adaptation knowledge. This reflexive turn about the foundational assumptions is itself one emerging trend in adaptation research (e.g., Preston et al., 2013; Nalau et al., 2015; Juhola, 2016; Atteridge and Remling, 2017). This signals the influence of more social science in adaptation research and increased awareness of the practical value of being transparent and critically reflective about the content, topics, frames and approaches that researchers use (Lacey et al., 2015; Nalau et al., 2021; Singh et al., 2021). For example, different conceptions of adaptation contribute to different definitions of 'adaptation success', different ideas about what 'effective' adaptation practice looks like and, thus, different conclusions about what is and is not working well (Berrang-Ford et al., 2019; Dilling et al., 2019; Magnan et al., 2020; Owen, 2020; Eriksen et al., 2021; Singh et al., 2021; Section 17.5.1.1). This diversity adds richness and options, but also poses challenges in constructing a conventional evidence base for decision and policymaking. Adaptation researchers are increasingly expected to offer clear and confident advice on adaptation success, yet are also increasingly aware of how context-specific and contested success is (see also Lacey et al., 2015 on ethics).

Grey literature on adaptation is also proliferating, typically authored by organisations funding and implementing adaptation. This literature often documents a range of adaptation strategies (Sections 9.8.3; 10.4.6.4; 14.4.3.3; 17.2.1.) and lived experiences of adaptation efforts, including helping give voice to marginalised groups, and highlighting the importance of IK and LK (Sections 4.7.5.4; 15.6.4; Box 9.2; Cross-Chapter Box INDIG in Chapter 18; Nunn et al., 2016; Petzold et al., 2020). However, most of the lessons learned through implementation of adaptation projects and programmes are still not captured in academic or even grey literature and thus remain less systematically analysed. Crucially, the large gaps in documentation of adaptation knowledge mean that a lack of published evidence about a given issue does not necessarily reflect its absence in real life—a qualification about adaptation research that readers of AR6 should appreciate.

The evolution of adaptation research trends

In the 1990s, climate change adaptation was constrained as a specific topic of inquiry by the dominant focus on mitigation of GHG emissions and the related assumption that successful mitigation would render unnecessary the need for adaptation beyond what human and natural systems could inherently manage (Pielke, 1998; Schipper, 2006; Schipper and Burton, 2009). Several key developments in the 1990s included IPCC's 2nd report (1996) and the establishment of several key journals including *Climatic Change* (1978), *Mitigation and Adaptation Strategies to Global Change* (1996) and the *Global Environmental Change* journal that strengthened more dedicated focus on climate change related research.

Many foundational papers on key concepts central to adaptation were published in the 1990s and early 2000s onwards (Burton, 1992; Smit, 1993; Smithers and Smit, 1997; Parry and Carter, 1998; Fankhauser et al., 1999; Smit et al., 1999; Pittock and Jones, 2000; Klein, 2003;

Cross-Chapter Box ADAPT (continued)

Adger et al., 2005), while adaptation began to gain more prominence in IPCC's 3rd assessment (2001) and 4th assessment (2007). For example, the Canada Climate Programme report (Smit, 1993) set out many of the principles of adaptation and was highly influential charting these concepts in IPCC's 3rd Assessment Report (Schipper and Burton, 2009). These papers and IPCC reports remain key foundations of climate adaptation science literature (Nalau and Verrall, 2021).

Helping to differentiate adaptation from mitigation during this period was a focus on theoretical principles and a framing of adaptation as local and context specific, in contrast to mitigation's global character (Nalau et al., 2015; Westoby et al., 2020), leading to locally oriented adaptation research and practice, including the rise of community-based adaptation (Kirkby et al., 2017). Since AR5, however, adaptation has extended beyond the local, recognising the 'borderless' character of many climate change risks and vulnerabilities (Benzie and Persson, 2019) and framing adaptation and global adaptation governance as a global public good (Persson, 2019). Encompassing this expanded scale is challenging for adaptation research compared to treating adaptation as a local issue, which fits more easily with social research methods. Adaptation now works across scales (Biesbroek et al., 2013; Dzebo and Stripple, 2015; Keskitalo and Preston, 2019a) and attends simultaneously to both the opportunities and risks arising from climate change (Juhola, 2016; Keskitalo and Preston, 2019a). This suggests that empirical adaptation research should incorporate multi-scalar research designs and methods.

A strong focus has been and remains on case studies of adaptation practice, but adaptation science literature reviews have become common. Recent systematic reviews cover topics such as adaptation effectiveness (Owen, 2020), public participation and engagement (Hügel and Davies, 2020), the role of LK (Klenk et al., 2017), adaptive capacity (Mortreux and Barnett, 2017; Siders, 2019a; Mortreux et al., 2020), evolution of adaptation science (Nalau and Verrall, 2021), empirical adaptation research in the Global South (Vincent and Cundill, 2021), how cities are adapting (Reckien et al., 2018), how decisions can be made (Siders and Pierce, 2021), IK (Petzold et al., 2020) and SIDS (Robinson, 2020). Review papers have developed common methodologies for how to undertake robust reviews in adaptation research (Berrang-Ford et al., 2015; Biesbroek et al., 2018; Lesnikowski et al., 2019a; Singh et al., 2020), and noted an existing imbalance as the majority of the literature still originates from the Global North compared to Global South (Robinson, 2020; Nalau and Verrall, 2021; Sietsma et al., 2021).

At the same time, adaptation research is also challenged by increasing attention to transformational adaptation, which refers to fundamental changes going beyond existing practices, including new approaches to adaptation decision making (Section 1.5). Whereas AR5 noted transformational adaptation as an area of future research (Klein et al., 2014b), it has continued to grow in profile since then. Rather than a future or fringe consideration—for example, an extreme action necessitated by the limits of incremental adaptation— transformational adaptation is increasingly an option that decision makers are considering today. This increasing attention to transformational adaptation is driven by a growing recognition of climate risks and impacts, as well as the need for urgent, systemic action as laid out in the IPCC's recent special reports (IPCC, 2018c). Yet what incremental and transformational adaptation look like, how they relate in practice and how to appropriately choose incremental or transformational options is uncertain and increasingly debated (Section 17.2.2.3; Termeer et al., 2016; Few et al., 2017; Vermeulen et al., 2018; Magnan et al., 2020; Wilson et al., 2020). One of the main challenges is now to generate empirical evidence and policy relevant insights on transformational adaptation (e.g., Jakku et al., 2016). Transformative approaches are especially being discussed in the context of COVID-19 (Schipper et al., 2020; Cross-Chapter Box COVID in Chapter 7).

Increasingly reflective adaptation research

Another characteristic of recent adaptation research is a stronger focus on ethics, justice and power (Byskov et al., 2021; Coggins et al., 2021; Eriksen et al., 2021; Singh et al., 2021). Researchers and practitioners are increasingly impatient to address the root causes of vulnerability and use inclusive climate adaptation processes to generate effective adaptation responses for marginalised and misrecognised groups (Tschakert et al., 2013; Eriksen et al., 2015; Scoones et al., 2015; Gillard et al., 2016; Wisner, 2016). Increasingly ambitious, normative adaptation research often challenges technological solutions that simply reinforce the existing *status quo* (Nightingale et al., 2019, p. 2) and calls for 'socially just pathways for change'. Here work on adaptation overlaps with mitigation, transitions and other large-scale social change, encouraging the move towards more systemic, integrated approaches that discern between options according to multiple criteria (Goldman et al., 2018).

Fundamental questions about equity and justice in adaptation include gender and intersectionality (see Cross-Chapter Box GENDER in Chapter 18; Section 1.4.1.1; Chapter 18;) and broader critiques of who participates in processes of adaptation planning and implementation, who receives investments, who and what benefits from them, who makes key decisions regarding adjustments through time (Taylor et al., 2014; Boeckmann and Zeeb, 2016; Nightingale et al., 2019; Pelling and Garschagen, 2019; Byskov et al., 2021; Eriksen et al., 2021) and

Cross-Chapter Box ADAPT (continued)

how climate justice intersects with other justice agendas. Attention is also turning to relations and tensions between different adaptation approaches, scales, constraints, limits, losses, enablers and outcomes (Barnett et al., 2015; Pelling et al., 2015; Mechler and Schinko, 2016; Crichton and Esteban, 2017; Gharbaoui and Blocher, 2017; Deshpande et al., 2018; McNamara and Jackson, 2019). Evident here is an ongoing, serious knowledge gap around the long-term repercussions of adaptation interventions. There is growing awareness of the need to address the potential for maladaptation (Sections 1.4.2.4; 5.13.3; 15.5.1; 17.5.2; Chapter 4). Concerns about maladaptation have led to renewed calls to open the 'black box' of decision making to examine the influence of power relationships, politics and institutional culture (Biesbroek et al., 2013; Eriksen et al., 2015; Goldman et al., 2018), including the power–adaptation linkage itself (Woroniecki et al., 2019), external factors outside the decision-making process (Eisenack et al., 2014) and the influence of leadership on adaptation processes and outcomes (Meijerink et al., 2014; Vignola et al., 2017).

All of these developments indicate that adaptation research is not only more reflexive about some of its central assumptions, methodologies and tools (Biesbroek et al., 2013; Conway and Mustelin, 2014; Nalau et al., 2015; Nightingale, 2015a; Porter et al., 2015; Eriksen et al., 2015; Lubell and Niles, 2019; Woroniecki et al., 2019; Singh et al., 2021), but also cognisant of the need to critically consider its underpinning goals, purpose and impact in the world.

national adaptation planning to better characterise its potential merits, shortcomings and effects (Woodruff and Regan, 2019; UNEP et al., 2021) and have compiled inventories of adaptation projects (Leiter, 2021) and local adaptation policies (Reckien et al., 2018;Lesnikowski et al., 2019b; Olazabal et al., 2019; see also Section 6.4.6). Chapters 16 and 17 of this report offer an initial synthesis, but efforts to compile a comprehensive global, empirical inventory of climate change adaptation remain in an early phase (e.g., Tompkins et al., 2010; Berrang-Ford et al., 2011; GEF, 2011; Ford et al., 2015; Lesnikowski et al., 2016; Fankhauser, 2017; Leiter, 2021; Tompkins et al., 2018).

Improving effectiveness: Information regarding the effectiveness of adaptation remains scarce (UNEP et al., 2021), which hinders efforts to improve adaptation practice. A recent comprehensive review found that only 2.3% of the close to 1700 articles identified by the Global Adaptation Mapping Initiative as documenting implemented adaptation provide evidence of risk reduction (Chapter 16; Berrang-Ford, 2020). However, there is limited but emerging evidence of the use of M&E by different actors to assess adaptation progress (Section 17.5.1).

Existing case studies use varying criteria for assessing effectiveness, complicating comparisons. Judgements regarding successful adaptation are contingent on the chosen scale and perspective (success for whom?) (Adger et al., 2005; Dilling et al., 2019) and on the level of risk, that is increasing climate risks may cause previously successful adaptation to become insufficient. Rather than a binary outcome (successful or unsuccessful), adaptation can be viewed on a continuum from successful adaptation to maladaptation (Section 17.5.2). Assessments of adaptation success need to account for distributional effects and differential vulnerability, as well as consider connections across different scales and complex interactions with other change processes (Section 17.5.1). Recent literature has begun to identify how adaptation can better achieve its intended objectives (Eriksen et al., 2021). For instance, inclusive M&E can legitimise and validate M&E and foster commitment and learning.

Informing ongoing adaptation: Iterative risk management involves an ongoing cycle of assessment, action, learning and response in which M&E plays a central, enabling role (Section 1.2.1.1). Assessing the risk reduction provided by adaptation, both planned and implemented, often requires projections of anticipated future climate, socioeconomic conditions, and the effectiveness and implications for justice of each option (Section 17.4.4). Understanding the potential for maladaptation may also require such assessments (Section 1.4.2). Processes, such as adaptive pathways, that involve anticipating future responses (Boxes 11.4; 11.6; Sections 11.7; 17.3) entail monitoring to detect early warning of approaching thresholds or changes in the solution space (e.g., more rapid than expected sea level rise or new social acceptance of managed retreat) that suggest the need or opportunity to adjust or expand current adaptation efforts (Haasnoot et al., 2021).

1.4.4 Limits to Adaptation

The effectiveness of adaptation efforts also depends on the constraints and limits that human and natural systems face when confronted with increasingly higher levels of climate risks. The concept of adaptation limits strongly affects any appropriate balance among adaptation and mitigation actions in the sense that less mitigation makes adaptation harder or even infeasible. **Adaptation limits** refer to the point at which an actor's objectives (or system needs) cannot be secured from intolerable risks through adaptive actions (Annex II: Glossary). Adaptation limits can be soft or hard. **Soft adaptation limits** occur when options may exist but are currently not available to avoid intolerable risks through adaptive actions and **hard adaptation limits** occur when no adaptive actions are possible to avoid intolerable risks. Intolerable risks are those which fundamentally threaten a private or social norm—threatening, for instance, public safety, continuity of traditions, a legal standard or a social contract—despite adaptive action having been taken (Dow et. al. 2013). Intolerable risks threaten core social objectives associated with health, welfare, security or sustainability (WGII AR5 Chapter 16, Klein et al., 2014b). Through the lens of resilience, hard limits represent the range of change or disturbance beyond which a system cannot maintain its essential function, identity and structure. Soft limits represent the range of change or disturbance of a system which can be sustained over time by innovation or policy changes. The level of GHG emissions reduction, adaptation and risk management measures are the key factors determining if and when adaptation limits are reached.

1.4.4.1 Limits to Adaptation and Relation to Transformation

A species' ability to adapt may be significantly impacted by the dynamics of interactions between the ecosystems and species, so that a species may reach its limit to adapt even in a gradually changing environment, leading to sudden changes in range fragmentation (Radchuk et al., 2019). As human interventions affect the ability of species and ecosystems to adapt, a deeper understanding on ecosystems and species interactions and evolution in response to climate change is important in order to reduce future biodiversity losses (Nadeau and Urban, 2019). Soft limits are usually associated with human systems whereas hard limits are more proximate for natural systems due to inability to adapt to biophysical changes (Chapter 16) (*medium confidence*). Many human and natural systems are near their soft adaptation limits for instance, terrestrial and aquatic species and ecosystems, coastal communities, water security, crop production, and human health (Chapters 2;3; 4; 5; 7; 16; Dow et al., 2013).

The concept of limits to adaptation is dynamic in terms of the temporal, spatial and contextual dimensions of climate change risks, impacts and responses (Chapter 17; Storch, 2018). Adaptation limits depend on a complex function of interactions between social, ecological, technological and climatic elements, which appear to have thresholds beyond which adaptation can be infeasible and represent limits to adaptation. Such thresholds are endogenous to society and hence contingent on ethics, knowledge, attitudes, culture, governance, institutions and policies (Abrahamson et al., 2009; Tschakert et al., 2017). Since AR5, the evidence on limits to adaptation has been advanced across regions and sectors. Many adaptation constraints (financial, governance, institutional and policy, etc.) lead to soft adaptation limits (see Chapter 16 for detailed evidence on constraints and adaptation limits). The ability of actors to overcome these constraints including social constraints to behavioural changes, depends on additional adaptation implementation. (Abrahamson et al., 2009; Juan, 2011; Di Virgilio et al., 2019). Thus, socioeconomic, technological, governance and institutional systems or policies can be changed or transformed in responses to the different dimension of adaptation limits to climate change and extreme events.

When a limit (soft) is reached, then intolerable risks and impacts may occur, and additional adaptations (incremental or transformational) are required.to reduce or avoid these risks and impacts (Chapters 16; 17). IPCC SR1.5 defined incremental adaptation that maintains the essence and integrity of a system or process at a given scale, whereas transformational adaptation that changes the fundamental attributes of a socio-ecological system in anticipation of climate change and its impacts. When incremental adaptation is insufficient to avoid intolerable risks, transformational adaptation may be able to extend the potential to sustain human and natural systems (IPCC, 2018a; Cross-Chapter Box LOSS in Chapter 17; Klein et al., 2014b). Transformational adaptation can allow a system to extend beyond its soft limits and prevent soft limits from becoming hard limits. This report provides evidence of assessing transformational adaptation in terms of scope, depth, speed and limits to adaptation (Chapter 16).

This report assesses adaptation limits (soft and hard) and residual risks for some actors and systems (Chapter 16). **Residual risk** is the risk that remains following adaptation and risk reduction efforts (SROCC). Residual risk is also used as other terms such as 'residual impacts', 'residual loss and damage' and 'residual damage'. As noted in AR5 WGII (IPCC, 2014a, b), the residual risk is larger or smaller depending on a society's choices about the appropriate level of adaptation and its ability to achieve an appropriate level. The intersection of inequality and poverty presents significant adaptation limits, resulting in residual impacts for vulnerable groups, including women, youth, elderly, ethnic and religious minorities, Indigenous People and refugees (Section 8.4.5). An appropriate level of adaptation, which ideally reflects a balance between the desired level of risk and the actions needed to achieve that level of risk, depends on the solution space, the society's views on climate justice, the tolerance for climate-related risks, the society's tolerance for the costs and other impacts of the actions needed to reduce risk. IPCC's special reports stated that residual risks rise with increasing global temperatures from 1.5°C to 2°C (SR 1.5) and emerge from irreversible forms of land degradation (SRCCL). Among other risks, this report evidenced that, at risk to coastal flooding from sea level rise, nature-based adaptation measures (e.g., coral reefs, mangroves, marshes) reach hard limits beginning at 1.5◦C of global warming (Chapter 16). Residual risks may lead to exceeding the limits of adaptation, hence, this report underscores on the role of decision making on transformational adaptation for dealing with residual risk as well as soft and hard adaptation limits (Cross-Chapter Box LOSS in Chapter 17). Section 1.5 addresses transformational adaptation in the context of climate resilient development pathways since such adaptation is inseparable from mitigation and sustainable development.

1.4.4.2 Emerging Importance of Loss and Damage

The concept of **Loss and Damage** (with capitalised letters, L&D) refers to the discussion point under the UNFCCC, which is to 'address loss and damage associated with impacts of climate change, including extreme events and slow onset events, in developing countries that are particularly vulnerable to the adverse effects of climate change'. Lowercase letters of **losses and damages** refer broadly to harm from (observed) impacts and (projected) risks (IPCC, 2018a). The IPCC report uses the latter for its assessment on loss and damage which may provide useful information for the former. L&D associated with climate change has gained importance supported by the robust scientific evidence on anthropogenic climate change amplifying the frequency, intensity and duration of climate-related hazards (Mechler et al., 2019). Loss and damage associated with those residual losses and damages that are felt beyond the adaptation actions taken imply a sense of limits to adaptation at a given time and within a spatial context (Tschakert et al., 2017). IPCC's SRCCL also underlined the unavoidable loss and damage due to changes in tropical and extratropical cyclones and marine heatwaves, where adaptation and resilience limits are being exceeded for the people and ecosystems (Cross-Chapter Box LOSS in Chapter 17; IPCC, 2019a).

Loss and damage has emerged as an important topic in international climate policy (Surminski and Lopez, 2015; Roberts and Pelling, 2016;

Boyd et al., 2017). It originated in assessing compensation for SIDS, related to sea level rise impacts. It has since become formalised under the UNFCCC, through the establishment of the Warsaw International Mechanism (UNFCCC, 2013) and Article 8 of the Paris Agreement (UNFCCC, 2015b). The Warsaw International Mechanism promotes the implementation of comprehensive risk management approaches, improves understanding of slow onset events, non-economic losses and human mobility (migration, displacement), and enhances action and support, including finance, technology and capacity building to avert, minimise and address loss and damage associated with climate change impacts, particularly on vulnerable and developing countries (UNFCCC, 2021). Different actors have defined loss and damage differently in reference to climate change impacts and responses (Surminski and Lopez, 2015; Roberts and Pelling, 2016; Boyd et al., 2017; McNamara and Jackson, 2019). These understandings include the following: (a) an adaptation and mitigation perspective linking all human-induced climate change impacts to potential loss and damage and a mandate to avoid dangerous anthropogenic interference; (b) a risk management perspective emphasising interconnections among disaster risk reduction, climate change adaptation and humanitarian efforts; (c) a limits to adaptation perspective focused on residual loss and damage beyond adaptation and mitigation; and (d) an existential perspective highlighting inevitable harm and unavoidable transformation for some people and systems. This report assesses the growing literature on loss and damage across sectors and regions linking with adaptation constraints and limits, GWL and incremental and or transformational adaptation to climate risks (Section 8.3.4; Cross-Chapter Box LOSS in Chapter 17; Box 10.7).

To assess the projected losses and damages, residual risks also need to be taken into account. The loss and damage associated with the future climate change impacts, beyond the limits to adaptation, is an area of increasing focus, although yet to be fully developed in terms of methods of assessment. This includes non-economic losses and damages, as well as identifying means to avoid and reduce both economic (loss of asset, infrastructure, land etc.) and non-economic (loss of societal beliefs and values, cultural heritage, biodiversity and ecosystem services) losses and damages (Fankhauser and Dietz, 2014; Andrei et al., 2015). There is increasing evidence of economic and non-economic losses due to climate extremes and slow onset events under observed increases in global temperatures (Section 8.3.4; Coronese et al., 2019; Grinsted et al., 2019; Kahn et al., 2019), however assessment of non-economic losses and damages is lacking and needs more attention (Serdeczny et al., 2016; Tschakert et al., 2019). The aggregate losses and damages would be higher if non-economic values are considered in such assessment (Laurila-Pant et al., 2015; McShane, 2017). To reduce or avoid loss and damage, there is a need for robust conceptual framework and analysis, focusing on future losses rather than past losses (Preston, 2017). This should have an emphasis on avoiding versus addressing loss and damage and the role of justice (Boyd et al., 2017), clarity on detection and attribution (Sections 8.2.1; 8.3.3), effectiveness of risk management and adaptation (Cross-Chapter Box FEASIB in Chapter 18; Section 1.4), the concepts of risk transfer, liability and financing (Cross-Chapter Box FINANCE in Chapter 17; Section 17.4.2) and the role of transformation (Section 1.5).

1.5 Facilitating Long-Term Transformation

This report highlights that transformative system change is required to meet the SDGs (Chapter 18). **Transformation** is defined as 'a change in the fundamental attributes of a system including altered goals or values' (SR 1.5). The related concept of **transition** is defined as 'the process of changing from one state or condition to another in a given period of time' (IPCC SR 1.5/SRCCL; also see Section 1.5.2).

Many time scales have been assessed that shape the context for any such transformations: including the present, 2030 and mid-century (Cross-Chapter Box CLIMATE in Chapter 1). In the present, significant changes in the climate system have already occurred in many places (WGI), while commensurate adaptation actions have in general been lacking (Chapter 16). By 2030, the SDGs call for significant societal changes, many of which would be more difficult to achieve without significant reductions in climate risk and impacts. By mid-century, global emissions pathways consistent with the Paris Agreement 1.5°C target drop to zero net GHG emissions with no overshoot and roughly a decade later with overshoot (Cross-Chapter Box CLIMATE in Chapter 1). Pathways consistent with the Paris 2°C target drop to zero net emissions in the latter half of the 21st century. Even in low emission scenarios, temperatures, storm intensities, sea levels and other climate parameters are expected to continue to change for decades (IPCC, 2021a).

The concepts of transition and transformation help organise assessments of near- and longer-term adaptation actions that may prove feasible and effective in achieving societal goals related to climate and sustainable development.

1.5.1 Understanding Transformation

Over the last 200 years, human society has undergone a rapid and profound transformation, with population and income per capita expanding by an order of magnitude or more after many millennia of relative stasis in living standards (Dasgupta et al., 2018). The transformations associated with sustainable development and managing climate risk may be of similar scale as these historic transformations. In the past, changes in technologies and economies of this scale are not separate from, but are necessarily embedded alongside changes in political, religious and social relationships (Polanyi, 1957). Future transformation may similarly involve such interlinked social, cultural, economic, environmental, technical and political factors (Chapter 18; Section 1.5.2). Technology-led, market-led or state-led transitions aimed at meeting Paris Agreement and SDGs may fail without integrating dimensions of social justice and addressing the social and political exclusion that prevent the disadvantaged from accessing such improvements and increasing their incomes (Burkett et al., 2014; Scoones et al., 2015) (*medium confidence*).

As used in the global environmental change literature, transformation is a pluralistic concept embracing many interpretations (Box 18.3), but all focus on the general idea of fundamental change in society as opposed to change that is minor, marginal or incremental. Uses of the term can differ with respect to: (a) how the system undergoing change is conceptualised, (b) the extent to which change is continuous or discontinuous and the time scales involved, (c) the extent to which transformation is guided towards desired goals or emerges without intent and (d) whether the usage focuses on descriptions of societal processes or includes normative judgements as to which outcomes should or should not occur (Feola, 2015) . The literature generally uses transformation as an analytic-descriptive concept, which aims to describe significant change in couple human–natural systems, or as a solutions-oriented concept, which aims to inform or contribute to societal change.

The IPCC Fifth Assessment cycle, starting with its Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation (SREX), first highlighted the concept of transformation, drawing primarily on the solutions-oriented approaches of O'Brien (2011) and Pelling (2011). This Sixth Assessment report also generally employs transformation as a solutions-oriented concept, with mention in almost all chapters and significant emphasis in the synthesis chapters.

The IPCC Sixth Assessment cycle also highlights the concept of transition, drawn from the sustainability transitions literature (Köhler et al., 2019). The 1.5 SR organises its assessments of feasibility and potential policy actions around transitions in four socio-technical system: energy, land, urban and infrastructure, and industrial systems (IPCC, 2018b, Chapter 4). This report adds a fifth system transition—a societal transition focused on attributes that drive innovation, the evolution of patterns of consumption and development and power relationships among societal actors (Section 18.1.4). The AR6 WGIII report is organised around six systems transitions: energy; agricultural, forestry, other land use; urban; buildings; transportation; and industry, which includes supply chains and the circular economy.

The literature offers multiple views on the relationships between transition and transformation (Box 18.3). The 1.5 SR suggests that transformation is needed to generate the four system transitions. In many literatures, transformation is considered a more expansive process than transition, with the former less exclusively focused on socio-technical systems and more engaged with questions of power, politics, capabilities, culture, identity and sense-making (Gillard et al., 2016; Hölscher et al., 2018; Linnér and Wibeck, 2019). This report generally takes this more expansive view of transformation to engage with issues of equity, climate justice and large-scale institutional and societal change (Box 18.3).

This WGII report has a particular focus on **transformational adaptation** (Section 1.4.4.1), which it views as laying on a continuum from incremental and transformational with no sharp division between them (Sections 1.5.2; 17.2.2.3).

The IPCC first highlighted the concept of transformational adaptation in SREX. SREX generally used the phrase transformation to refer to fundamental societal changes that advance climate adaptation, disaster risk management and sustainable development. Transformation was seen as one part of the solution space alongside options such as reducing vulnerability and exposure, and increasing resilience for managing risk. WGII of the IPCC Fifth Assessment Report used the phrase 'transformational adaptation' to contrast with 'incremental adaptation'. That report used the former term to refer to: (a) adaptation at large scope or scale, (b) the type of adaptation that occurs once soft limits have been breached, or (c) change that addresses root causes of vulnerability as well as redressing long-standing inequities. The Fifth Assessment Report's WGIII employed the concepts of transformation and transformation pathways to assess the large-scale societal changes needed to meet GHG emission reduction goals.

This WGII report focuses on transformational adaptation as one component of climate resilient development in which adaptation, mitigation and development solutions are pursued together to exploit synergies and reduce trade-offs among these actions (Section 1.5.3; Chapter 18). Chapter 16 assesses the extent to which transformational adaptation is currently being implemented, using criteria including the scope, depth and speed of the adaptation actions, as well as the extent to which limits to adaptation have been considered (Section 16.3.2.4). Chapter 17 ranks potential adaptation options by where they lie on the incremental to transformational continuum (Section 17.2.2.4).

Societal transformation can arise without explicit intent as, arguably, did the industrial revolution and some of the trends re-making today's society (see Section 1.1). In order to help policymakers achieve societal goals, this report seeks to identify the conditions for **deliberate transformations**, that is, those envisioned and intended by at least some societal actors (Linnér and Wibeck, 2019).

Figure 1.9 connects several key concepts that this report employs to help distinguish pathways that lead to deliberative and forced transformations. As shown in the figure, adaptation goals might imply a desired level of adaptation: (a) accessible by actions within the solution space of the existing system or (b) beyond the solution space of the existing system. In the former case, incremental adaptation may stay within soft limits and hold risks to tolerable levels that avoid threatening private or social norms (also see Figure 17.6). In the latter case, deliberate transformational adaptation is necessary to reach the goals. Alternatively, if deliberate transformation does not successfully occur or hard limits are exceeded, the system may nonetheless undergo some type of forced transformation which results in outcomes inconsistent with societal goals. While the figure shows single decision points, multiple actors are involved at each stage. Thus, some people may find themselves coping with what they regard as intolerable risks which are not otherwise avoided. Often such coping situations display significant inequities, with tolerable risks for powerful groups and intolerable ones for marginalised groups.

Multiple narratives describe pathways for pursuing deliberate transformations (Cavanagh and Benjaminsen, 2017). While building on the new 'green economy' framing that emerged with the Rio+20 conference in 2012 (UNEP, 2011; De Mello and Dutz, 2012; OECD, 2012), these narratives reflect differing trade-offs among values and differing assumptions about the factors driving system change (see WGIII). The narratives range from 'business-as-usual' scenarios focused on modernisation of sectors such as energy, agriculture and use of natural resources to more transformational propositions such as various green new deal proposals (European Commission, 2019), the new climate economy (Global Commission on the Economy and Climate, 2018), and 'doughnut economics' (Raworth, 2017). Some literature suggests significant benefits from such new climate economy proposals, claiming

Alternative Pathways to Transformation

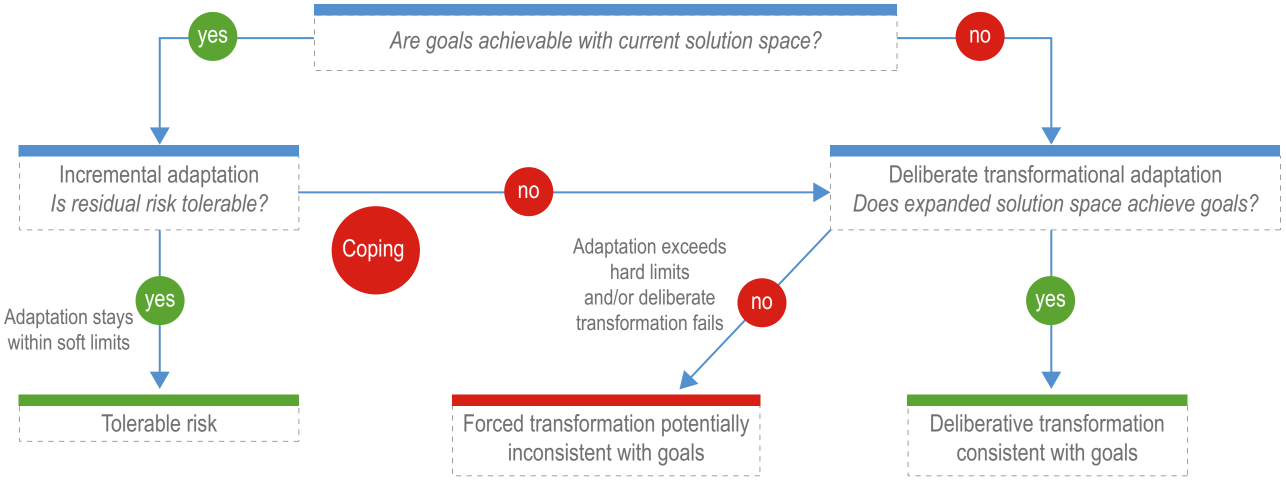


Figure 1.9 | Alternative pathways to transformation. Adaptation goals may be accessible by actions within or beyond the existing solution space. In the former case, incremental adaptation may stay within soft limits and hold risks to tolerable levels. In the latter case, deliberate transformational adaptation becomes necessary to achieve goals. If a successful deliberate transformation does not occur, the system may nonetheless undergo a forced transformation. Multiple actors are involved at each stage so that some people may nonetheless find themselves coping with what they regard as intolerable risks.

tens of trillions in economic benefits, tens of millions of new jobs and close to a million fewer premature deaths from pollution over the coming decade (Global Commission on the Economy and Climate, 2018).

Two contrasting schools of thought, called ecomodernism and degrowth (D'Alisa et al., 2014), offer important bounding narratives for 'green economy' approaches that aim achieve the SDGs and Paris Agreement goals.

Ecomodernism aims to decouple GHG emissions and other environmental impacts from GDP growth (WGIII Section 1.4.1; Desrochers and Szurmak., 2020) through three primary strategies: (a) 'green' technological innovation, (b) resource efficiency or productivity improvements and (c) the sustainable intensification of land use in both rural and urban areas (Asafu-Adjaye et al., 2015; Isenhour, 2016). Such efforts to mobilise large-scale investment in climate change adaptation and to decouple GDP growth from environmental impacts could generate substantial employment opportunities and open up profitable investment frontiers (Asafu-Adjaye et al., 2015; Adelman, 2018), which could help achieve SDG 8, which calls for accelerated annual growth rates of at least 7% in least developed countries and achieve SDG 10, which calls for 'income growth of the bottom 40% of the population at a rate higher than the national average'.

Degrowth proponents question the feasibility of decoupling at a scale and rate sufficient to meet Paris Agreement goals (Kallis, 2017; Parrique et al., 2019; Gómez-Baggethun, 2020; Hickel and Kallis, 2020). Using precautionary principle-rooted arguments (Latouche, 2001), degrowth aims for intentional decreases in both GDP and coupled GHG emissions (Kallis, 2011) using policy mechanisms such a 'cap and share' framework for distributing emissions permits on an annually declining basis with legislation to prohibit the overshoot of established carbon budgets (Douthwaite, 2012; Kallis et al., 2012). Degrowth thus seeks to minimise reliance on negative emissions technologies, such as the large-scale deployment of BECCS (e.g., illustrative emissions reduction pathway labelled P4 in IPCC SR1.5, IPCC, 2018b; also WGIII Chapter 3) and aims to generate progress toward achieving the SDGs by prioritising redistribution rather than GDP growth. SDGs potentially addressed by degrowth include universal basic income (SDGs 1 and 10), work-sharing to guarantee full employment (SDGs 8 and 10) and shifting taxation burdens from income to resource and energy extraction (SDGs 8 and 12).

The contrasting premises of ecomodernism and degrowth have prompted a series of mutual counterarguments. Degrowth scholars emphasise that global absolute decoupling is currently not proceeding fast enough to meet Paris Agreement targets (Ward et al., 2016; Moreau et al., 2019; Haberl et al., 2020). Ecomodernists point to important progress towards achieving absolute decoupling at the national or regional scale—as shown by Le Quéré et al. (2019) in 18 developed countries—and the future potential of emerging technologies and policy reforms (Asafu-Adjaye et al., 2015)

1.5.2 Enabling Transformation

As one important theme, this Sixth Assessment report assesses who needs to take what actions and when in order that transformations unfold at sufficient speed and scale to meet the Paris Agreement, the SDGs and other policy goals. A number of literatures inform these assessments.

Various literatures describe multiple, co-evolving societal elements which organise themselves into stable regimes that, under some circumstances, can undergo significant change. The sustainability transitions literature provides one central focus for understanding such processes and potential intervention points for actors seeking change

(Köhler et al., 2019). This literature identifies three, interacting scales: the micro, meso and macro.(Geels, 2004; Köhler et al., 2019) The micro level reflects changing individual choices, attitudes and motivations. The meso reflects socio-technical systems, 'a cluster of elements, including technology, regulations, user practices and markets, cultural meanings, infrastructure, maintenance networks and supply networks' (Geels, 2004, p. 436). The macro reflects the cultures, institutions, norms, governance and other broad organising features of society. The sustainability transitions literature generally focuses on change that originates and occurs within the meso scale, while the transformation literature focuses on change within and among all scales. This Working Group II report often considers three interacting scales labelled personal, practical and political (O'Brien and Sygna, 2013). Working Group III often employs the multi-level perspectives framework (Geels, 2004) and the more actor-oriented three domains of decision making framework (WGIII Section 1.6.4; Grubb et al., 2014;) to describe related societal scales.

These literatures describe similar processes through which these interacting elements generate significant system change. In the sustainability transitions literature, the process begins with a stable system of actors, technologies and institutions (Köhler et al., 2019). Radical innovations begin in niches or protected spaces, sometimes introduced by new entrants or outsiders. Successful innovations expand in scale, scope and geographically, and ultimately help generate new regimes. Incumbent actors can support or resist innovations through combinations of government policies, economic forces and institutional and behavioural pressures. Such processes can, but need not, follow a common S-curve pattern of initial adoption, take-off, acceleration and stabilisation (Rotmans et al., 2001). The multi-level perspectives literature in WGIII similarly describes innovations as moving from niches to socio-technical regimes, at first mediated by and then potentially altering exogenous socio-technical landscapes (WGIII Section 1.6.4; Smith et al., 2010).

The socio-ecological systems literature, a main source of the resilience concept, focuses on the system elements of society and ecosystems, their interdependence and on how they change in response to shocks (Section 1.2.1.4). Coupled human and natural systems maintain their vital functions through what are called adaptive cycles that begin with growth, reach a period of stasis, experience a disruption and then reorganise. This repeating cycle can leave the system unchanged or transition it to new states. Human agency can alter system characteristics so that after any disruption the system will reorganise into a different, more desired state, guide the reorganisation in desired directions after a system shock (such as a natural disaster) or provide the shock that catalyses a reorganisation.

These literatures view incremental and transformational change as linked processes. In the transformational adaptation literature, Park et al. (2012) consider incremental and transformational adaptation as two concentric and linked action-learning cycles with similar steps that include monitoring and learning. Systems generally reside in the incremental cycle but can temporarily jump to the transformational cycle before returning to the incremental, albeit in a state with fundamentally changed attributes. Shifts from the incremental to transformational cycle are made possible by knowledge and skills, as well as adjustments to vision, agendas and coalitions achieved through monitoring and learning. The incremental cycle is characterised by reactive responses to external drivers and performance evaluation relative to past performance. Shifts to the transformational cycle are characterised by more pro-active responses and more expansive problem framings.

The socio-ecological and sustainability transitions literature describes transitions as often nonlinear, characterised by tipping point behaviour with periods of relative stability interspersed with periods of more rapid change as thresholds are crossed (van Ginkel et al., 2020). Actors seeking transformation may take incremental steps that aim to induce such tipping point behaviour (Otto et al., 2020b). For instance, full accounting of climate risk in insurance and financial lending decisions could similarly act as such social tipping point interventions for adaptation (Hill and Martinez-Diaz, 2019). Transformations need not, however, be equitable or smooth. Historical examples suggest the potential for rigidity traps, in which suppression of innovation and a high degree of connectivity in a system delay an eventual transformation, which, when it eventually occurs, unfolds as exceptionally harsh (Hegmon et al., 2008).

Many actors can contribute to launching or blocking significant system change. Pelling et al. (2015) highlights power relationships within and among activity spheres that influence the process of transformational adaptation and distribution of risks. In the sustainability transitions literature each set of actors—including those from academia, politics, industry, civil society and households—brings their own resources, capabilities, beliefs, strategies and interests, which affects their interest, objectives, ability to affect the process and their ability to affect others (Kern and Rogge, 2018).

There is no consensus in the literature on the best means for actors to pursue deliberate transformation (Section 1.5.1) and the extent to which actors can guide the process. The transitions and some transformation literature derive from a complex systems perspective (Section 1.3.1.2; Köhler et al., 2019; Linnér and Wibeck, 2019) in which behaviours can be understood but not predicted (Chapter 17; Mitchell, 2009). These literatures suggest that interventions in such systems will rarely result in them evolving along some pre-determined pathway. Rather, successful interventions more often resemble iterative processes of action, observation and response, which are described in the literature with terms such as iterative risk management (Section 17.2.1), clumsy solutions (Thompson and Rayner, 1998; Linnér and Wibeck, 2019), probe and response (Chapter 17; French, 2013) and what Young (2017) calls adaptive governance.

These literatures view transformation as a collective action challenge among actors with both common and differing values, interests and capabilities interacting over time with a mix of cooperation and competition (Young, 2017; Dasgupta et al., 2018). Concepts such as radical incremental transformation (Göpel, 2016), direct incrementalism (Grunwald 2007) and progressive incrementalism (Levin et al., 2012) envision strategies in which actors pursue incremental actions in one or more niches that move the current system towards tipping points which, once crossed, will drive the system to a new state (Tàbara et al., 2018). The incremental actions aim to promote learning, remove barriers to change (Dasgupta et al., 2018; Baresi et al., 2020), create a series of wins that generate momentum and generate positive feedbacks (e.g., by creating constituencies) such that the speed and scale of the climate action grows over time (Levin et al., 2012). However, incremental strategies can fail to move fast enough, can succumb to path-dependency that locks in initially helpful but long-term adverse responses (such as the well-known levee effect) (Sadoff 2015; Haasnoot 2019) or can result in a transition that meets some goals (e.g., environmental) but not others (e.g., equity) (*high confidence*).

This report describes decision frameworks and tools that can help those involved in such a process—acting independently or collectively—identify, evaluate, seek compromise on and then implement sequences of solutions that lead to pathways with more desirable outcomes and avoid pathways with less desirable outcomes (Section 17.3.1). For instance, adaptive (also called adaptation) pathways (Cross-Chapter Boxes SLR in Chapter 3 and DEEP in Chapter 17) explicitly chart alternative sequences of actions including near-term steps, indicators to monitor and contingency actions to take if pre-determined monitoring thresholds are breached. Employed in contexts with multiple actors and contested values, adaptive pathways frame deliberate transformation as both a near-term decision problem focused on physical, financial and natural resources, as well as a social change process of co-evolving knowledge, policies, institutions, values, rules and norms (Fazey et al., 2016). Transition management (Loorbach, 2010), rooted in the sustainability transitions literature, supports arenas of actors that co-produce visions of future change, plan pathways and recruit additional actors into the change process.

As a central feature, such frameworks and tools embrace: (a) multiple objectives and measures (Section 1.4.1.2) to help identify and consider trade-offs among parties with a diversity of interests, values and objectives and (b) multiple scenarios that enable stress-testing of proposed actions to identify conditions in which they would fail to meet their goals and thus inform consideration of ways to make those actions more robust and resilient over multiple futures in the near and longer term (Chapter 17; Cross-Chapter Box DEEP in Chapter 17). A focus on single or overly aggregated measures (Section 1.4.1.2) and single scenarios can privilege some actors' views over others, reduce transparency and make it more difficult to identify resilient and equitable solutions to complex, deeply uncertain, non-linear and contested problems (Schoen and and Rein, 1994; Renn, 2008; Jones et al., 2014; Lempert and Turner, 2020) (*medium confidence*).

Nonetheless, most concepts of deliberate transformation also emphasise the importance of common goals and principles within a process of goal setting, acting on those goals, M&E and readjustment. Such goals encourage pro-active action, help align the activities of multiple, loosely co-ordinated actors (Göpel, 2016; Dasgupta et al., 2018) and provide benchmarks against which to measure progress (Young, 2017). The Paris Agreement and SDGs aim to provide such common goals for the world as a whole and implement what some have described as goal-based as opposed to rule-based governance for galvanising collective action (Sachs, 2015; Kanie and Biermann, 2017). As intended, many public sector, private sector and civil society actors have developed their own goals that aim to align with the Paris Agreement and the SDGs (see Section 1.1). The existence of goals that help people envision a future significantly different than present can be one, often key, difference between decision processes that pursue transformational as opposed to incremental change (Park et al., 2012; Chapter 17). Narratives that help explain where a community is, where it wants to go and how it intends to get there are an important enabler of transformation (Sections 1.5.1; 1.2.3; Linnér and Wibeck, 2019; Fazey et al., 2020).

1.5.3 Climate Resilient Development

Adaptation and mitigation can reduce climate-related risks. Implementing these two types of climate action together increases their effectiveness by exploiting synergies and reducing trade-offs among them. In addition, implementing adaptation and mitigation as an integral part of development can similarly make all three more effective (Section 18.2.3). The link between climate change and sustainable development has long been recognised and has been assessed in every Working Group II report since AR3. AR5 introduced the concept of climate resilient development to help assess development trajectories that include co-ordinated adaptation and mitigation actions aimed at reducing climate risk.

Building on AR5, this AR6 report expands the focus with increased attention to equity and the processes needed to follow such trajectories. AR6 thus defines **climate resilient development** as 'a process of implementing GHG mitigation and adaptation solutions to support sustainable development for all' (Section 18.1.1). In AR6 WGII, some chapters have a section dedicated to climate resilient development, emphasising the need for integrative and transformative solutions within a sector or region that address the uneven distribution of climate risks among different groups and geographies, as well as extend the goals of these solutions to more than reducing risk, such as in improving social, economic and ecological outcomes (Sections 2.6.7; 4.1; 5.14.4; 6.4.8; 7.4.3.5; 7.4.5; 10.6; 11.8; 15.7; 17.6; Boxes 4.7; 13.3; 8.10). Multiple chapters also employ the concept of climate resilient development to identify and balance trade-offs and make progress on achieving the SDGs (Sections 6.1.3; 7.4.5; 10.6; 13.11; 15.7; 16.6.4.3; Box 4.7; Chapter 18).

Climate resilient development requires large and equitable changes in human and natural systems. As noted in Section 1.5.1, the SR1.5 finds that four transitions in socioeconomic systems—energy, land and ecosystems, urban and infrastructure, and industrial—must occur at large scale and rapid rate in order to achieve climate resilient development. This report notes that transitions of such scale, even when beneficial for many people, can also impose significant adverse impacts on others, in particular on marginal and vulnerable populations (Section 18.1.2). This report identifies a fifth socioeconomic transition, that in societal systems that 'drive innovation, preferences for alternative patterns of consumption and development, and the power relationships among different actors that engage in climate resilient development (Section 18.1.4). Such societal transitions are necessary to ensure the other four transitions unfold at sufficient speed and scale to meet the goals of Paris and the SDGs, as well as to ensure equity in these transitions.

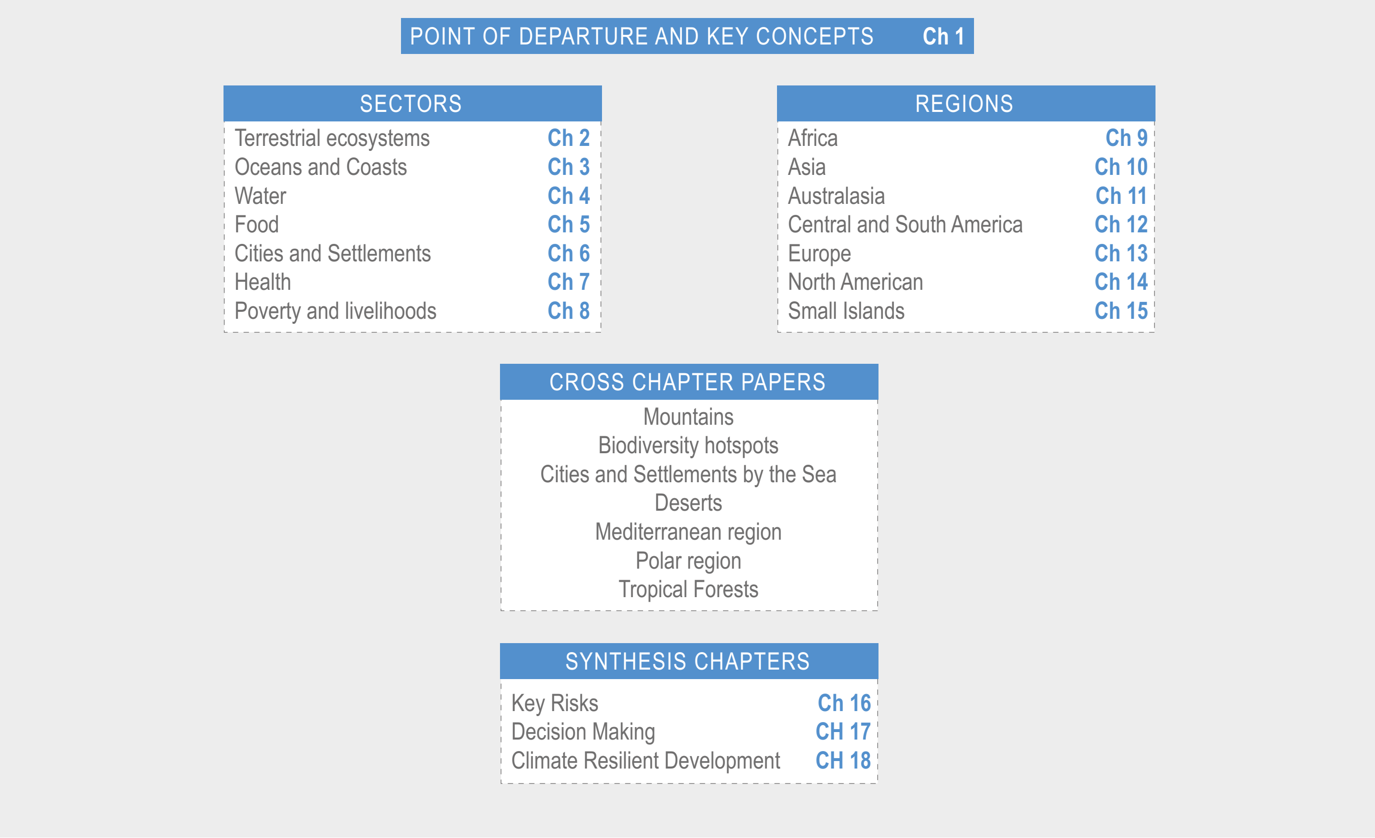
Introduced in the WGII AR5 (Olsson et al., 2014), and further addressed in SR1.5, climate resilient development pathways are trajectories that strengthen sustainable development and efforts to eradicate poverty and reduce inequalities, while promoting fair and equitable reductions of GHG emissions, and serve to steer societies towards low-carbon, prosperous and ecologically safe futures. This report defines a **climate resilient development pathway** as a trajectory in time reflecting a particular sequence of actions and consequences against a background of autonomous developments leading to a specific future situation (Section 18.1.2). Such a pathway emerges from the spatially and temporally distributed choices of many different actors in government, business, civic organisations and households at the individual, community, national and international levels. As such, there is no single or preferred pathway for climate resilient development and no single best combination of adaptation, mitigation and sustainable development strategies. All pathways involve complex trade-offs and synergies among different actions (Sections 18.1.4; 18.2.2). All pathways are subject to hard-to-predict shocks, both adverse, such as climate disasters, and beneficial, such as new technologies or shifts in public values. The pathway that emerges will represent the results of negotiation, cooperation and competition among actors at many scales, whose differing values and objectives would favour differing trajectories (Section 18.1.4). Individual actors at various scales will determine the mix of adaptation, mitigation and development appropriate for their development context and goals, while also influenced by the desire for their collective actions to become consistent with the global policy goals, such as those in the Paris Agreement and the SDGs (Section 18.1.2). The norms, institutions and power relationships that mediate such choices determine the extent to which the process unfolds consistent with principles of equity and social justice (*high confidence*).

Enabling conditions that can accelerate climate resilient development include governance, finance, economy, and science, technology and information (Sections 18.4.2; 18.9.2). The pursuit of equity and justice are both an enabler and an outcome of climate resilient development (Section 18.1.4). Climate resilient development involves a process of action, learning and response (Section 1.5.2), so the capability for such monitoring and iterative risk management also represents an important enabling condition (Section 18.1.4.2). Governments have an important role to play in expanding the solution space, often focusing on technology, policy and finance. Expanding the solution space also requires a broader set of actors. Chapter 18 and other chapters in this report use the climate resilient development concept to highlight the role of citizens, civil society, knowledge institutions, media, investors and businesses, and the importance of expanding the arenas of engagement in which they interact.

1.6 Structure of the Report

The IPCC mandate involves the provisioning of available scientific information and evidence to inform climate action by multiple actors, notably governments (including international alliances) in the context of UNFCCC. Increasingly, IPCC assessments also aim to provide valuable information to non-governmental organisations, small and large enterprises, and citizens.

Figure 1.10 shows the structure of this report, organised into three sections comprising chapters and cross-chapter papers. This first chapter provides the point of departure for this assessment, defines key concepts and describes the connections among them.



POINT OF DEPARTURE AND KEY CONCEPTS **Ch 1**

SECTORS	
Terrestrial ecosystems	Ch 2
Oceans and Coasts	Ch 3
Water	Ch 4
Food	Ch 5
Cities and Settlements	Ch 6
Health	Ch 7
Poverty and livelihoods	Ch 8

REGIONS	
Africa	Ch 9
Asia	Ch 10
Australasia	Ch 11
Central and South America	Ch 12
Europe	Ch 13
North American	Ch 14
Small Islands	Ch 15

CROSS CHAPTER PAPERS

Mountains
Biodiversity hotspots
Cities and Settlements by the Sea
Deserts
Mediterranean region
Polar region
Tropical Forests

SYNTHESIS CHAPTERS	
Key Risks	Ch 16
Decision Making	CH 17
Climate Resilient Development	CH 18

Figure 1.10 | Structure of the Working Group II Sixth Assessment Report

The next group of chapters assess risks, adaptation and sustainability for systems impacted by climate change from the vantage of seven sectoral chapters, The next group of chapters organises the assessment from the vantage of seven regional chapters.

In contrast to previous assessments, the current report embeds adaptation in each regional and sectoral chapter rather than in separate adaptation chapters, in order to reflect the increasing prevalence of adaptation and the extent to which many current risk, impacts and vulnerability estimates incorporate adaptation actions already taken. In addition, CCPs integrate across chapter topics, sectors and regions in particular types of geographies or ecosystems, termed typological regions, such as mountains, cities by the sea or tropical forests. CCPs are a new element in WGII AR6 included at the request of governments to highlight and expand relevant material from chapters and beyond into one place to ensure the integrated treatment of particular systems or regions and to improve accessibility of the report to readers.

Finally, section three highlights sustainable development pathways integrating adaptation and mitigation through three synthesis chapters. The synthesis chapters summarise findings across all the chapters, CCPs and literatures on key risks, decision-making options and climate resilient development pathways that can lead from the current situation to a future more consistent with the stated policy goals. This report also assesses the adaptation options available, the extent to which such options can reduce risk, the effectiveness of current adaptation efforts, and their interactions with mitigation and sustainable development.

Frequently Asked Questions

FAQ 1.1 | What are the goals of climate change adaptation?

The goals of climate change adaptation, as a broad concept, are to reduce risk and vulnerability to climate change, strengthen resilience, enhance well-being and the capacity to anticipate, and respond successfully to change. Existing international frameworks provide a high-level direction for coordinating, financing and assessing progress toward these goals. However, specifying the goals for specific adaptation actions is not straightforward because the impacts of climate change affect people and nature in many different ways requiring different adaptation actions. Thereby, goals that accompany these actions are diverse. Goals can relate to health, water or food security, jobs and employment, poverty eradication and social equity, biodiversity and ecosystem services at international, national and local levels.

Climate change adaptation entails the process of adjustment to actual or expected climate change and its effects in order to moderate harm or exploit beneficial opportunities. At a high level, international frameworks, including the Paris Agreement and the SDGs, have come to provide a direction for coordinating, financing and assessing global progress in these terms. The Paris Agreement calls for climate change adaptation actions, referring to these actions as those that reduce risk and vulnerability, strengthen resilience, enhance the capacity to anticipate and respond successfully, and ensure the availability of necessary financial resources, as these processes and outcomes relate to climate change. In addition, the Sustainable Development Goals include 17 targets (with a specific goal SDG 13 on climate action) to fulfil its mission to end extreme poverty by 2030, protect the planet and build more peaceful, just and inclusive societies. These goals are difficult to reach without successful adaptation to climate change. Other notable frameworks that identify climate change adaptation as important global priorities include the SFDRR, the finance-oriented Addis Ababa Action Agenda and the New Urban Agenda.

While vital for international finance, coordination and assessment, the global goals set forth by these frameworks and conventions do not necessarily provide sufficient guidance to plan, implement or evaluate specific adaptation efforts at the community level. Specifying goals of adaptation is harder than setting goals for reducing emissions of climate-warming GHG emissions. For instance, emission reduction effort is ultimately measured by the total amount of GHGs in the Earth's atmosphere. Instead, adaptation aims to reduce risk and vulnerability from climate change and helps to enhance well-being in each individual community worldwide.

Because the impacts of climate change affect people and nature in so many different ways, the specific goals of adaptation depend on the impact being managed and the action being taken. For human systems, adaptation includes actions aimed at reducing a specific risk, such as by fortifying a building against flooding, or actions aimed at multiple risks, such as requiring climate risk assessments in financial reporting in anticipation of different kinds of risk. At the local level, communities can take actions that include updating building codes and land use plans, improving soil management, enhancing water use efficiency, supporting migrants and taking measures to reduce poverty. For natural systems, adaptation includes organisms changing behaviours, migrating to new locations and genetic modifications in response to changing climate conditions. The goals for these adaptation actions can relate to health, water or food security, jobs and employment, poverty eradication and social equity, biodiversity and ecosystem services, among others. Articulating the goals of adaptation thus requires engaging with the concepts of equity, justice and effectiveness at the international, national and local levels.

Frequently Asked Questions

FAQ 1.2 | Is climate change adaptation urgent?

Climate impacts, such as stronger heat waves, longer droughts, more frequent floods, accelerating sea level rise and storm surges, are already being observed in some regions, and people around the world are increasingly perceiving changing climates, regarding these changes as significant and considering climate action as a matter of high urgency. Reducing climate risk to levels that avoid threatening private or social norms and ensuring sustainable development will require immediate and long-term adaptation efforts by governments, business, civil society and individuals at a scale and speed significantly faster than the current trends.

Current observed climate impacts and expected future risks include stronger and longer heat waves, unprecedented droughts and floods, accelerating sea level rise and storm surges affecting many geographies and communities. People around the world are increasingly perceiving changing climates, regarding these changes as significant and considering climate action as a matter of high urgency. In particular, marginalised and poor people, as well as island and coastal communities, experience relatively higher risks and vulnerability. The available evidence suggests that current adaptation efforts may be insufficient to help ensure sustainable development and other societal goals in many communities worldwide even under the most optimistic GHG emissions scenarios.

Climate change adaptation is, therefore, urgent to the extent that meeting important societal goals requires immediate and long-term action by governments, business, civil society and individuals at a scale and speed significantly faster than that represented by current trends.

Frequently Asked Questions

FAQ 1.3 | What constitutes successful adaptation to climate change?

The success of climate change adaptation is dependent on the extent to which relevant actions reduce risk and vulnerability, as well as achieve their respective goals. At a global scale, these goals are set and tracked according to international frameworks and conventions. At smaller scales, such as local and national, goals are dependent on the specific impacts being managed, the actions being taken and the relevant scale. While success can take shape as uniquely as goals can, the degree to which an adaptation is feasible, effective and conforms to principles of justice represents important attributes for measuring success across actions. Adaptation responses that lead to increased risk and impacts are considered maladaptation.

Altogether, adaptation success is dependent on the extent to which adaptation actions achieve their respective goals of reducing climate risk, increasing resilience and pursuing other climate-related societal goals. Viewed globally, successful adaptation consists of actions anticipated to make significant contributions to meeting SDGs, such as ending extreme poverty, hunger and discrimination, and reduce risks to ecosystems, water, food systems, human settlements, and health and well-being. Viewed locally, successful adaptation consists of actions that help communities meet their diverse goals, including reducing anticipated current and future risks, enhancing capacity to adapt and transform, avoiding maladaptation, yielding benefits greater than costs and serving vulnerable populations, and arising from an inclusive, evidence-based and equitable decision process.

While success can be unique to an adaptation action, there are important attributes that constitute it as a successful solution. These include the extent to which an action is considered feasible, effective and conforms to principles of justice.

The degree to which an action is *feasible* is the extent to which it is appraised as possible and desirable, taking into consideration barriers, enablers, synergies and trade-offs. These considerations are based on financial or economic, political, physical, historical and social factors, depending on what is required for an action to be implemented. The degree to which an action is *effective* depends on the extent it reduces climate risk, as well as the extent an action achieves its intended goals or outcomes. An adaptation action can sometimes—usually inadvertently—increase risk or vulnerability for some or all affected individuals or communities. In some cases, such risk increases will be sufficient to call the actions maladaptation. The degree to which an action is *just* is when its outcomes, the process of implementing the action and the process of choosing the action respects principles of distributive, procedural and recognitional justice. Distributive justice refers to the different distributions of benefits and burdens of an

FAQ 1.3 (continued)

action across members of society; procedural justice refers to ensuring the opportunity for fairness, transparency, inclusion and impartiality in the decision making of an action; and recognitional justice insists on recognising and including those who are or may be most affected by an action.

These attributes of adaptation success can be assessed throughout the adaptation process of planning, implementation, Monitoring & Evaluation, adjustment and learning. However, at the same time, the success of many adaptation actions depends strongly on context and time. For instance, the effectiveness of adaptation will depend on the success of GHG mitigation efforts, as adaptation has strong synergies and trade-offs with mitigation efforts

Frequently Asked Questions

FAQ 1.4 | What is transformational adaptation?

Continuing and expanding current adaptation efforts can reduce some climate risks. But even with emission reductions sufficient to meet the Paris Agreement goals, transformational adaptation will be necessary.

Over six assessment reports, the IPCC has documented transformative changes in the Earth's climate and ecosystems caused by human actions. These changes are now unequivocal and projected to become even more significant in the years and decades ahead. This AR6 report also highlights climate adaptation actions people are taking and can take in response to these significant changes in the climate system.

Some adaptation is incremental, which only modifies existing systems. Other actions are transformational, leading to changes in the fundamental characteristics of a system. For instance, building a seawall to protect a coastal community from flooding might exemplify incremental adaptation. Changing land use regulations in that community and establishing a programme of managed retreat might exemplify transformational adaptation. There is no definitive line between incremental and transformational adaptation. Some incremental actions stay incremental. Others may expand the future space of solutions. For instance, including climate risk in mortgages and insurance might at first seem incremental but might lead to more transformational change over time.

Transformation can be deliberate, envisioned and intended by at least some societal actors, or forced, arising without explicit intent.

Deliberate transformational adaptation is not without risks because change can disturb existing power relationships and can unfold in difficult to predict and unintended ways. But transformational adaptation is important to consider because it may be needed to avoid intolerable risks from climate change and to help meet development goals as articulated in the SDGs. In addition, some types of societal transformation may be inevitable and deliberate rather than forced transformation and may bring society closer to its goals.

Some types of transformation may be inevitable because the amount of transformational adaptation needed to avoid intolerable risks depends in part on the level of GHG mitigation. Low concentration pathways consistent with Paris Agreement goals require deliberate transformations that lead to significant and rapid change in energy, land, urban and infrastructure, and industrial systems. Even with low concentration pathways, some transformational adaptation will be necessary to limit intolerable risks. But with higher concentration pathways, more extensive transformational adaptation would be required to limit (though not entirely avoid) intolerable risks. In such circumstances, insufficient deliberate transformation could lead to undesirable forced transformations.

Frequently Asked Questions

FAQ 1.5 | What is new in this 6th IPCC report on impacts, adaptation and vulnerability?

Since IPCC Fifth Assessment Report, many new sources of knowledge have been employed to provide better understanding of climate change risks, impacts, vulnerability and also societal responses through adaptation, mitigation and sustainable development. This new, more integrative assessment focuses more on risk and solutions, social justice, different forms of knowledge including IK and LK, the role of transformation and the urgency of fast climate actions.

The IPCC Sixth Assessment Report (AR6) has played a prominent role in science–policy–society interactions on the climate issue since 1988 and has advanced in interdisciplinary climate change assessment since AR5. Many new sources of knowledge have been employed to provide better understanding of climate change risks, impacts, vulnerability and also societal responses through adaptation, mitigation and sustainable development.

This AR6 assessment focuses more on risk and solutions. The risk framing for the first time spans all three Working Groups. It includes risks from the responses to climate change, considers dynamic and cascading consequences, describes with more geographic detail risks to people and ecosystems, and assesses such risks over a range of scenarios. The solutions framing encompasses the interconnections among climate responses, sustainable development and transformation, and the implications for governance across scales within the public and private sectors. The assessment therefore includes climate-related decision making and risk management, climate resilient development pathways, implementation and evaluation of adaptation, and also limits to adaptation and loss and damage.

The AR6 emphasises the emergent issue on social justice and different forms of knowledge. As climate change impacts and responses are implemented, there is heightened awareness of the ways that climate responses interact with issues of justice and social progress. In this report, there is expanded attention on inequity in climate vulnerability and responses, the role of power and participation in processes of implementation, unequal and differential impacts, and climate justice. The historic focus on scientific literature is also accompanied by increased consideration and incorporation of Indigenous knowledge and local knowledge and associated scholars.

The AR6 has a more extensive focus on the role of transformation and the urgency of fast climate actions in meeting societal goals. This report assesses extensive literatures with an increasing diversity of topics and geographical areas with more sectoral and regional details. The literature also increasingly evaluates the lived experiences of climate change—the physical changes underway, the impacts for people and ecosystems, the perceptions of the risks, and adaptation and mitigation responses planned and implemented.

The assessment in AR6 is more integrative across multiple disciplines and combines experts across Working Groups, chapters, papers and disciplines, such as natural and social sciences, medical and health sciences, engineering, humanities, law and business administration. The emphasis on knowledge for action has also included the role of public communication, stories and narratives within assessment and associated outreach.

References

Abrahamson, V., et al., 2009: Perceptions of heatwave risks to health: interview-based study of older people in London and Norwich, UK. *J. Public Health*, **31**, 119–126.

Abreu, R.C., et al., 2017: The biodiversity cost of carbon sequestration in tropical savanna. *Sci. Adv.*, **3**(8), e1701284.

Adelman, S., 2018: The sustainable development goals, anthropocentrism and neoliberalism. In: *Sustainable Development Goals*. Edward Elgar Publishing, Cheltenham, Glos; Northampton, Massachusetts.

Adger, N.W., N.W. Arnell and E.L. Tompkins, 2005: Successful adaptation to climate change across scales. *Glob. Environ. Change*, **15**(2), 77–86.

Adger, W.N., 2010: Climate change, human well-being and insecurity. *New Polit. Econ.*, **15**(2), 275–292.

Adger, W.N., 2016: Place, well-being, and fairness shape priorities for adaptation to climate change. *Glob. Environ. Change*, **38**, A1–A3.

Adger, W.N., J. Barnett, K. Brown, N. Marshall and K. O'brien, 2013: Cultural dimensions of climate change impacts and adaptation. *Nat. Clim. Change*, **3**(2), 112–117.

Adger, W.N., T.A. Benjaminsen, K. Brown and H. Svarstad, 2001: Advancing a political ecology of global environmental discourses. *Dev. Change*, **32**(4), 681–715.

Adger, W.N., I. Brown and S. Surminski, 2018: Advances in risk assessment for climate change adaptation policy. *Philos. Trans. Royal Soc. A Math. Phys. Eng. Sci.*, **376**(2121). doi: https://dx.doi.org/10.1098%2Frsta.2018.0106.

Adler, M., 2012: *Well-being and fair distribution: beyond cost-benefit analysis*. Oxford University Press, New York, NY, USA.

Adler, M.D., et al., 2016: Priority for the worse off and the social cost of carbon. *Nat. Clim. Change*, 7, 443–449.

Agrawal, A. and M.C. Lemos, 2015: Adaptive development. *Nat. Clim. Change*, **5**(3), 185.

Aldunce, P., R. Beilin, M. Howden and J. Handmer, 2015: Resilience for disaster risk management in a changing climate: practitioners' frames and practices. *Glob. Environ. Change Hum. Policy Dimens.*, **30**, 1–11.

Allen, C.R. and C. Holling, 2010: Novelty, adaptive capacity, and resilience. Ecology and Society 15(3): 24. doi: https://doi.org/10.5751/ES-03720-150324.

Allen, M., O.P. Dube, W. Solecki, F. Aragón–Durand, W. Cramer, S. Humphreys, M. Kainuma, J. Kala, N. Mahowald, Y. Mulugetta, R. Perez, M. Wairiu and K. Zickfeld, 2018: Framing and context. In: *Global Warming of 1.5°C. An IPCC Special Report on the Impacts of Global Warming of 1.5°C Above Pre-industrial Levels and Related Global Greenhouse Gas Emission Pathways, in the Context of Strengthening the Global Response to the Threat of Climate Change, Sustainable Development, and Efforts to Eradicate Poverty*. Cambridge University Press, Cambridge, UK and New York, NY, USA.

Altieri, M. A. and C.I. Nicholls, 2017: The adaptation and mitigation potential of traditional agriculture in a changing climate. *Clim. Change*, **140**(1), 33–45.

Anderegg, W.R., E.S. Callaway, M.T. Boykoff, G. Yohe and T.L. Root, 2014: Awareness of both type 1 and 2 errors in climate science and assessment. *Bull. Am. Meteorol. Soc.*, **95**(9), 1445–1451.

Anderson, D.G., et al., 2017: Sea-level rise and archaeological site destruction: an example from the southeastern United States using DINAA (Digital Index of North American Archaeology). *PLoS ONE*, **12**(11), e188142–e188142.

Andrei, S., G. Rabbani, H. Khan, M. Haque and D. Ali, 2015: *Non-Economic Loss and Damage Caused by Climatic Stressors in Selected Coastal Districts of Bangladesh*. Report for the Asian Development Bank. Bangladesh Centre for Advanced Studies, Bangladesh.

Andrijevic, M., J. Crespo Cuaresma, R. Muttarak and C.-F. Schleussner, 2020: Governance in socioeconomic pathways and its role for future adaptive capacity. *Nat. Sustain.*, **3**(1), 35–41.

Anguelovski, I., et al., 2016: Equity impacts of urban land use planning for climate adaptation: critical perspectives from the global north and south. *J. Plan. Educ. Res.*, **36**(3), 333–348.

Archer, D., et al., 2014: Moving towards inclusive urban adaptation: approaches to integrating community-based adaptation to climate change at city and national scale. *Clim. Dev.*, **6**(4), 345–356.

Arias, P.A., N. Bellouin, E. Coppola, R.G. Jones, G. Krinner, J. Marotzke, V. Naik, M.D. Palmer, G.-K. Plattner, J. Rogelj, M. Rojas, J. Sillmann, T. Storelvmo, P.W. Thorne, B. Trewin, K. Achuta Rao, B. Adhikary, R.P. Allan, K. Armour, G. Bala, R. Barimalala, S. Berger, J.G. Canadell, C. Cassou, A. Cherchi, W. Collins, W.D. Collins, S.L. Connors, S. Corti, F. Cruz, F.J. Dentener, C. Dereczynski, A. Di Luca, A. Diongue Niang, F.J. Doblas-Reyes, A. Dosio, H. Douville, F. Engelbrecht, V. Eyring, E. Fischer, P. Forster, B. Fox-Kemper, J.S. Fuglestvedt, J.C. Fyfe, N.P. Gillett, L. Goldfarb, I. Gorodetskaya, J.M. Gutierrez, R. Hamdi, E. Hawkins, H.T. Hewitt, P. Hope, A.S. Islam, C. Jones, D.S. Kaufman, R.E. Kopp, Y. Kosaka, J. Kossin, S. Krakovska, J.-Y. Lee, J. Li, T. Mauritsen, T.K. Maycock, M. Meinshausen, S.-K. Min, P.M.S. Monteiro, T. Ngo-Duc, F. Otto, I. Pinto, A. Pirani, K. Raghavan, R. Ranasinghe, A.C. Ruane, L. Ruiz, J.-B. Sallée, B.H. Samset, S. Sathyendranath, S.I. Seneviratne, A.A. Sörensson, S. Szopa, I. Takayabu, A.-M. Tréguier, B. van den Hurk, R. Vautard, K. von Schuckmann, S. Zaehle, X. Zhang, and K. Zickfeld, 2021: Technical Summary. In *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA. In Press.

Arneth, A., et al., 2020: Post-2020 biodiversity targets need to embrace climate change. *Proc. Natl. Acad. Sci.*, **117**(49), 30882–30891.

Asafu-Adjaye, J., et al., 2015: *An ecomodernist manifesto*. Available at: http://www.ecomodernism.org/manifesto-english

Atteridge, A. and E. Remling, 2017: Is adaptation reducing vulnerability or redistributing it? *WIREs Clim. Change*, **9**(1). doi: https://doi.org/10.1002/wcc.500.

Aven, T., 2016: Risk assessment and risk management: review of recent advances on their foundation. *Eur. J. Oper. Res.*, **253**(1), 1–13.

Banerjee, A., J.C. Fyfe, L.M. Polvani, D. Waugh and K.-L. Chang, 2020: A pause in Southern Hemisphere circulation trends due to the Montreal Protocol. *Nature*, **579**(7800), 544–548.

Banerjee, S.B., 2003: Who sustains whose development? Sustainable development and the reinvention of nature. *Organ. Stud.*, **24**(1), 143–180.

Baresi, U., K.J. Vella and N.G. Sipe, 2020: A limits-oriented adaptive approach for strategic environmental assessment. *Environ. Sci. Policy*, **114**, 128–139.

Barnes, D.K., et al., 2011: Scott's collections help reveal accelerating marine life growth in Antarctica. *Curr. Biol.*, **21**(4), R147–8.

Barnett, J., et al., 2015: From barriers to limits to climate change adaptation: path dependency and the speed of change. *Ecol. Soc.*, **20**(3), 5.

Barnosky, A.D., et al., 2017: Merging paleobiology with conservation biology to guide the future of terrestrial ecosystems. *Science*, **355**(6325). DOI: 10.1126/science.aah4787

Barragán, J.M. and M. de Andrés, 2015: Analysis and trends of the world's coastal cities and agglomerations. *Ocean Coast. Manag.*, **114**, 11–20.

Bawaka Country, et al., 2015: Co-becoming Bawaka. *Prog. Hum. Geogr.*, **40**(4), 455–475.

Bayleyegn, D., P. Ericksen and D. Solomon, 2018: *Climate Resilient Green Economy Strategy*: Sector-wise GTP II Implementation Monitoring Checklist. CCAFS, Addis Ababa, Ethiopia.

Beck, S. and M. Mahony, 2018: The IPCC and the new map of science and politics. *Wiley Interdiscip. Rev. Clim. Change*, **9**(6), e547.

Begum, R.A., M.S.K. Sarkar, A.H. Jaafar and J.J. Pereira, 2014: Toward conceptual framework for linking disaster risk reduction and climate change adaptation. *Int. J. Disaster Risk Reduct.*, **10**, 362–373.

Béné, C., et al., 2011: Testing resilience thinking in a poverty context: experience from the Niger River basin. *Glob. Environ. Change*, **21**(4), 1173–1184.

Benjaminsen, T.A., H. Svarstad and I. Shaw of Tordarroch, 2021: Recognising recognition in climate justice. *IDS Bull.*, **52**. DOI: 10.19088/1968-2021.127

Benton, M.J., 2018: Hyperthermal-driven mass extinctions: killing models during the Permian–Triassic mass extinction. *Philos. Trans. Royal Soc. A*, **376**(2130), 20170076.

Benzie, M., et al., 2018: Meeting the global challenge of adaptation by addressing transboundary climate risk. A joint collaboration between SEI, IDDRI, and ODI. Discussion Brief. Stockholm Environment Institute, Stockholm, Sweden.

Benzie, M. and Å. Persson, 2019: Governing borderless climate risks: moving beyond the territorial framing of adaptation. *Int. Environ. Agreem. Polit. Law Econ.*, **19**(4-5), 369–393.

Bergstrand, K., B. Mayer, B. Brumback and Y. Zhang, 2015: Assessing the relationship between social vulnerability and community resilience to hazards. *Soc. Indic. Res.*, **122**(2), 391–409.

Berrang-Ford, L., 2020: Mapping evidence of human adaptation to climate change. *Nat. Clim. Change*. DOI: 10.21203/rs.3.rs-100873/v1

Berrang-Ford, L., et al., 2019: Tracking global climate change adaptation among governments. *Nat. Clim. Change*, **9**(6), 440–449.

Berrang-Ford, L., J.D. Ford and J. Paterson, 2011: Are we adapting to climate change? *Glob. Environ. Change*, **21**(1), 25–33.

Berrang-Ford, L., T. Pearce and J.D. Ford, 2015: Systematic review approaches for climate change adaptation research. *Reg. Environ. Change*, **15**(5), 755–769.

Berry, H.L., K. Bowen and T. Kjellstrom, 2010: Climate change and mental health: a causal pathways framework. *Int. J. Public Health*, **55**(2), 123–132.

Betti, L., et al., 2020: Climate shaped how Neolithic farmers and European hunter-gatherers interacted after a major slowdown from 6,100 bce to 4,500 bce. *Nat. Hum. Behav.*, **4**(10), 1004–1010.

Bezner Kerr, R., et al., 2019: Participatory agroecological research on climate change adaptation improves smallholder farmer household food security and dietary diversity in Malawi. *Agric. Ecosyst. Environ.*, **279**, 109–121.

Biesbroek, G.R., J.E.M. Klostermann, C.J.A.M. Termeer and P. Kabat, 2013: On the nature of barriers to climate change adaptation. *Reg. Environ. Change*, **13**(5), 1119–1129.

Biesbroek, R., et al., 2018: Data, concepts and methods for large-n comparative climate change adaptation policy research: a systematic literature review. *WIREs Clim. Change*, **9**(6).

Biesbroek, R. and A. Delaney, 2020: Mapping the evidence of climate change adaptation policy instruments in Europe. *Environ. Res. Lett.*, **15**(8), 83005.

Bindoff, N.L., P.A. Stott, K.M. AchutaRao, M.R. Allen, N. Gillett, D. Gutzler, K. Hansingo, G. Hegerl, Y. Hu, S. Jain, I.I. Mokhov, J. Overland, J. Perlwitz, R. Sebbari, and X. Zhang, 2013: Detection and attribution of climate change: From global to regional. In *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. T.F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Doschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley, Eds. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 867–952, doi:10.1017/CBO9781107415324.022

Bizikova, L., J.-E. Parry, J. Karami and D. Echeverria, 2015: Review of key initiatives and approaches to adaptation planning at the national level in semi-arid areas. *Reg. Environ. Change*, **15**(5), 837–850.

Boé, J., et al., 2020: Past long-term summer warming over western Europe in new generation climate models: role of large-scale atmospheric circulation. *Environ. Res. Lett.*, **15**(8), 84038.

Boeckmann, M. and H. Zeeb, 2016: Justice and equity implications of climate change adaptation: a theoretical evaluation framework. *Healthcare*, **4**(3), 65.

Bond, D.P.G. and S.E. Grasby, 2017: On the causes of mass extinctions. *Palaeogeogr. Palaeoclimatol. Palaeoecol.*, **478**, 3–29.

Boonstra, W.J., 2016: Conceptualizing power to study social-ecological interactions. *Ecol. Soc.*, **21**(1), 21–33.

Booth, B.B.B., et al., 2017: Narrowing the range of future climate projections using historical observations of atmospheric CO_2. *J. Clim.*, **30**(8), 3039–3053.

Boyd, E., R.A. James, R.G. Jones, H.R. Young and F.E.L. Otto, 2017: A typology of loss and damage perspectives. *Nat. Clim. Change*, **7**(10), 723.

Bremer, S., et al., 2019: Toward a multi-faceted conception of co-production of climate services. *Clim. Serv.*, **13**, 42–50.

Brovkin, V., et al., 2021: Past abrupt changes, tipping points and cascading impacts in the Earth system. *Nat. Geosci.*, **14**(8), 550–558.

Brown, K., 2014: Global environmental change I: a social turn for resilience? *Prog. Hum. Geogr.*, **38**(1), 107–117.

Brysse, K., N. Oreskes, J. O'Reilly and M. Oppenheimer, 2013: Climate change prediction: erring on the side of least drama? *Glob. Environ. Change*, **23**(1), 327–337.

Büntgen, U., et al., 2011: 2500 years of European climate variability and human susceptibility. *Science*, **331**(6017), 578–582.

Burke, A., et al., 2021: The archaeology of climate change: the case for cultural diversity. *Proc. Natl. Acad. Sci.*, **118**(30), e2108537118.

Burkett, V.R., A.G. Suarez, M. Bindi, C. Conde, R. Mukerji, M.J. Prather, A.L.S. Clair and G.W. Yohe, 2014: Point of departure. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel of Climate Change*. [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea and L.L. White (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 169–194.

Burton, I., et al., 2012: Managing the Risks: International Level and Integration across Scales. In: *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change (IPCC)*. [Field, C.B., V. Barros, T.F. Stocker, D. Qin, D.J. Dokken, K.L. Ebi, M.D. Mastrandrea, K.J. Mach, G.K. Plattner, S.K. Allen, M. Tignor and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 393–435.

Butler, E.E., N.D. Mueller and P. Huybers, 2018: Peculiarly pleasant weather for US maize. *Proc. Natl. Acad. Sci.*, **115**(47), 11935–11940.

Byskov, M.F., et al., 2021: An agenda for ethics and justice in adaptation to climate change. *Clim. Dev.*, **13**(1), 1–9.

Callaghan, M., et al., 2021: Machine learning-based evidence and attribution mapping of 100,000 climate impact studies. *Nat. Clim. Change*,**11**, 966–972.

Calliari, E., A. Staccione and J. Mysiak, 2019: An assessment framework for climate-proof nature-based solutions. *Sci. Total Environ.*, **656**, 691–700.

Calosi, P., H.M. Putnam, R.J. Twitchett and F. Vermandele, 2019: Marine metazoan modern mass extinction: improving predictions by integrating fossil, modern, and physiological data. *Annu. Rev. Mar. Sci.*, **11**, 369–390.

Campbell, B.M.S. and F. Ludlow, 2020: Climate, disease and society in late-medieval Ireland. *Proc. Royal Ir. Acad. Archaeol. Cult. Hist. Lit.*, **120C**, 159–252.

Canadell, J.G., P.M.S. Monteiro, M.H. Costa, L. Cotrim da Cunha, P.M. Cox, A.V. Eliseev, S. Henson, M. Ishii, S. Jaccard, C. Koven, A. Lohila, P.K. Patra, S. Piao, J. Rogelj, S. Syampungani, S. Zaehle, and K. Zickfeld, 2021: Global Carbon and other Biogeochemical Cycles and Feedbacks. In *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press. In Press.

Caney, S., 2014: Two kinds of climate justice: avoiding harm and sharing burdens. *J. Polit. Philos.*, **22**(2), 125–149.

Cantin, N.E., A.L. Cohen, K.B. Karnauskas, A.M. Tarrant and D.C. McCorkle, 2010: Ocean warming slows coral growth in the central Red Sea. *Science*, **329**(5989), 322–325.

Capela Lourenço, T., et al., 2019: Are European decision-makers preparing for high-end climate change? *Reg. Environ. Change*, **19**(3), 629–642.

Cardona, O.D., M.K. van Aalst, J. Birkmann, M. Fordham, G. McGregor, R. Perez, R.S. Pulwarty, E.L.F. Schipper and B.T. Sinh, 2012: Determinants of Risk: Exposure and Vulnerability. In: *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change (IPCC)*. [Field, C.B., V.R. Barros, T.F. Stocker, D. Qin, D.J. Dokken, K.L. Ebi, M.D. Mastrandrea, K.J. Mach, G.K. Plattner, S.K. Allen, M. Tignor and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 65–108.

Carolin, S.A., et al., 2019: Precise timing of abrupt increase in dust activity in the Middle East coincident with 4.2 ka social change. *Proc. Natl. Acad. Sci.*, **116**(1), 67–72.

Carotenuto, F., et al., 2018: The well-behaved killer: late Pleistocene humans in Eurasia were significantly associated with living megafauna only. *Palaeogeogr. Palaeoclimatol. Palaeoecol.*, **500**, 24–32.

Carr, E.R., 2019: Properties and projects: reconciling resilience and transformation for adaptation and development. *World Dev.*, **122**, 70–84.

Carr, E.R. and M.C. Thompson, 2014: Gender and climate change adaptation in agrarian settings: current thinking, new directions, and research frontiers. *Geogr. Compass*, **8**(3), 182–197.

Cavanagh, C.J. and T.A. Benjaminsen, 2017: Political ecology, variegated green economies, and the foreclosure of alternative sustainabilities. *J. Polit. Ecol.*, **24**, 200–216.

CBD, 2011: *Strategic Plan for Biodiversity 2011–2020, Including Aichi Biodiversity Targets*. The Convention on Biological Diversity, Nagoya, Japan.

Chambwera, M., et al., 2014: Economics of adaptation. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel of Climate Change*. [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea and L.L. White (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 945–977.

Chase-Dunn, C. and P. Almeida, 2020: *Global Struggles and Social Change: From Prehistory to World Revolution in the Twenty-First Century*. Johns Hopkins University Press, Baltimore, MD, USA.

Chatterton, P., D. Featherstone and P. Routledge, 2013: Articulating climate justice in Copenhagen: antagonism, the commons, and solidarity. *Antipode*, **45**(3), 602–620.

Chen, C., M. Doherty, J. Coffee, T. Wong and J. Hellmann, 2016: Measuring the adaptation gap: a framework for evaluating climate hazards and opportunities in urban areas. *Environ. Sci. Policy*, **66**, 403–419.

Chen, D., M. Rojas, B.H. Samset, K. Cobb, A. Diongue Niang, P. Edwards, S. Emori, S.H. Faria, E. Hawkins, P. Hope, P. Huybrechts, M. Meinshausen, S.K. Mustafa, G.-K. Plattner, and A.-M. Tréguier, 2021: Framing, Context, and Methods. In *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA. In Press.

Chiotis, E., 2018: *Climate Changes in the Holocene: Impacts and Human Adaptation*. CRC Press, Boca Raton, FL, USA.

Chollet, A. and R. Felli, 2015: Le catastrophisme écologique contre la démocratie. *VertigO*, 15(2). DOI: https://doi.org/10.4000/vertigo.16427.

Chu, E. and K. Michael, 2018: Recognition in urban climate justice: marginality and exclusion of migrants in Indian cities. *Environ. Urban.*, **31**(1), 139–156.

Ciais, P., C. Sabine, G. Bala, L. Bopp, V. Brovkin, J. Canadell, A. Chhabra, R. De Fries, J. Galloway, M. Heimann, C. Jones, C. Le Quéré, R.B. Myneni, S. Piao and P. Thornton, 2013: Carbon and Other Biogeochemical Cycle. In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. [Stocker, D.Q. T.F., G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, pp. 465–570.

City of Santa Monica, 2018: *The Well Being Project*. Available at: https://wellbeing.smgov.net/about/project-resources. Retrieved October 4, 2019.

Ciullo, A., J.H. Kwakkel, K.M. De Bruijn, N. Doorn and F. Klijn, 2020: Efficient or fair? Operationalizing ethical principles in flood risk management: a case study on the Dutch-German Rhine. *Risk Anal.* 40(9):1844–1862. doi: 10.1111/risa.13527

Clapham, M. E. and P.R. Renne, 2019: Flood basalts and mass extinctions. *Annu. Rev. Earth Planet. Sci.*, **47**(1), 275–303.

Clark, G.A., C. Michael Barton and L.G. Straus, 2019: Landscapes, climate change & forager mobility in the Upper Paleolithic of northern Spain. *Quat. Int.*, **515**, 176–187.

Clarke, L., et al., 2018: Sector interactions, multiple stressors, and complex systems. In: *Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment*, Vol. II, U.S. Global Change Research Program, Washington, DC, USA.

Climate & Development Knowledge Network, 2017: *Annual Report*. CDKN Global, London, UK; Islamabad, Pakistan; Capetown, South Africa; Quito, Ecuador.

Climate Change Cultural Heritage Working Group International, 2019: *The Future of Our Pasts: Engaging Cultural Heritage in Climate Action Outline of Climate Change and Cultural Heritage* Technical Report. ICOMOS, Paris. 62 pp.

Coates, K., 2004: *A Global History of Indigenous Peoples*. Palgrave Macmillan, London, UK.

Coggins, S., et al., 2021: Empirical assessment of equity and justice in climate adaptation literature: a systematic map. *Environ. Res. Lett.*, **16**(7), 73003.

Cohen, J.M., M.J. Lajeunesse and J.R. Rohr, 2018: A global synthesis of animal phenological responses to climate change. *Nat. Clim. Change*, **8**(3), 224–228.

Cohen-Shacham, E., G. Walters, C. Janzen and S. Maginnis, 2016: *Nature-based Solutions to Address Global Societal Challenges*. IUCN, Gland, Switzerland, 97.

Conant, R.T., C.E. Cerri, B.B. Osborne and K. Paustian, 2017: Grassland management impacts on soil carbon stocks: a new synthesis. *Ecol. Appl.*, **27**(2), 662–668.

Connelly, A., J. Carter, J. Handley and S. Hincks, 2018: Enhancing the practical utility of risk assessments in climate change adaptation. *Sustainability*, **10**(5), 1399.

Conway, D. and J. Mustelin, 2014: Strategies for improving adaptation practice in developing countries. *Nat. Clim. Change*, **4**(5), 339–342.

Cook, G.D., S. Jackson and R.J. Williams, 2012: A revolution in northern Australian fire management: recognition of Indigenous knowledge, practice and management. In: *Flammable Australia*. CSIRO Publishing, Collingwood, pp. 293–305.

Cookson, E., D.J. Hill and D. Lawrence, 2019: Impacts of long term climate change during the collapse of the Akkadian Empire. *J. Archaeol. Sci.*, **106**, 1–9.

Coronese, M., F. Lamperti, K. Keller, F. Chiaromonte and A. Roventini, 2019: Evidence for sharp increase in the economic damages of extreme natural disasters. *Proc. Natl. Acad. Sci.*, **116**(43), 21450–21455.

Cote, M. and A.J. Nightingale, 2012: Resilience thinking meets social theory: situating social change in socio-ecological systems (SES) research. *Prog. Hum. Geogr.*, **36**(4), 475–489.

Cousins, J.J., 2021: Justice in nature-based solutions: research and pathways. *Ecol. Econ.*, **180**, 106874.

Cramer, W., G.W. Yohe, M. Auffhammer, C. Huggel, U. Molau, M.A.F.S. Dias, A. Solow, D.A. Stone and L. Tibig, 2014: Detection and attribution of observed impacts. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the*

Fifth Assessment Report of the Intergovernmental Panel of Climate Change [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea and L.L. White(eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 979–1037.

Crichton, R. and M. Esteban, 2017: Limits to coastal adaptation in Samoa: insights and experiences. In: *Climate Change Management*. Springer International Publishing, New York, NY, pp. 283–300.

D'Alisa, G., F. Demaria and G. Kallis, 2014: *Degrowth: A Vocabulary for a New Era*. Routledge, London, UK.

d'Alpoim Guedes, J. and R.K. Bocinsky, 2018: Climate change stimulated agricultural innovation and exchange across Asia. *Sci. Adv.*, **4**(10), eaar4491.

D'Andrea, W.J., Y. Huang, S.C. Fritz and N.J. Anderson, 2011: Abrupt Holocene climate change as an important factor for human migration in West Greenland. *Proc. Natl. Acad. Sci.*, **108**(24), 9765–9769.

Dasgupta, P., O. Edenhofer, A.M. A. Amezquita, A. Bento, S. Caney, D.D.I. Croix, A. Fosu, M. Jakob, M. Saam, K. Shrader-Frechette, J. Weyant, L. You, G.C. Delgado-Ramos, M.J. Dorsch, C. Flachsland, D. Klenert, R. Lempert, J. Leroux, K. Lessmann, J. Liu, L. Mattauch, C. Perrings, G. Schwerhoff, K. Seyboth, J. Steckel, J. Strefler and K. Seyboth, 2018: Economic growth, human development, and welfare. In: *Rethinking Society for the 21st Century: Report of the International Panel on Social Progress* [IPSP(ed.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 141–186.

David-Chavez, D.M. and M.C. Gavin, 2018: A global assessment of Indigenous community engagement in climate research. *Environ. Res. Lett.*, **13**(12), 123005.

Dawson, R., 2015: Handling interdependencies in climate change risk assessment. *Climate*, **3**(4), 1079–1096.

De Mello, L. and M. A. Dutz, 2012: *Promoting Inclusive Growth: Challenges and Policies*. OECD and the World Bank, Paris.

Degorska, B. and M. Degorski, 2018: Influence of climate change on environmental hazards and human well-being in the urban areas – Warsaw case study versus general problems. In: *Climate Change, Extreme Events and Disaster Risk Reduction: Towards Sustainable Development Goals*, Springer International Publishing, New York, NY, USA, pp. 43–57.

Demortain, D., 2019: Une société (de l'analyse) du risque ? *Nat. Sci. Soc.*, **27**(4), 390–398.

Deshpande, T., K. Michael and K. Bhaskara, 2018: Barriers and enablers of local adaptive measures: a case study of Bengaluru's informal settlement dwellers. *Local Environ.*, **24**(3), 167–179.

Desrochers, P. and J. Szurmak, 2020: Seven billion solutions strong: why markets, growth, and innovation are the antidote to eco-pessimism. *Breakthrough Journal*, **12**. Retrieved March 16, 2022: https://thebreakthrough.org/journal/no-12-winter-2020/seven-billion-solutions.

Di Virgilio, G., et al., 2019: Climate change increases the potential for extreme wildfires. *Geophys. Res. Lett.* DOI: https://doi.org/10.1029/2019GL083699

Diffenbaugh, N.S. and M. Burke, 2019: Global warming has increased global economic inequality. *Proc. Natl. Acad. Sci.*, **116**(20), 9808–9813.

Dilling, L., et al., 2019: Is adaptation success a flawed concept? *Nat. Clim. Change*, **9**(8), 572–574.

Doblas-Reyes, F.J., A.A. Sörensson, M. Almazroui, A. Dosio, W.J. Gutowski, R. Haarsma, R. Hamdi, B. Hewitson, W.-T. Kwon, B.L. Lamptey, D. Maraun, T.S. Stephenson, I. Takayabu, L. Terray, A. Turner, and Z. Zuo, 2021: Linking Global to Regional Climate Change. In *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [Masson- Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press. In Press.

Donner, S.D., M. Kandlikar and S. Webber, 2016: Measuring and tracking the flow of climate change adaptation aid to the developing world. *Environ. Res. Lett.*, **11**(5), 54006.

Doppelt, B., 2017: *Transformational Resilience*. Routledge, London, UK.

Douthwaite, R., 2012: Degrowth and the supply of money in an energy-scarce world. *Ecol. Econ.*, **84**, 187–193.

Dow, K., et al., 2013: Limits to adaptation. *Nat. Clim. Change*, **3**, 305.

Dryzek, J., R. Norgaard and D. Schlosberg, 2013: *Climate challenged society*. Oxford University Press, Oxford.

Dupuis, J. and R. Biesbroek, 2013: Comparing apples and oranges: the dependent variable problem in comparing and evaluating climate change adaptation policies. *Glob. Environ. Change*, **23**(6), 1476–1487.

Dzebo, A. and J. Stripple, 2015: Transnational adaptation governance: an emerging fourth era of adaptation. *Glob. Environ. Change*, **35**, 423–435.

Easterling, D.R., K.E. Kunkel, M.F. Wehner and L. Sun, 2016: Detection and attribution of climate extremes in the observed record. *Weather. Clim. Extrem.*, **11**, 17–27.

Eisenack, K., et al., 2014: Explaining and overcoming barriers to climate change adaptation. *Nat. Clim. Change*, **4**(10), 867–872.

Elliott, J., 2005: *Using Narrative in Social Research: Qualitative and Quantitative Approaches*. Sage Publications, New York, NY, USA.

England, M.I., et al., 2018: Climate change adaptation and cross-sectoral policy coherence in southern Africa. *Reg. Environ. Change*, **18**(7), 2059–2071.

Eriksen, S., et al., 2021: Adaptation interventions and their effect on vulnerability in developing countries: help, hindrance or irrelevance? *World Dev.*, **141**, 105383.

Eriksen, S.H., A.J. Nightingale and H. Eakin, 2015: Reframing adaptation: the political nature of climate change adaptation. *Glob. Environ. Change*, **35**, 523–533.

European Commission, 2019: *Communication from the Commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee and the Committee of the Regions–The European Green Deal*. Document 52019DC0640, 640.

Fagan, M.A.H.C., 2019: *A Look at How People Around the World View Climate Change*. Pew Research Center, Washington, DC, USA.

Faivre, N., M. Fritz, T. Freitas, B. de Boissezon and S. Vandewoestijne, 2017: Nature-Based Solutions in the EU: Innovating with Nature to Address Social, Economic and Environmental Challenges. *Environ. Res.*, **159**, 509–518.

Fankhauser, S., 2017: Adaptation to climate change. *Annu. Rev. Resour. Econ.*, **9**, 209–230.

Fankhauser, S. and S. Dietz, 2014: *Non-economic Losses in the Context of the UNFCCC Work Programme on Loss and Damage*.

Fanning, A.L. and D.W. O'Neill, 2019: The Wellbeing-Consumption paradox: happiness, health, income, and carbon emissions in growing versus non-growing economies. *J. Clean. Prod.*, **212**, 810–821.

Fazey, I., et al., 2020: Transforming knowledge systems for life on Earth: Visions of future systems and how to get there. *Energy Res. Soc. Sci.*, **70**, 101724.

Fazey, I., et al., 2016: Past and future adaptation pathways. *Clim. Dev.*, **8**(1), 26–44.

Feola, G., 2015: Societal transformation in response to global environmental change: a review of emerging concepts. *Ambio*, **44**(5), 376–390.

Fernández-Llamazares, Á., et al., 2017: An empirically tested overlap between indigenous and scientific knowledge of a changing climate in Bolivian Amazonia. *Reg. Environ. Change*, **17**(6), 1673–1685.

Few, R., D. Morchain, D. Spear, A. Mensah and R. Bendapudi, 2017: Transformation, adaptation and development: relating concepts to practice. *Palgrave Commun.*, **3**(1), 17092.

Fisher, S., 2015: The emerging geographies of climate justice. *Geogr. J.*, **181**(1), 73–82.

Fisichelli, N.A., G.W. Schuurman and C.H. Hoffman, 2016: Is 'resilience' maladaptive? Towards an accurate lexicon for climate change adaptation. *Environ. Manag.*, **57**(4), 753–758.

Fleurbaey M., S. Kartha, S. Bolwig, Y. L. Chee, Y. Chen, E. Corbera, F. Lecocq, W. Lutz, M. S. Muylaert, R. B. Norgaard, C. Oker- eke, and A. D. Sagar, 2014: Sustainable Development and Equity. In: *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment*

Report of the Intergovernmental Panel on Climate Change [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J.C. Minx (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA.

Flood, S. and J. Schechtman, 2014: The rise of resilience: evolution of a new concept in coastal planning in Ireland and the US. *Ocean Coast. Manag.*, **102**, 19–31.

Flynn, C., et al., 2021: *The Peoples' Climate Vote*. UNDP and University of Oxford, Oxford, UK.

Folke, C., 2006: Resilience: the emergence of a perspective for social–ecological systems analyses. *Glob. Environ. Change*, **16**(3), 253–267.

Folke, C., et al., 2010: Resilience thinking: integrating resilience, adaptability and transformability. *Ecol. Soc.*, **15**(4). Retrieved on March 16, 2022: http://www.ecologyandsociety.org/vol15/iss4/art20/

Ford, J.D., et al., 2015: Adaptation tracking for a post-2015 climate agreement. *Nat. Clim. Change*, **5**(11), 967–969.

Ford, J.D., et al., 2016: Including indigenous knowledge and experience in IPCC assessment reports. *Nat. Clim. Change*, **6**(4), 349.

Ford, J.D., et al., 2018: Vulnerability and its discontents: the past, present, and future of climate change vulnerability research. *Clim. Change*, **151**(2), 189–203.

Fordham, D.A., et al., 2020: Using paleo-archives to safeguard biodiversity under climate change. *Science*, **369**(6507), eabc5654.

Forsyth, T., 2018: Is resilience to climate change socially inclusive? Investigating theories of change processes in Myanmar. *World Dev.*, **111**, 13–26.

Foster, G.L., P. Hull, D.J. Lunt and J.C. Zachos, 2018: Placing our current 'hyperthermal' in the context of rapid climate change in our geological past. *Philos. Trans. Royal Soc. A*, **376**(2130), 20170086.

Frame, D.J., M.F. Wehner, I. Noy and S.M. Rosier, 2020: The economic costs of Hurricane Harvey attributable to climate change. *Clim. Change*, **160**(2), 271–281.

Frank, T.D., et al., 2021: Pace, magnitude, and nature of terrestrial climate change through the end-Permian extinction in southeastern Gondwana. *Geology*, 49(9), 1089–1095.

Fraser, D. and S.K. Lyons, 2020: Mammal community structure through the paleocene-eocene thermal maximum. *Am. Nat.*, **196**(3), 271–290.

Fraser, N., 1999: Social justice in the age of identity politics: redistribution, recognition, and participation. In: *Culture and Economy After the Cultural Turn*, SAGE Publications, New York, NY, USA, pp. 25.

French, S., 2013: Cynefin, statistics and decision analysis. *J. Oper. Res. Soc.*, **64**(4), 547–561.

Friend, R., et al., 2014: Mainstreaming urban climate resilience into policy and planning; reflections from Asia. *Urban Clim.*, **7**, 6–19.

Gagnon-Lebrun, F. and S. Agrawala, 2007: Implementing adaptation in developed countries: an analysis of progress and trends. *Clim. Policy*, **7**(5), 392–408.

Gao, Q., 2018: Mainstreaming climate change into the EIA procedures: a perspective from China. *Int. J. Clim. Change Strateg. Manag.*, **10**(3), 342–358.

Geels, F.W., 2004: From sectoral systems of innovation to socio-technical systems: insights about dynamics and change from sociology and institutional theory. *Res. Policy*, **33**(6-7), 897–920.

GEF, 2011: Climate Change Adaptation Tracking Tool. Retrieved March 16, 2022: https://www.thegef.org/documents/gef-climate-change-adaptation-tracking-tool.

Gelcich, S., et al., 2010: Navigating transformations in governance of Chilean marine coastal resources. *Proc. Natl. Acad. Sci.*, **107**(39), 16794–16799.

Gerten, C., S. Fina and K. Rusche, 2019: The sprawling planet: simplifying the measurement of global urbanization trends. *Front. Environ. Sci.*, **7**, 140.

Gharbaoui, D. and J. Blocher, 2017: Limits to adapting to climate change through relocations in Papua-New Guinea and Fiji. In: *Climate Change Management*. Springer International Publishing, New York, NY, USA, pp. 359–379.

Gibbs, S.J., et al., 2016: Ocean warming, not acidification, controlled coccolithophore response during past greenhouse climate change. *Geology*, **44**(1), 59–62.

Gillard, R., A. Gouldson, J. Paavola and J. Van Alstine, 2016: Transformational responses to climate change: beyond a systems perspective of social change in mitigation and adaptation. *Wiley Interdiscip. Rev. Clim. Change*, **7**(2), 251–265.

Gillett, N.P., et al., 2021: Constraining human contributions to observed warming since the pre-industrial period. *Nat. Clim. Change*, **11**(3), 207–212.

Giosan, L., et al., 2018: Neoglacial climate anomalies and the Harappan metamorphosis. *Clim. Past*, **14**(11), 1669–1686.

Global Commission on Adaptation, 2019: *Adapt Now: A Global Call for Leadership on Climate Resilience*. Global Commission on Adaptation, Rotterdam, the Netherlands.

Global Commission on the Economy and Climate, 2018: *Unlocking the Inclusive Growth Story of the 21st Century: Accelerating Climate Action in Urgent Times*. New Climate Economy, Washington, DC, USA.

Goldman, M.J., M.D. Turner and M. Daly, 2018: A critical political ecology of human dimensions of climate change: epistemology, ontology, and ethics. *WIREs Clim. Change*, **9**(4). DOI: https://doi.org/10.1002/wcc.526

Gómez-Baggethun, E., 2020: More is more: scaling political ecology within limits to growth. *Polit. Geogr.*, **76**, 102095.

Göpel, M., 2016: *The Great Mindshift: How a New Economic Paradigm and Sustainability Transformations Go Hand in Hand*. Springer Nature, London, UK and New York, NY.

Gorddard, R., M.J. Colloff, R.M. Wise, D. Ware and M. Dunlop, 2016: Values, rules and knowledge: adaptation as change in the decision context. *Environ. Sci. Policy*, **57**, 60–69.

Gough, I., 2015: Climate change and sustainable welfare: the centrality of human needs. *Camb. J. Evon.*, **39**(5), 1191–1214.

Grantham Research Institute on Climate Change and the Environment and Sabin Center for Climate Change Law, 2021: *Climate Change Laws of the World Database*. LSE, London, UK.

Green, D., S. Jackson and J. Morrison, 2009: *Risks from Climate Change to Indigenous Communities in the Tropical North of Australia*. Department of Climate Change, Commonwealth of Australia, Sydney, Australia.

Grinsted, A., P. Ditlevsen and J.H. Christensen, 2019: Normalized US hurricane damage estimates using area of total destruction, 1900–2018. *Proc. Natl. Acad. Sci.*, **116**(48), 23942–23946.

Grose, M.R., et al., 2020: The warm and extremely dry spring in 2015 in Tasmania contained the fingerprint of human influence on the climate. *J. South. Hemisphere Earth Syst. Sci.*, **69**(1), 183–195.

Grubb, M., J.-C. Hourcade and K. Neuhoff, 2014: *Planetary Economics: Energy, Climate Change and the Three Domains of Sustainable Development*. Routledge, London, UK and New York, NY, USA.

Gulev, S.K., P.W. Thorne, J. Ahn, F.J. Dentener, C.M. Domingues, S. Gerland, D. Gong, D.S. Kaufman, H.C. Nnamchi, J. Quaas, J.A. Rivera, S. Sathyendranath, S.L. Smith, B. Trewin, K. von Shuckmann and R.S. Vose, 2021: Changing State of the Climate System. In: *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu and B. Zhou (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA.

Gutiérrez, J.M., R.G. Jones, G.T. Narisma, L.M. Alves, M. Amjad, I. V. Gorodetskaya, M. Grose, N.A.B. Klutse, S. Krakovska, J. Li, D. Martínez-Castro, L.O. Mearns, S.H. Mernild, T. Ngo-Duc, B. van den Hurk, and J.-H. Yoon, 2021: Atlas. In *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E.

Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press. In Press.

Gutmann, A. and D.F. Thompson, 2009: *Why Deliberative Democracy?* Princeton University Press, Princeton, New Jersey, USA.

Haasnoot, M., et al., 2020: Defining the solution space to accelerate climate change adaptation. *Reg. Environ. Change*, **20**(2), 1–5.

Haasnoot, M., et al., 2019a: Generic adaptation pathways for coastal archetypes under uncertain sea-level rise. *Environ. Res. Commun.*, **1**(7), 71006.

Haasnoot, M., J. Lawrence and A.K. Magnan, 2021: Pathways to coastal retreat. *Science*, **372**(6548), 1287–1290.

Haasnoot, M., A. Warren and J.H. Kwakkel, 2019b: Dynamic adaptive policy pathways (DAPP). In: *Decision Making under Deep Uncertainty*. Springer, Cham, pp. 71–92.

Haberl, H., et al., 2020: A systematic review of the evidence on decoupling of GDP, resource use and GHG emissions, part II: synthesizing the insights. *Environ. Res. Lett.*, **15**(6), 65003.

Hale, T.N., et al., 2021: Sub- and non-state climate action: a framework to assess progress, implementation and impact. *Clim. Policy*, **21**(3), 406–420.

Hall, J.A., et al., 2019: Rising sea levels: helping decision-makers confront the inevitable. *Coast. Manag.*, **47**(2), 127–150.

Hamborg, S., J.N. Meya, K. Eisenack and T. Raabe, 2020: Rethinking resilience: a cross-epistemic resilience framework for interdisciplinary energy research. *Energy Res. Soc. Sci.*, **59**, 101285.

Hansen, G., D. Stone, M. Auffhammer, C. Huggel and W. Cramer, 2016: Linking local impacts to changes in climate: a guide to attribution. *Reg. Environ. Change*, **16**(2), 527–541.

Hansen, J., M. Sato, G. Russell and P. Kharecha, 2013: Climate sensitivity, sea level and atmospheric carbon dioxide. *Philos. Trans. Royal Soc. A Math. Phys. Eng. Sci.*, **371**(2001), 20120294.

Hanssen, S., et al., 2020: The climate change mitigation potential of bioenergy with carbon capture and storage. *Nat. Clim. Change*, **10**, 1023–1029.

Hassanali, K., 2017: Challenges in mainstreaming climate change into productive coastal sectors in a Small Island State – the case of Trinidad and Tobago. *Ocean Coast. Manag.*, **142**, 136–142.

Hauser, M., R. Orth and S.I. Seneviratne, 2016: Role of soil moisture versus recent climate change for the 2010 heat wave in western Russia. *Geophys. Res. Lett.*, **43**(6), 2819–2826.

Hausfather, Z. and G.P. Peters, 2020: Emissions – the 'business as usual' story is misleading. *Nature*, **577**(7792), 618–620.

Haywood, A.M., et al., 2019: What can Palaeoclimate modelling do for you? *Earth Syst. Environ.*, **3**(1), 1–18.

Heck, V., D. Gerten, W. Lucht and A. Popp, 2018: Biomass-based negative emissions difficult to reconcile with planetary boundaries. *Nat. Clim. Change*, **8**(2), 151–155.

Hegerl, G.C., O. Hoegh-Guldberg, G. Casassa, M.P. Hoerling, R. Kovats, C. Parmesan, D.W. Pierce and P.A. Stott, 2010: Good practice guidance paper on detection and attribution related to anthropogenic climate change. In: *Meeting Report of the Intergovernmental Panel on Climate Change Expert Meeting on Detection and Attribution of Anthropogenic Climate Change*. IPCC Working Group I Technical Support Unit, University of Bern, Bern.

Hegmon, M., et al., 2008: Social transformation and its human costs in the Prehispanic U.S. Southwest. *Am. Anthropol.*, **110**(3), 313–324.

Heimhofer, U., et al., 2018: Vegetation response to exceptional global warmth during Oceanic Anoxic Event 2. *Nat. Commun.*, **9**(1), 3832.

Herrero, C., R. Martínez and A. Villar, 2012: A newer human development index. *J. Human. Dev. Capabil*, **13**(2), 247–268.

Herring, S.C., N. Christidis, A. Hoell, M.P. Hoerling and P.A. Stott, 2021: Explaining extreme events of 2019 from a climate perspective. *Bull. Am. Meteorol. Soc.*, **102**(1), 1–S116.

Herrmann, J. and E. Guenther, 2017: Exploring a scale of organizational barriers for enterprises' climate change adaptation strategies. *J. Clean. Prod.*, **160**, 38–49.

Hickel, J. and G. Kallis, 2020: Is green growth possible? *New Polit. Econ.*, **25**(4), 469–486.

Hill, A.C. and L. Martinez-Diaz, 2019: *Building a Resilient Tomorrow: How to Prepare for the Coming Climate Disruption*. Oxford University Press, USA.

Hochman, Z., D.L. Gobbett and H. Horan, 2017: Climate trends account for stalled wheat yields in Australia since 1990. *Glob. Change Biol.*, **23**(5), 2071–2081.

Hoegh-Guldberg, O., et al., 2019: The human imperative of stabilizing global climate change at 1.5° C. *Science*, **365**(6459), eaaw6974.

Hoekstra, R. and J.C.J.M. van den Bergh, 2003: Comparing structural decomposition analysis and index. *Energy Econ.*, **25**(1), 39–64.

Hollesen, J., et al., 2018: Climate change and the deteriorating archaeological and environmental archives of the Arctic. *Antiquity*, **92**(363), 573–586.

Holling, C.S., 1973: Resilience and stability of ecological systems. *Annu. Rev. Ecol. Syst.*, **4**(1), 1–23.

Holman, I.P., C. Brown, T.R. Carter, P.A. Harrison and M. Rounsevell, 2019: Improving the representation of adaptation in climate change impact models. *Reg. Environ. Change*, **19**(3), 711–721.

Hölscher, K., J.M. Wittmayer and D. Loorbach, 2018: Transition versus transformation: what's the difference. *Environ. Innov. Soc. Transit.*, **27**, 1–3.

Hong, L. and S.E. Page, 2004: Groups of diverse problem solvers can outperform groups of high-ability problem solvers. *Proc. Natl. Acad. Sci.*, **101**(46), 16385–16389.

Horton, R.M., A. de Sherbinin, D. Wrathall and M. Oppenheimer, 2021: Assessing human habitability and migration. *Science*, **372**(6548), 1279–1283.

Hourdequin, M., 2016: Justice, recognition and climate change. In: *Climate Justice and Geoengineering: Ethics and Policy in the Atmospheric Anthropocene*, pp. 33–48.

Hügel, S. and A.R. Davies, 2020: Public participation, engagement, and climate change adaptation: a review of the research literature. *WIREs Clim. Change*, **11**(4).

Huggel, C., D. Stone, H. Eicken and G. Hansen, 2015: Potential and limitations of the attribution of climate change impacts for informing loss and damage discussions and policies. *Clim. Change*, **133**(3), 453–467.

Hughes, T.P., C. Linares, V. Dakos, I. A. Van De Leemput and E.H. Van Nes, 2013: Living dangerously on borrowed time during slow, unrecognized regime shifts. *Trends Ecol. Evol.*, **28**(3), 149–155.

Hulvey, K.B., et al., 2013: Benefits of tree mixes in carbon plantings. *Nat. Clim. Change*, **3**(10), 869–874.

Huurdeman, E.P., et al., 2021: Rapid expansion of meso-megathermal rain forests into the southern high latitudes at the onset of the Paleocene-Eocene Thermal Maximum. *Geology*, **49**(1), 40–44.

IAC, 2010: *Climate Change Assessments. Review of the Processes and Procedures of the IPCC*. IAC, Amsterdam, The Netherlands.

Iglesias, V., C. Whitlock, T.R. Krause and R.G. Baker, 2018: Past vegetation dynamics in the Yellowstone region highlight the vulnerability of mountain systems to climate change. *J. Biogeogr.*, **45**(8), 1768–1780.

Ignatowski, J.A. and J. Rosales, 2013: Identifying the exposure of two subsistence villages in Alaska to climate change using traditional ecological knowledge. *Clim. Change*, **121**(2), 285–299.

ILO, 1989: *Convention on Indigenous and Tribal Peoples*. Geneva, Switzerland.

ILO, 2013: Understanding the Indigenous and Tribal people Convention, 1989 (No. 169). In: *Handbook for ILO Tripartite Constituents*. International Labour Office, Geneva, Switzerland.

ILO, 2019: *Indigenous and Tribal Peoples Convention, 1989 (No. 169) Committee of Experts on the Application of Conventions and Recommendations*. International Labour Organization, Geneva.

Inoue, T., 2019: Carbon sequestration in mangroves. In: *Blue Carbon in Shallow Coastal Ecosystems: Carbon Dynamics, Policy, and Implementation* [Kuwae, T. and M. Hori(eds.)]. Springer Singapore, Singapore, pp. 73–99.

Inuit Tapiriit Kanatami, 2018: *National Inuit Strategy on Research*. Inuvialuit Regional Corporation, Inuvik, NT, Canada.

IPBES, 2018: *The IPBES Assessment Report on Land Degradation and Restoration*. Secretariat of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services, Bonn, Germany.

IPBES, 2019a: *Summary for Policymakers of the Global Assessment Report on Biodiversity and Ecosystem Services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services*. IPBES secretariat, Bonn, Germany.

IPBES, 2019b: Summary for policymakers of the global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. In: *Global Assessment Report on Biodiversity and Ecosystem Services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services*. Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) Secretariat, Bonn, Germany.

IPCC, 2005: *Guidance Notes for Lead Authors of the IPCC Fourth Assessment Report on Addressing Uncertainties*. Intergovernmental Panel on Climate Change. Retrieved March 16, 2022: https://www.ipcc.ch/report/ar4/wg1/uncertainty-guidance-note-for-the-fourth-assessment-report/

IPCC, 2012: Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation (SREX). In: *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change (IPCC)*. [Field, C.B., V. Barros, T.F. Stocker, D. Qin, D.J. Dokken, K.L. Ebi, M.D. Mastrandrea, K.J. Mach, G.K. Plattner, S.K. Allen, M. Tignor and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 3–21.

IPCC, 2013: Summary for Policymakers. In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, UK and New York, NY, USA.

IPCC, 2014a: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA. 1132 pp.

IPCC, 2014b: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Barros, V.R., C.B. Field, D.J. Dokken, M.D. Mastrandrea, K.J. Mach, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA. 688 pp.

IPCC, 2014c: Summary for Policymakers. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea and L.L. White (eds.)]. Cambridge University Press, Cambridge, UK, and New York, NY, USA, pp. 1–32.

IPCC, 2014d: *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J.C. Minx (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA.

IPCC, 2018a: Annex I: Glossary. In: *Global Warming of 1.5°C. An IPCC Special Report on the Impacts of Global Warming of 1.5°C Above Pre-Industrial Levels and Related Global Greenhouse Gas Emission Pathways, in the Context of Strengthening the Global Response to the Threat of Climate Change, Sustainable Development, and Efforts to Eradicate Poverty*. [Matthews, R. (ed.)]. Cambridge University Press, Cambridge, UK, and New York, NY, US.

IPCC, 2018b: *Global Warming of 1.5°C. An IPCC Special Report on the Impacts of Global Warming of 1.5°C Above Pre-Industrial Levels and Related Global Greenhouse Gas Emission Pathways, in the Context of Strengthening the Global Response to the Threat of Climate Change, Sustainable Development, and Efforts to Eradicate Poverty*. Cambridge University Press, Cambridge, UK, and New York, NY, US.

IPCC, 2018c: Summary for Policymakers, Global Warming of 1.5°C. In: *Global Warming of 1.5°C. An IPCC Special Report on the Impacts of Global Warming of 1.5°C Above Pre-Industrial Levels and Related Global Greenhouse Gas Emission Pathways, in the Context of Strengthening the Global Response to the Threat of Climate Change, Sustainable Development, and Efforts to Eradicate Poverty*. [Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor and T. Waterfield (eds.)]. World Meteorological Organization, Geneva, Switzerland, pp. 32 pp.

IPCC, 2019a: *Climate Change and Land: an IPCC Special Report on Climate Change, Desertification, Land Degradation, Sustainable Land Management, Food Security, and Greenhouse Gas Fluxes in Terrestrial Ecosystems (SRCCL)*. Cambridge University Press, Cambridge, UK, and New York, NY, US.

IPCC, 2019b: *Special Report on the Ocean and Cryosphere in a Changing Climate (SROCC)*.

IPCC, 2019c: Summary for Policymakers. In: *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate* (In press). Cambridge University Press, Cambridge, UK, and New York, NY, US.

IPCC, 2020: *The Concept of Risk in the IPCC Sixth Assessment Report: a summary of Cross-Working Group Discussions*. Cambridge University Press, Cambridge, UK, and New York, NY, USA.

IPCC, 2021a: *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA. In Press.

IPCC, 2021b: Annex VII: Glossary [Matthews, J.B.R., V. Möller, R. van Diemen, J.S. Fuglestvedt, V. Masson- Delmotte, C. Méndez, S. Semenov, A. Reisinger (eds.)]. In *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA. In Press.

IPCC, 2021c: Summary for Policymakers. In: *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, UK, and New York, NY, USA.

Isenhour, C., 2016: Unearthing human progress? Ecomodernism and contrasting definitions of technological progress in the Anthropocene. *Econ. Anthropol.*, **3**(2), 315–328.

Ivany, L.C., et al., 2018: Little lasting impact of the Paleocene-Eocene Thermal Maximum on shallow marine molluscan faunas. *Sci. Adv.*, **4**(9), eaat5528.

Jackson, R.B., J.L. Banner, E. G. Jobbágy, W.T. Pockman and D.H. Wall, 2002: Ecosystem carbon loss with woody plant invasion of grasslands. *Nature*, **418**(6898), 623–626.

Jafry, T., M. Mikulewicz and K. Helwig, 2018: Introduction: justice in the era of climate change. In: *Routledge Handbook of Climate Justice*. Routledge, London, UK, pp. 1–9.

Jakku, E., et al., 2016: Learning the hard way: a case study of an attempt at agricultural transformation in response to climate change. *Clim. Change*, **137**(3-4), 557–574.

Janif, S.Z., et al., 2016: Value of traditional oral narratives in building climate-change resilience: insights from rural communities in Fiji. *Ecol. Soc.*, **21**(2). DOI: http://dx.doi.org/10.5751/ES-08100-210207

Jézéquel, A., et al., 2018: Behind the veil of extreme event attribution. *Clim. Change*, **149**(3), 367–383.

Jonas, H., 1985: *The Imperative of Responsibility: in Search of an Ethics for the Technological Age*. University of Chicago Press, Chicago, IL, USA.

Jones, C., 2019: Climate change and farming response in a temperate oceanic zone—the exploitation of a Karstic region in Western Ireland in the third and second millennia BC. *J. Isl. Coast. Archaeol.*, 1–22. DOI: https://doi.org/10.1080/15564894.2019.1614115

Jones, C., et al., 2013: Twenty-first-century compatible CO_2 emissions and airborne fraction simulated by CMIP5 earth system models under four representative concentration pathways. *J. Clim.*, **26**(13), 4398–4413.

Jones, L. and E. Boyd, 2011: Exploring social barriers to adaptation: insights from Western Nepal. *Glob. Environ. Change*, **21**(4), 1262–1274.

Jones, R.N., A. Patwardhan, S.J. Cohen, S. Dessai, A. Lammel, R.J. Lempert, M.M.Q. Mirza and H. von Storch, 2014: Foundations for decision making. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea and L.L. White (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 195–228.

Jones, R.N. and B.L. Preston, 2011: Adaptation and risk management. *WIREs Clim. Chang.*, (2). DOI: 10.1002/wcc.97.

Jorgenson, A.K., et al., 2019: Social science perspectives on drivers of and responses to global climate change. *WIREs Clim. Chang.*, **10**(1), e554.

Juan, S., 2011: *La transition écologique*. Érès, Toulouse, France.

Juhola, S., 2016: Barriers to the implementation of climate change adaptation in land use planning. *Int. J. Clim. Change Strateg. Manag.*, **8**(3), 338–355.

Jurgilevich, A., A. Räsänen, F. Groundstroem and S. Juhola, 2017: A systematic review of dynamics in climate risk and vulnerability assessments. *Environ. Res. Lett.*, **12**(1), 13002.

Kahn, M. E., et al., 2019: *Long-term macroeconomic effects of climate change: a cross-country analysis*. National Bureau of Economic Research. DOI: 0.3386/w26167

Kallis, G., 2011: In defence of degrowth. *Ecol. Econ.*, **70**(5), 873–880.

Kallis, G., 2017: Radical dematerialization and degrowth. *Philos. Trans. Royal Soc. A Math. Phys. Eng. Sci.*, **375**(2095), 20160383.

Kallis, G., C. Kerschner and J. Martinez-Alier, 2012: *The Economics of Degrowth*. Elsevier. DOI: http://dx.doi.org/10.1016/j.ecolecon.2012.08.017.

Kanie, N. and F. Biermann, 2017: *Governing Through Goals: Sustainable Development Goals as Governance Innovation*. MIT Press, Cambridge, MA, USA.

Kay, R. and J. Adler, 2017: *Coastal Planning and Management*. CRC Press, Boca Raton, FL, USA.

Kemp, D.B., K. Eichenseer and W. Kiessling, 2015: Maximum rates of climate change are systematically underestimated in the geological record. *Nat. Commun.*, **6**, 8890.

Kern, F. and K.S. Rogge, 2018: Harnessing theories of the policy process for analysing the politics of sustainability transitions: a critical survey. *Environ. Innov. Soc. Transit.*, **27**, 102–117.

Keskitalo, E. and B. Preston, 2019a: *Research Handbook on Climate Change Adaptation Policy*. Edward Elgar Publishing, Cheltenham, Glos; Northampton, Massachusetts..

Keskitalo, E.C.H. and M. Pettersson, 2016: Can adaptation to climate change at all be mainstreamed in complex multi-level governance systems? A case study of forest-relevant policies at the EU and Swedish levels. In: *Implementing Climate Change Adaptation in Cities and Communities*. Springer, New York, NY, USA, pp. 53–74.

Keskitalo, E.C.H. and B.L. Preston, 2019b: *Research Handbook on Climate Change Adaptation Policy*. Edward Elgar Publishing, Cheltenham, Glos; Northampton, Massachusetts.

Kienberger, S., T. Blaschke and R.Z. Zaidi, 2013: A framework for spatio-temporal scales and concepts from different disciplines: the 'vulnerability cube'. *Nat. Hazards*, **68**(3), 1343–1369.

Kiessling, W., C. Simpson, B. Beck, H. Mewis and J.M. Pandolfi, 2012: Equatorial decline of reef corals during the last Pleistocene interglacial. *Proc. Natl. Acad. Sci. U.S.A.*, **109**(52), 21378–21383.

Kirkby, P., C. Williams and S. Huq, 2017: Community-based adaptation (CBA): adding conceptual clarity to the approach and establishing its principles and challenges. *Clim. Dev.*, **10**(7), 577–589.

Kitcher, P., 2011: *Science in a Democratic Society*. In: Scientific Realism and Democratic Society. Brill Rodopi, Lieden, the Netherlands, pp. 95–112.

Klauer, B., 1999: Defining and achieving sustainable development. *Int. J. Sustain. Dev. World Ecol.*, **6**(2), 114–121.

Klein, J.A., et al., 2014a: Unexpected climate impacts on the Tibetan Plateau: local and scientific knowledge in findings of delayed summer. *Glob. Environ. Change*, **28**, 141–152.

Klein, R.J.T., G.F. Midgley, B.L. Preston, M. Alam, F.G.H. Berkhout, K. Dow and M.R. Shaw, 2014b: Adaptation opportunities, constraints, and limits. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel of Climate Change*. [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea and L.L. White (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 899–943.

Klenk, N., A. Fiume, K. Meehan and C. Gibbes, 2017: Local knowledge in climate adaptation research: moving knowledge frameworks from extraction to co-production. *WIREs Clim. Change*, **8**(5).

Knapp, A.B. and S.W. Manning, 2016: Crisis in context: the end of the Late Bronze Age in the eastern Mediterranean. *Am. J. Archaeol.*, **120**(1), 99–149.

Koch, F., 2018: Mainstreaming adaptation: a content analysis of political agendas in Colombian cities. *Clim. Dev.*, **10**(2), 179–192.

Köhler, J., et al., 2019: An agenda for sustainability transitions research: state of the art and future directions. *Environ. Innov. Soc. Transit.*, **31**, 1–32.

Kohler, T.A., S.G. Ortman, K.E. Grundtisch, C.M. Fitzpatrick and S.M. Cole, 2014: The better angels of their nature: declining violence through time among Prehispanic farmers of the Pueblo Southwest. *Am. Antiq.*, **79**(3), 444–464.

Kopp, R.E., K. Hayhoe, D.R. Easterling, T. Hall, R. Horton, K.E. Kunkel, and A.N. LeGrande, 2017: Poten- tial surprises – compound extremes and tipping elements. In: *Climate Science Special Report: Fourth Nation- al Climate Assessment, Volume I* [Wuebbles, D.J., D.W. Fahey, K. A. Hibbard, D.J. Dokken, B.C. Stewart, and T.K. Maycock (eds.)]. U.S. Global Change Research Program, Washington, DC, USA, pp. 411–429, doi: 10.7930/J0GB227J.

Koren, H.S. and C.D. Butler, 2006: The interconnection between the built environment ecology and health. In: *Environmental Security and Environmental Management: The Role of Risk Assessment*, Vol. 5, pp. 111.

Kröger, B., 2017: Changes in the latitudinal diversity gradient during the Great Ordovician Biodiversification Event. *Geology*, **46**(2), 127–130.

Kuil, L., et al., 2019: Learning from the Ancient Maya: exploring the impact of drought on population dynamics. *Ecol. Econ.*, **157**, 1–16.

Kuruppu, N., 2009: Adapting water resources to climate change in Kiribati: the importance of cultural values and meanings. *Environ. Sci. Policy*, **12**(7), 799–809.

Lacey, J., S.M. Howden, C. Cvitanovic and A.-M. Dowd, 2015: Informed adaptation: ethical considerations for adaptation researchers and decision-makers. *Glob. Environ. Change*, **32**, 200–210.

Lamb, W.F. and J.K. Steinberger, 2017: Human well-being and climate change mitigation. *Wiley Interdiscip. Rev. Change*, **8**(6). DOI: https://doi.org/10.1002/wcc.485.

Landemore, H., 2013: Deliberation, cognitive diversity, and democratic inclusiveness: an epistemic argument for the random selection of representatives. *Synthese*, **190**(7), 1209–1231.

Latouche, S., 2001: *La déraison de la raison économique*. Albin Michel, Paris.

Laurila-Pant, M., A. Lehikoinen, L. Uusitalo and R. Venesjärvi, 2015: How to value biodiversity in environmental management? *Ecol. Indic.*, **55**, 1–11.

Lavell, A., M. Oppenheimer, C. Diop, J. Hess, R. Lempert, J. Li, R. Muir-Wood and S. Myeong, 2012: Climate Change: New Dimensions in Disaster Risk, Exposure, Vulnerability, and Resilience. In: *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation*. [Field, C.B. V.R. Barros, T.F. Stocker, D. Qin, D.J. Dokken, K.L. Ebi, M.D. Mastrandrea, K.J. Mach, G.K. Plattner, S.K. Allen, M. Tignor and P.M. Midgley (eds.)], A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change (IPCC). Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 25–64.

Lawrence, D., A. Palmisano and M.W. de Gruchy, 2021: Collapse and continuity: a multi-proxy reconstruction of settlement organization and population trajectories in the Northern Fertile Crescent during the 4.2kya Rapid Climate Change event. *PLoS ONE*, **16**(1), e244871.

Le Quéré, C., et al., 2019: Drivers of declining CO 2 emissions in 18 developed economies. *Nat. Clim. Change*, **9**(3), 213–217.

Leakey, R.R.B., 2020: A re-boot of tropical agriculture benefits food production, rural economies, health, social justice and the environment. *Nat. Food*, **1**(5), 260–265.

Leal Filho, W., et al., 2018: Reinvigorating the sustainable development research agenda: the role of the sustainable development goals (SDG). *Int. J. Sustain. Dev. World Ecol.*, **25**(2), 131–142.

Lee, J.Y., J. Marotzke, G. Bala, L. Cao, S. Corti, J.P. Dunne, F. Engelbrecht, E. Fischer, J.C. Fyfe, C. Jones, A. Maycock, J. Mutemi, O. Ndiaye, S. Panickal and T. Zhou, 2021: Future Global Climate: Scenario-Based Projections and Near-Term Information. In: *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu and B. Zhou (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA.

Lee, S.J., Y. Kim and R. Phillips (eds.), 2015: *Exploring the Intersection of Community Well-Being and Community Development. Community Well-Being and Community Development*. SpringerBriefs in Well-Being and Quality of Life Research. Springer, Cham.

Lehmann, P., M. Brenck, O. Gebhardt, S. Schaller and E. Süßbauer, 2015: Barriers and opportunities for urban adaptation planning: analytical framework and evidence from cities in Latin America and Germany. *Mitig. Adapt. Strateg. Glob. Change*, **20**(1), 75–97.

Leifeld, J. and L. Menichetti, 2018: The underappreciated potential of peatlands in global climate change mitigation strategies. *Nat. Commun.*, **9**(1), 1–7.

Leiter, T., 2021: Progress in implementing adaptation: insights from project proposals and scientific literature. In: *The Adaptation Gap Report 2020*. UNEP, Nairobi, Kenya, pp. 33–40.

Lejeune, Q., E.L. Davin, L. Gudmundsson, J. Winckler and S.I. Seneviratne, 2018: Historical deforestation locally increased the intensity of hot days in northern mid-latitudes. *Nat. Clim. Change*, **8**(5), 386–390.

Lempert, R., J.G. Arnold, R. Pulwarty, K. Gordon, C. Greig, C. Hawkins Hoofman, D. Sands and C. Werrell, 2018: Reducing risks through adaptation actions. In: *Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment* [Reidmiller, D.R., C.W. Avery, K.E. Easterling, K.L.M. Knkel, T.K. Maycock and B.C. Stewart(eds.)] Vol.II, U.S. Global Change Research Program, Washington, DC.

Lempert, R.J. and S. Turner, 2020: Engaging multiple worldviews with quantitative decision support: a robust decision-making demonstration using the lake model. *Risk Anal.* DOI: https://doi.org/10.1111/risa.13579

Lesnikowski, A., et al., 2019a: Frontiers in data analytics for adaptation research: topic modeling. *WIREs Clim. Chang.*, **10**(3). DOI: https://doi.org/10.1002/wcc.576

Lesnikowski, A., et al., 2017: What does the Paris Agreement mean for adaptation? *Clim. Policy*, **17**(7), 825–831.

Lesnikowski, A., J.D. Ford, R. Biesbroek and L. Berrang-Ford, 2019b: A policy mixes approach to conceptualizing and measuring climate change adaptation policy. *Clim. Change*, 156(4), 447–469.

Lesnikowski, A.C., J.D. Ford, R. Biesbroek, L. Berrang-Ford and J. Heymann, 2016: National level progress on adaptation. *Nat. Clim .Change*, **6**, 261–264.

Levin, K., B. Cashore, S. Bernstein and G. Auld, 2012: Overcoming the tragedy of super wicked problems: constraining our future selves to ameliorate global climate change. *Policy Sci.*, **45**(2), 123–152.

Lewis, S.C., A.D. King, S.E. Perkins-Kirkpatrick and M.F. Wehner, 2019: Toward calibrated language for effectively communicating the results of extreme event attribution studies. *Earth's Future*, **7**(9), 1020–1026.

Lewis, S.L. and M.A. Maslin, 2015: Defining the Anthropocene. *Nature*, **519**(7542), 171–180.

Lindström, S., 2016: Palynofloral patterns of terrestrial ecosystem change during the end-Triassic event – a review. *Geol. Mag.*, **153**(2), 223–251.

Linnér, B.-O. and V. Wibeck, 2019: *Sustainability Transformations Across Societies: Agents and Drivers Across Societies*. Cambridge University Press, Cambridge, UK and New York, NY, USA.

Llavador, H., J.E. Roemer and J. Silvestre, 2010: Intergenerational justice when future worlds are uncertain. *J. Math. Econ.*, **46**(5), 728–761.

Loorbach, D., 2010: Transition management for sustainable development: a prescriptive, complexity-based governance framework. *Governance*, **23**(1), 161–183.

Lövbrand, E., et al., 2015: Who speaks for the future of Earth? How critical social science can extend the conversation on the Anthropocene. *Glob. Environ. Change*, **32**, 211–218.

Lubell, M. and M.T. Niles, 2019: The limits of capacity building. *Nat. Clim. Change*, **9**(8), 578–579.

MacDonald, J.P., et al., 2015: Protective factors for mental health and well-being in a changing climate: perspectives from Inuit youth in Nunatsiavut, Labrador. *Soc. Sci. Med.*, **141**, 133–141.

MacFarling Meure, C., et al., 2006: Law Dome CO_2, CH4 and N2O ice core records extended to 2000 years BP. *Geophys. Res. Lett.*, **33**(14). DOI: 10.1029/2006GL026152.

Mach, K.J. and C.B. Field, 2017: Toward the next generation of assessment. *Annu. Rev. Environ. Resour.*, **42**(1), 569–597.

Mach, K.J., et al., 2019: Climate as a risk factor for armed conflict. *Nature*, **571**, 193–197.

Mach, K.J., M.D. Mastrandrea, T.E. Bilir and C.B. Field, 2016: Understanding and responding to danger from climate change: the role of key risks in the IPCC AR5. *Clim. Change*, **136**(3-4), 427–444.

Mach, K.J., M.D. Mastrandrea, P.T. Freeman and C.B. Field, 2017: Unleashing expert judgment in assessment. *Glob. Environ. Change*, **44**, 1–14.

MacKinnon, D. and K.D. Derickson, 2013: From resilience to resourcefulness: a critique of resilience policy and activism. *Prog. Hum. Geogr.*, **37**(2), 253–270.

Magnan, A.K., E.L.F. Schipper and V.K.E. Duvat, 2020: Frontiers in climate change adaptation science: advancing guidelines to design adaptation pathways. *Curr. Clim. Change Rep.*, **6**(4), 166–177.

Malm, A. and A. Hornborg, 2014: The geology of mankind? A critique of the Anthropocene narrative. *Anthropocene Rev.*, **1**(1), 62–69.

Maor, M., J. Tosun and A. Jordan, 2017: Proportionate and disproportionate policy responses to climate change: core concepts and empirical applications. *J. Environ. Policy Plan.*, **19**(6), 599–611.

Marjanac, S., L. Patton and J. Thornton, 2017: Acts of God, human influence and litigation. *Nat. Geosci*, **10**(9), 616–619.

Markhvida, M., B. Walsh, S. Hallegatte and J. Baker, 2020: Quantification of disaster impacts through household well-being losses. *Nat. Sustain.*, 1–10. DOI:10.1038/s41893-020-0508-7.

Mastrandrea, M.D., C.B. Field, T.F. Stocker, O. Edenhofer, K.L. Ebi, D.J. Frame, H. Held, E. Kriegler, K.J. Mach and P.R. Matschoss, 2010: *Guidance Note for Lead Authors of the IPCC Fifth Assessment Report on Consistent Treatment of Uncertainties*.

Mastrandrea, M.D. and K.J. Mach, 2011: Treatment of uncertainties in IPCC Assessment Reports: past approaches and considerations for the Fifth Assessment Report. *Clim. Change*, **108**(4), 659.

Mathes, G.H., J. van Dijk, W. Kiessling and M.J. Steinbauer, 2021: Extinction risk controlled by interaction of long-term and short-term climate change. *Nat. Ecol. Evol.*, **5**, 304–310.

Matthews, H.D., 2016: Quantifying historical carbon and climate debts among nations. *Nat. Clim. Change*, **6**(1), 60–64.

Mavrodieva, A.V., O.K. Rachman, V.B. Harahap and R. Shaw, 2019: Role of social media as a soft power tool in raising public awareness and engagement in addressing climate change. *Climate*, **7**(10), 122.

McDowell, G., J. Ford and J. Jones, 2016: Community-level climate change vulnerability research: trends, progress, and future directions. *Environ. Res. Lett.*, **11**(3), 33001.

McNamara, K.E. and G. Jackson, 2019: Loss and damage: a review of the literature and directions for future research. *Wiley Interdiscip. Rev. Chang.*, **10**(2). DOI: 10.1002/wcc.564

McShane, K., 2017: Values and harms in loss and damage. *Ethics Policy Environ.*, **20**(2), 129–142.

Mechler, R., et al., 2019: Science for loss and damage. Findings and propositions. In: *Loss and Damage from Climate Change*. Springer, New York, NY, USA, pp. 3–37.

Mechler, R. and T. Schinko, 2016: Identifying the policy space for climate loss and damage. *Science*, **354**(6310), 290–292.

Meerow, S., J.P. Newell and M. Stults, 2016: Defining urban resilience: a review. *Landsc. Urban Plan.*, **147**, 38–49.

Meijerink, S., et al., 2014: The role of leadership in regional climate change adaptation: a comparison of adaptation practices initiated by governmental and non-governmental actors. *J. Water Clim. Change*, **6**(1), 25–37.

Mellegård, V. and W.J. Boonstra, 2020: Craftsmanship as a carrier of indigenous and local ecological knowledge: photographic insights from Sámi Duodji and archipelago fishing. *Soc. Nat. Resour.*, 1–21. DOI: 10.1080/08941920.2020.1729911.

Metzger, J., et al., 2021: The flexibility gamble: challenges for mainstreaming flexible approaches to climate change adaptation. *J. Environ. Policy Plan.*, 1–16. DOI: 10.1080/1523908X.2021.1893160.

Miller, C.A., J. O'Leary, E. Graffy, E.B. Stechel and G. Dirks, 2015: Narrative futures and the governance of energy transitions. *Futures*, **70**, 65–74.

Mimura, N., R.S. Pulwarty, D.M. Duc, I. Elshinnawy, M.H. Redsteer, H.Q. Huang, J.N. Nkem and R.A.S. Rodriguez, 2014: Adaptation planning and implementation. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel of Climate Change*. [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea and L.L. White (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 869–898.

Minx, J.C., M. Callaghan, W.F. Lamb, J. Garard and O. Edenhofer, 2017: Learning about climate change solutions in the IPCC and beyond. *Environ. Sci. Policy*, **77**, 252–259.

Mistry, J., B.A. Bilbao and A. Berardi, 2016: Community owned solutions for fire management in tropical ecosystems: case studies from Indigenous communities of South America. *Philos. Trans. Royal Soc. B Biol. Sci.*, **371**(1696), 20150174.

Mitchell, R.B., W.C. Clark, D.W. Cash and N.M. Dickson, 2006: *Global Environmental Assessments: Information and Influence*. MIT Press, Cambridge, MA, USA.

Mitchell, S.D., 2009: *Unsimple Truths: Science, Complexity, and Policy*. University of Chicago Press, Chicago, IL, USA.

Moreau, V., C.A.D.O. Neves and F. Vuille, 2019: Is decoupling a red herring? The role of structural effects and energy policies in Europe. *Energy Policy*, **128**, 243–252.

Morgan, M.G., 2014: Use (and abuse) of expert elicitation in support of decision making for public policy. *Proc. Natl. Acad. Sci.*, **111**(20), 7176–7184.

Morgan, M.S. and M.N. Wise, 2017: Narrative science and narrative knowing. Introduction to special issue on narrative science. *Stud. Hist. Philos. Sci. Part A*, **62**, 1–5.

Mortreux, C. and J. Barnett, 2017: Adaptive capacity: exploring the research frontier. *WIREs Clim. Change*, **8**(4). DOI: 10.1002/wcc.467

Mortreux, C., S. O'Neill and J. Barnett, 2020: Between adaptive capacity and action: new insights into climate change adaptation at the household scale. *Environ. Res. Lett.*, **15**(7), 74035.

Moser, S., S. Meerow, J. Arnott and E. Jack-Scott, 2019a: The turbulent world of resilience: interpretations and themes for transdisciplinary dialogue. *Clim. Change*, **153**(1-2), 21–40.

Moser, S.C. and M.T. Boykoff, 2013: *Successful Adaptation to Climate Change: Linking Science and Policy in a Rapidly Changing World*. Routledge, London, UK.

Moser, S.C., J.A. Ekstrom, J. Kim and S. Heitsch, 2019b: Adaptation finance archetypes: local governments' persistent challenges of funding adaptation to climate change and ways to overcome them. *Ecol. Soc.*, **24**(2). DOI: 10.5751/ES-10980-240228

Moss, R.H., et al., 2010: The next generation of scenarios for climate change research and assessment. *Nature*, **463**(7282), 747–756.

Moss, R.H. and S.H. Schneider, 2000: *Towards Consistent Assessment and Reporting of Uncertainties in the IPCC TAR: Initial Recommendations for Discussion by Authors*. TERI, New Delhi.

Muiderman, K., A. Gupta, J. Vervoort and F. Biermann, 2020: Four approaches to anticipatory climate governance: different conceptions of the future and implications for the present. *Wiley Interdiscip. Rev. Clim. Change*, **11**(6), e673.

Munia, H.A., J.H. Guillaume, N. Mirumachi, Y. Wada and M. Kummu, 2018: How downstream sub-basins depend on upstream inflows to avoid scarcity: typology and global analysis of transboundary rivers. *Hydrol. Earth Syst. Sci.*, **22**, 2795–2809.

Mureva, A., D. Ward, T. Pillay, P. Chivenge and M. Cramer, 2018: Soil organic carbon increases in semi-arid regions while it decreases in humid regions due to woody-plant encroachment of grasslands in South Africa. *Sci. Rep.*, **8**(1), 1–12.

Nadeau, C.P. and M.C. Urban, 2019: Eco-evolution on the edge during climate change. *Ecography*. DOI: 10.1111/ecog.04404

Nadin, R. and E. Roberts, 2018: *Moving Towards a Growing Global Discourse on Transboundary Adaptation*. ODI, London, UK.

Nagy, G., U. Azeiteiro, J. Heimfarth, J. Verocai and C. Li, 2018: An assessment of the relationships between extreme weather events, vulnerability, and the impacts on human wellbeing in Latin America. *Int. J. Environ. Res. Public Health*, **15**(9), 1802.

Nalau, J., et al., 2016: The practice of integrating adaptation and disaster risk reduction in the south-west Pacific. *Clim. Dev.*, **8**(4), 365–375.

Nalau, J., B.L. Preston and M.C. Maloney, 2015: Is adaptation a local responsibility? *Environ. Sci. Policy*, **48**, 89–98.

Nalau, J., E. Torabi, N. Edwards, M. Howes and E. Morgan, 2021: A critical exploration of adaptation heuristics. *Clim. Risk Manag.*, **32**, 100292.

Nalau, J. and B. Verrall, 2021: Mapping the evolution and current trends in climate change adaptation science. *Clim. Risk Manag.*, **32**, 100290.

National Academies of Sciences, Engineering, and Medicine, 2016: *Attribution of Extreme Weather Events in the Context of Climate Change*. The National Academies Press, Washington, DC, 186.

National Research Council, 2009: *Informing Decisions in a Changing Climate*. National Academies Press, Washington, DC, USA.

Nauels, A., et al., 2019: Attributing long-term sea-level rise to Paris Agreement emission pledges. *Proc. Natl. Acad. Sci.*, **116**(47), 23487–23492.

Naveau, P., et al., 2018: Revising return periods for record events in a climate event attribution context. *J. Clim.*, **31**(9), 3411–3422.

ND-GAIN, 2019: ND-GAIN. [Database]. University of Notre Dame, Notre Dame, Indiana, USA.

NEAA, 2010: *Assessing an IPCC Assessment: An Analysis of Statements on Projected Regional Impacts in the 2007 Report*. PBL Netherlands Environmental Assessment Agency, The Hague, The Netherlands.

Neaves, T.T. and G.A. Royer, 2017: The social construction of disasters in the United States: a historical and cultural phenomenon. *J. Emerg. Manag.*, **15**(3), 175–187.

Nepstad, D., et al., 2006: Inhibition of Amazon deforestation and fire by parks and indigenous lands. *Conserv. Biol.*, **20**(1), 65–73.

Nesshöver, C., et al., 2017: The science, policy and practice of nature-based solutions: an interdisciplinary perspective. *Sci. Total Environ.*, **579**, 1215–1227.

Nightingale, A.J., 2015a: Adaptive scholarship and situated knowledges? Hybrid methodologies and plural epistemologies in climate change adaptation research. *Area*, **48**(1), 41–47.

Nightingale, A.J., 2015b: A socionature approach to adaptation. In: *Climate Change Adaptation and Development*. Routledge in association with GSE Research, London, UK, pp. 219–234.

Nightingale, A.J., et al., 2019: Beyond technical fixes: climate solutions and the great derangement. *Clim. Dev.*, 1–10. DOI: 10.1080/17565529.2019.1624495

Noble, I.R., S. Huq, Y.A. Anokhin, J. Carmin, D. Goudou, F.P. Lansigan, B. Osman-Elasha and A. Villamizar, 2014: Adaptation needs and options. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel of Climate Change*. [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea and L.L. White (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 833–868.

Nogués-Bravo, D., et al., 2018: Cracking the code of biodiversity responses to past climate change. *Trends Ecol. Evol.*, **33**(10), 765–776.

Nunn, P.D., J. Runman, M. Falanruw and R. Kumar, 2016: Culturally grounded responses to coastal change on islands in the Federated States of Micronesia, northwest Pacific Ocean. *Reg. Environ. Change*, **17**(4), 959–971.

Nursey-Bray, M., R. Palmer, T.F. Smith and P. Rist, 2019: Old ways for new days: Australian Indigenous peoples and climate change. *Local Environ.*, **24**(5), 473–486.

O'Neill, B.C., et al., 2017: IPCC reasons for concern regarding climate change risks. *Nat. Clim. Change*, **7**(1), 28.

O'Brien, K., 2011: Global environmental change II: from adaptation to deliberate transformation. *Prog. Hum. Geogr.*, **36**(5), 667–676.

O'Brien, K. and L. Sygna, 2013: Responding to climate change: the three spheres of transformation. *Proc. Transform. A Chang. Clim.*, 19–21.

O'Neill, B.C., et al., 2017: The roads ahead: narratives for shared socioeconomic pathways describing world futures in the 21st century. *Glob. Environ. Change*, **42**, 169–180.

Oberlack, C., 2017: Diagnosing institutional barriers and opportunities for adaptation to climate change. *Mitig. Adapt. Strateg. Glob. Change*, **22**(5), 805–838.

Oberlack, C. and K. Eisenack, 2014: Alleviating barriers to urban climate change adaptation through international cooperation. *Glob. Environ. Change*, **24**, 349–362.

Oberlack, C. and K. Eisenack, 2018: Archetypical barriers to adapting water governance in river basins to climate change. *J. Inst. Econ.*, **14**(3), 527–555.

OECD, 2012: *Incorporating Green Growth and Sustainable Development Policies into Structural Reform Agendas*. Organisation for Economic Co-operation and Development, Paris, France, 19.

Olazabal, M., E. Chu, V. Castán Broto and J. Patterson, 2021: Subaltern forms of knowledge are required to boost local adaptation. *One Earth*, **4**(6), 828–838.

Olazabal, M., I. Galarraga, J. Ford, E. Sainz De Murieta and A. Lesnikowski, 2019: Are local climate adaptation policies credible? A conceptual and operational assessment framework. *Int. J. Urban Sustain. Dev.*, **11**(3), 277–296.

Oppenheimer, M., M. Campos, R. Warren, J. Birkmann, G. Luber, B. O'Neill and K. Takahashi, 2014: Emergent risks and key vulnerabilities. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel of Climate Change*. [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea and L.L. White (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 1039–1099.

Oppenheimer, M., et al., 2019: *Discerning Experts: The Practices of Scientific Assessment for Environmental Policy*. University of Chicago Press, Chicago, IL, USA.

Orlove, B., C. Roncoli, M. Kabugo and A. Majugu, 2010: Indigenous climate knowledge in southern Uganda: the multiple components of a dynamic regional system. *Clim. Change*, **100**(2), 243–265.

Orlove, B., R. Shwom, E. Markowitz and S.-M. Cheong, 2020: Climate decision-making. *Annu. Rev. Environ. Resour.*, **45**(1), 271–303.

Ortega-Rosas, C.I., M.C. Peñalba and J. Guiot, 2008: Holocene altitudinal shifts in vegetation belts and environmental changes in the Sierra Madre Occidental, Northwestern Mexico, based on modern and fossil pollen data. *Rev. Palaeobot. Palynol.*, **151**(1), 1–20.

Otto, F.E., R.B. Skeie, J.S. Fuglestvedt, T. Berntsen and M.R. Allen, 2017: Assigning historic responsibility for extreme weather events. *Nat. Clim. Change*, **7**(11), 757.

Otto, F.E.L., et al., 2020a: Toward an inventory of the impacts of human-induced climate change. *Bull. Am. Meteorol. Soc.*, **101**(11), E1972–E1979.

Otto, I.M., et al., 2020b: Social tipping dynamics for stabilizing Earth's climate by 2050. *Proc. Natl. Acad. Sci.*, **117**(5), 2354–2365.

Owen, G., 2020: What makes climate change adaptation effective? A systematic review of the literature. *Glob. Environ. Change*, **62**, 102071.

Pachauri, R. K. , Allen, M. R. , Barros, V. R. , Broome, J. , Cramer, W. , Christ, R. , Church, J. A. , Clarke, L. , Dahe, Q. , Dasgupta, P. , Dubash, N. K. , Edenhofer, O. , Elgizouli, I. , Field, C. B. , Forster, P. , Friedlingstein, P. , Fuglestvedt, J. , Gomez-Echeverri, L. , Hallegatte, S. , Hegerl, G. , Howden, M. , Jiang, K. , Jimenez Cisneroz, B. , Kattsov, V. , Lee, H. , Mach, K. J. , Marotzke, J. , Mastrandrea, M. D. , Meyer, L. , Minx, J. , Mulugetta, Y. , O'Brien, K. , Oppenheimer, M. , Pereira, J. J. , Pichs-Madruga, R. , Plattner, G. K. , Pörtner, H. O. , Power, S. B. , Preston, B. , Ravindranath, N. H. , Reisinger, A. , Riahi, K. , Rusticucci, M. , Scholes, R. , Seyboth, K. , Sokona, Y. , Stavins, R. , Stocker, T. F. , Tschakert, P. , van Vuuren, D. and van Ypserle, J. P. (2014): Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, R. Pachauri and L. Meyer (editors), Geneva, Switzerland, IPCC, 151 p., ISBN: 978-92-9169-143-2 .

Palmisano, A., D. Lawrence, M.W. de Gruchy, A. Bevan and S. Shennan, 2021: Holocene regional population dynamics and climatic trends in the Near East: a first comparison using archaeo-demographic proxies. *Quat. Sci. Rev.*, **252**, 106739.

Papathoma-Kohle, M., C. Promper and T. Glade, 2016: A common methodology for risk assessment and mapping of climate change related hazards-implications for climate change adaptation policies. *Climate*, **4**(1). DOI: 10.3390/cli4010008.

Pardoe, J., K. Vincent and D. Conway, 2018: How do staff motivation and workplace environment affect capacity of governments to adapt to climate change in developing countries? *Environ. Sci. Policy*, **90**, 46–53.

Park, J., et al., 2019: Abrupt Holocene climate shifts in coastal East Asia, including the 8.2 ka, 4.2 ka, and 2.8 ka BP events, and societal responses on the Korean peninsula. *Sci. Rep.*, **9**(1), 10806.

Park, S.E., et al., 2012: Informing adaptation responses to climate change through theories of transformation. *Glob. Environ. Change*, **22**(1), 115–126.

Parmesan, C., et al., 2013: Beyond climate change attribution in conservation and ecological research. *Ecol. Lett.*, **16**(s1), 58–71.

Parmesan, C. and G. Yohe, 2003: A globally coherent fingerprint of climate change impacts across natural systems. *Nature*, **421**(6918), 37–42.

Parrique, T., J. Barth, F. Briens, A. Kuokkanen and J. Spangenberg, 2019: Evidence and arguments against green growth as a sole strategy for sustainability. Goumbook, United Arab Emirates. Retrieved March 16, 2022: https://goumbook.com/evidence-and-arguments-against-green-growth-as-a-sole-strategy-for-sustainability/.

Pasgaard, M., G. Van Hecken, A. Ehammer and N. Strange, 2017: Unfolding scientific expertise and security in the changing governance of Ecosystem Services. *Geoforum*, **84**, 354–367.

Pearce, W., S. Niederer, S.M. Özkula and N. Sánchez Querubín, 2019: The social media life of climate change: platforms, publics, and future imaginaries. *WIREs Clim. Change*, **10**(2), e569.

Pei, Q., H.F. Lee and D.D. Zhang, 2018: Long-term association between climate change and agriculturalists' migration in historical China. *Holocene*, **28**(2), 208–216.

Pelling, M. and M. Garschagen, 2019: Put equity first in climate adaptation. *Nature*, **569**(7756), 327–329.

Pelling, M. and D. Manuel-Navarrete, 2011: From resilience to transformation: the adaptive cycle in two Mexican urban centers. *Ecol. Soc.*, **16**(2).

Pelling, M., K. O'Brien and D. Matyas, 2015: Adaptation and transformation. *Clim. Change*, **133**(1), 113–127.

Penn, J.L., C. Deutsch, J.L. Payne and E.A. Sperling, 2018: Temperature-dependent hypoxia explains biogeography and severity of end-Permian marine mass extinction. *Science*, **362**(6419), eaat1327.

Persson, Å., 2019: Global adaptation governance: an emerging but contested domain. *Wiley Interdiscip. Rev. Clim. Change*, **10**(6), e618.

Persson, Å., K. Eckerberg and M. Nilsson, 2016: Institutionalization or wither away? Twenty-five years of environmental policy integration under shifting governance models in Sweden. *Environ. Plan. C Gov. Policy*, **34**(3), 478–495.

Pescaroli, G. and D. Alexander, 2018: Understanding compound, interconnected, interacting, and cascading risks: a holistic framework. *Risk Anal.*, **38**(11), 2245–2257.

Petzold, J., N. Andrews, J.D. Ford, C. Hedemann and J.C. Postigo, 2020: Indigenous knowledge on climate change adaptation: a global evidence map of academic literature. *Environ. Res. Lett.*, **15**(11), 113007.

Philip, S., et al., 2020: A protocol for probabilistic extreme event attribution analyses. *Adv. Stat. Clim. Meteorol. Oceanogr.*, **6**(2), 177–203.

Pielke, R.A., 1998: Rethinking the role of adaptation in climate policy. *Glob. Environ. Change*, **8**(2), 159–170.

Pilato, G., S. Sallu and M. Gaworek-Michalczenia, 2018: Assessing the integration of climate change and development strategies at local levels: insights from Muheza District, Tanzania. *Sustainability*, **10**(1), 174.

Pinsky, M.L., A.M. Eikeset, D.J. McCauley, J.L. Payne and J.M. Sunday, 2019: Greater vulnerability to warming of marine versus terrestrial ectotherms. *Nature*, **569**(7754), 108–111.

Polanyi, K., 1957: *The Great Transformation: The Political and Economic Origins of Our Time*. Beacon Press, Boston, MA, USA.

Poloczanska, E.S., et al., 2013: Global imprint of climate change on marine life. *Nat. Clim. Change*, **3**(10), 919–925.

Polsky, C., R. Neff and B. Yarnal, 2007: Building comparable global change vulnerability assessments: the vulnerability scoping diagram. *Glob. Environ. Change*, **17**(3-4), 472–485.

Porter, J.J., D. Demeritt and S. Dessai, 2015: The right stuff? Informing adaptation to climate change in British Local Government. *Glob. Environ. Change*, **35**, 411–422.

Pörtner, H. O., Scholes, R. J., Agard, J., Archer, E., Arneth, A., Bai, X., Barnes, D., Burrows, M., Chan, L., Cheung, W. L., Diamond, S., Donatti, C., Duarte, C., Eisenhauer, N., Foden, W., Gasalla, M., Handa, C., Hickler, T., Hoegh-Guldberg, O., ... Ngo, H. T. (2021). *IPBES-IPCC co-sponsored workshop report on biodiversity and climate change*. Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) and Intergovernmental Panel on Climate Change (IPCC), Bonn, Germany.

Pörtner, H.-O., 2021: Climate impacts on organisms, ecosystems and human societies: integrating OCLTT into a wider context. *J. Exp. Biol.*, **224**(Suppl 1), jeb238360.

Potts, R., 1998: Variability selection in hominid evolution. *Evol. Anthropol.*, **7**(3), 81–96.

Potts, R., et al., 2020: Increased ecological resource variability during a critical transition in hominin evolution. *Sci. Adv.*, **6**(43), eabc8975.

Prabhakar, S.V.R.K., S.B. Raj and A.A. F. Corral, 2018: *Transboundary Impacts of Climate Change in Asia: Making a Case for Regional Adaptation Planning and Cooperation*. Institute for Global Environmental Strategies, Hayama, Japan.

Preston, B.L., J. Mustelin and M.C. Maloney, 2013: Climate adaptation heuristics and the science/policy divide. *Mitig. Adapt. Strateg. Glob. Change*, **20**(3), 467–497.

Preston, C.J., 2017: Challenges and opportunities for understanding non-economic loss and damage. *Ethics Policy Environ.*, **20**(2), 143–155.

Radchuk, V., et al., 2019: Adaptive responses of animals to climate change are most likely insufficient. *Nat. Commun.*, **10**(1), 1–14.

Raia, P., et al., 2020: Past extinctions of homo species coincided with increased vulnerability to climatic change. *One Earth*, **3**(4), 480–490.

Ran, M. and L. Chen, 2019: The 4.2 ka BP climatic event and its cultural responses. *Quat. Int.*, **521**, 158–167.

Ranasinghe, R., A.C. Ruane, R. Vautard, N. Arnell, E. Coppola, F.A. Cruz, S. Dessai, A.S. Islam, M. Rahimi, D. Ruiz Carrascal, J. Sillmann, M.B. Sylla, C. Tebaldi, W. Wang, and R. Zaaboul, 2021: Climate Change Information for Regional Impact and for Risk Assessment. In *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [Masson- Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA. In Press.

Rao, N.D. and J. Min, 2018: Decent living standards: material prerequisites for human wellbeing. *Soc. Indic. Res.*, **138**(1), 225–244.

Raupach, M.R., et al., 2007: Global and regional drivers of accelerating CO_2 emissions. *Proc. Natl. Acad. Sci.*, **104**(24), 10288–10293.

Raworth, K., 2017: *Doughnut Economics: Seven Ways to Think Like a 21st-Century Economist*. Chelsea Green Publishing, White River Junction, Hartford, VT.

Ray, D.K., J.S. Gerber, G.K. MacDonald and P.C. West, 2015: Climate variation explains a third of global crop yield variability. *Nat. Commun.*, **6**(1), 5989.

Reckien, D., et al., 2017: Climate change, equity and the Sustainable Development Goals: an urban perspective. *Environ. Urban.*, **29**(1), 159–182.

Reckien, D., et al., 2018: How are cities planning to respond to climate change? Assessment of local climate plans from 885 cities in the EU-28. *J. Clean. Prod.*, **191**, 207–219.

Reckien, D., et al., 2019: Dedicated versus mainstreaming approaches in local climate plans in Europe. *Renew. Sustain. Energy Rev.*, **112**, 948–959.

Redclift, M., 2005: An oxymoron comes of age sustainable development (1987–2005). *Sustain. Dev.*, **13**, 212–227.

Reddin, C.J., Á.T. Kocsis and W. Kiessling, 2018: Marine invertebrate migrations trace climate change over 450 million years. *Glob. Ecol. Biogeogr.*, **27**(6), 704–713.

Reddin, C.J., P.S. Nätscher, Á.T. Kocsis, H.-O. Pörtner and W. Kiessling, 2020: Marine clade sensitivities to climate change conform across timescales. *Nat. Clim. Change*, **10**(3), 249–253.

Reghezza-Zitt, M., S. Rufat, G. Djament-Tran, A. Le Blanc and S. Lhomme, 2012: What resilience is not: uses and abuses. *Cybergeo*. DOI: 10.4000/cybergeo.25554

Rehdanz, K., H. Welsch, D. Narita and T. Okubo, 2015: Well-being effects of a major natural disaster: the case of Fukushima. *J. Econ. Behav. Organ.*, **116**, 500–517.

Reisinger, Andy, Mark Howden, Carolina Vera, et al. (2020) *The Concept of Risk in the IPCC Sixth Assessment Report: A Summary of Cross-Working Group Discussions*. Intergovernmental Panel on Climate Change, Geneva, Switzerland. pp15

Renn, O., 2008: *Risk governance: coping with uncertainty in a complex world*. Routledge, London, UK.

Ribes, A., S. Qasmi and N.P. Gillett, 2021: Making climate projections conditional on historical observations. *Sci. Adv.*, **7**(4), eabc671.

Richerson, P.J., R. Boyd and R.L. Bettinger, 2001: Was agriculture impossible during the pleistocene but mandatory during the holocene? A climate change hypothesis. *Am. Antiq.*, **66**(3), 387–411.

Riris, P. and M. Arroyo-Kalin, 2019: Widespread population decline in South America correlates with mid-Holocene climate change. *Sci. Rep.*, **9**(1), 6850.

Rittel, H. and M. Webber, 1973: Dilemmas in a general theory of planning. *Policy Sci.*, **4**, 155–169.

Roberts, E. and M. Pelling, 2016: Climate change-related loss and damage. *Clim. Dev.*, 1–14.DOI: 10.1080/17565529.2016.1184608.

Robinson, S., 2020: Climate change adaptation in SIDS: a systematic review of the literature pre and post the IPCC Fifth Assessment Report. *WIREs Clim. Change*, **11**(4), e653.

Rockman, M. and C. Hritz, 2020: Expanding use of archaeology in climate change response by changing its social environment. *Proc. Natl. Acad. Sci.*, **117**(15), 8295–8302.

Roe, E., 1994: *Narrative Policy Analysis: Theory and Practice*. Duke University Press, Durham, NC, USA.

Roe, E., 2017: *Except-Africa: Remaking Development, Rethinking Power*. Routledge, New York, NY, USA.

Roe, E.M., 1991: Development narratives, or making the best of blueprint development. *World Dev.*, **19**(4), 287–300.

Roggero, M., 2015: Adapting institutions: exploring climate adaptation through institutional economics and set relations. *Ecol. Econ.*, **118**, 114–122.

Rohling, E.J., G. Marino, K.M. Grant, P.A. Mayewski and B. Weninger, 2019: A model for archaeologically relevant Holocene climate impacts in the Aegean-Levantine region (easternmost Mediterranean). *Quat. Sci. Rev.*, **208**, 38–53.

Rosa, E.A. and T. Dietz, 2012: Human drivers of national greenhouse-gas emissions. *Nat. Clim. Change*, **2**(8), 581–586.

Rose, S. and M.M. Scott, 2020: *Review of 1.5°C and Other Newer Global Emissions Scenarios: Insights for Company and Financial Climate Low-Carbon Transition Risk Assessment and Greenhouse Gas Goal Setting*. EPRI, Palo Alto, CA, USA.

Rose, S. and A.M. Scott, 2018: *Grounding Decisions: A Scientific Foundation for Companies Considering Global Climate Scenarios and Greenhouse Gas Goals*. EPRI, Palo Alto, CA, USA.

Rotmans, J., R. Kemp and M. Van Asselt, 2001: More evolution than revolution: transition management in public policy. *Foresight*, **3**(1), 15–31.

Rufat, S., E. Tate, C.G. Burton and A.S. Maroof, 2015: Social vulnerability to floods: review of case studies and implications for measurement. *Int. J. Disaster Risk Reduct.*, **14**, 470–486.

Russel, D., et al., 2020: Policy coordination for national climate change adaptation in Europe: all process, but little power. *Sustainability*, **12**(13), 5393.

Sachs, J.D., 2015: Goal-based development and the SDGs: implications for development finance. *Oxf. Rev. Econ. Policy*, **31**(3-4), 268–278.

Saltré, F., et al., 2019: Climate-human interaction associated with southeast Australian megafauna extinction patterns. *Nat. Commun.*, **10**(1), 5311.

Sandom, C., S. Faurby, B. Sandel and J.-C. Svenning, 2014: Global late Quaternary megafauna extinctions linked to humans, not climate change. *Proc. R. Soc. B.*, **281**(1787). DOI: 10.1098/rspb.2013.3254.

Sangha, K.K., et al., 2019: Recognising the role of local and Indigenous communities in managing natural resources for the greater public benefit: case studies from Asia and Oceania region. *Ecosyst. Serv.*, **39**, 100991.

Santer, B.D., et al., 2019: Quantifying stochastic uncertainty in detection time of human-caused climate signals. *Proc. Natl. Acad. Sci.*, **116**(40), 19821–19827.

Sauer, I., et al., 2021: Climate signals in river flood damages emerge under sound regional disaggregation. *Nature*. Nature Portfolio. DOI: 10.1038/s41467-021-22153-9.

Schaller, N., et al., 2016: Human influence on climate in the 2014 southern England winter floods and their impacts. *Nat. Clim. Change*, **6**(6), 627–634.

Scheffer, M., S. Carpenter, J.A. Foley, C. Folke and B. Walker, 2001: Catastrophic shifts in ecosystems. *Nature*, **413**(6856), 591.

Scheffer, M., S.R. Carpenter, V. Dakos and E.H. van Nes, 2015: Generic indicators of ecological resilience: inferring the chance of a critical transition. *Annu. Rev. Ecol. Evol. Syst.*, **46**, 145–167.

Scheffer, M., et al., 2012: Anticipating critical transitions. *Science*, **338**(6105), 344–348.

Scheffer, M., E.H. van Nes, D. Bird, R.K. Bocinsky and T.A. Kohler, 2021: Loss of resilience preceded transformations of pre-Hispanic Pueblo societies. *Proc. Natl. Acad. Sci.*, **118**(18), e2024397118.

Schipper, E.L.F., 2006: Conceptual history of adaptation in the UNFCCC process. *Rev. Eur. Commun. Int. Environ. Law*, **15**(1), 82–92.

Schipper, E.L.F. and I. Burton, 2009: *Understanding Adaptation: Origins, Concepts, Practice and Policy. The Earthscan Reader on Adaptation to Climate Change*. Routledge, London, UK and Sterling, VA, USA, 1–9.

Schipper, E.L.F., S.E. Eriksen, L.R. Fernandez Carril, B.C. Glavovic and Z. Shawoo, 2020: Turbulent transformation: abrupt societal disruption and climate resilient development. *Clim. Dev.*, **13**(6), 467–474.

Schipper, E.L.F., F. Thomalla, G. Vulturius, M. Davis and K. Johnson, 2016: Linking disaster risk reduction, climate change and development. *Int. J. Disaster Resil. Built Environ.*, **7**(2), 216–228.

Schlosberg, D., 2003: The justice of environmental justice: reconciling equity, recognition, and participation in a political movement. In: *Moral and Political Reasoning in Environmental Practice*, A. Light and B. Russo (editors). MIT Press, Cambridge, MA, USA, pp. 77–106.

Schlosberg, D., 2009: *Defining Environmental Justice: Theories, Movements, and Nature*. Oxford University Press.

Schlosberg, D., 2013: Theorising environmental justice: the expanding sphere of a discourse. *Environ. Polit.*, **22**(1), 37–55.

Schoen, D. and M. Rein, 1994: *Reframing: Towards the Resolution of Intractable Policy Controversies*. Basic Books, New York.

Schwab, K., 2017: *The Fourth Industrial Revolution*. Crown, Switzerland.

Schwalm, C.R., S. Glendon and P.B. Duffy, 2020: RCP8.5 tracks cumulative CO(2) emissions. *Proc. Natl. Acad. Sci. U.S.A.*, **117**(33), 19656–19657.

Schwindt, D.M., et al., 2016: The social consequences of climate change in the central Mesa Verde region. *Am. Antiq.*, **81**(1), 74–96.

Scoones, I., M. Leach and P. Newell, 2015: *The Politics of Green Transformations*. Routledge, London, UK.

Seddon, N., B. Turner, P. Berry, A. Chausson and C.A. Girardin, 2019: Grounding nature-based climate solutions in sound biodiversity science. *Nat. Clim. Change*, **9**(2), 84–87.

Sekulova, F. and J.C.J.M. van den Bergh, 2013: Climate change, income and happiness: an empirical study for Barcelona. *Glob. Environ. Change Policy Dimens.*, **23**(6), 1467–1475.

Sen, A., 1985: Well-being, agency and freedom: the Dewey lectures 1984. *J. Philos.*, **82**(4), 169–221.

Sengupta, T., et al., 2020: Did the Harappan settlement of Dholavira (India) collapse during the onset of Meghalayan stage drought? *J. Quat. Sci.*, **35**(3), 382–395.

Sera, F., et al., 2020: Air conditioning and heat-related mortality: a multi-country longitudinal study. *Epidemiology*, **31**(6), 779–787.

Serdeczny, O., E. Waters and S. Chan, 2016: *Non-Economic Loss and Damage in the Context of Climate Change: Understanding the Challenges*. German Development Institute/Deutsches Institut für Entwicklungspolitik (DIE), Bonn, Germany.

Setzer, J. and C. Higham, 2021: *Global Trends in Climate Change Litigation: 2021 Snapshot*. Grantham Research Institute on Climate Change and the Environment and Centre for Climate Change Economics and Policy, London School of Economics and Political Science, London.

Shepherd, T.G., et al., 2018: Storylines: an alternative approach to representing uncertainty in physical aspects of climate change. *Clim. Change*, **151**(3-4), 555–571.

Siders, A.R., 2019a: Adaptive capacity to climate change: a synthesis of concepts, methods, and findings in a fragmented field. *WIREs Clim. Change*, **10**(3).

Siders, A.R., 2019b: Social justice implications of US managed retreat buyout programs. *Clim. Change*, **152**(2), 239–257.

Siders, A.R. and J.M. Keenan, 2020: Variables shaping coastal adaptation decisions to armor, nourish, and retreat in North Carolina. *Ocean Coast. Manag.*, **183**, 105023.

Siders, A.R. and A.L. Pierce, 2021: Deciding how to make climate change adaptation decisions. *Curr. Opin. Environ. Sustain.*, **52**, 1–8.

Sieber, I.M., R. Biesbroek and D. de Block, 2018: Mechanism-based explanations of impasses in the governance of ecosystem-based adaptation. *Reg. Environ. Change*, **18**(8), 2379–2390.

Sietsma, A.J., J.D. Ford, M.W. Callaghan and J.C. Minx, 2021: Progress in climate change adaptation research. *Environ. Res. Lett.*, **16**(5), 54038.

Simpson, N.P., Mach, K.J., Constable, A., Hess, J., Hogarth, R., Howden, M., Lawrence, J., Lempert, R.J., Muccione, V., Mackey, B. and New, M.G., 2021. A framework for complex climate change risk assessment. *One Earth*, 4(4), pp.489–501

Singer, D.J., 2019: Diversity, not randomness, trumps ability. *Philos. Sci.*, **86**(1), 178–191.

Singh, C., J. Ford, D. Ley, A. Bazaz and A. Revi, 2020: Assessing the feasibility of adaptation options: methodological advancements and directions for climate adaptation research and practice. *Clim. Change*, **162**(2), 255–277.

Singh, C., et al., 2021: Interrogating 'effectiveness' in climate change adaptation: 11 guiding principles for adaptation research and practice. *Clim. Dev.* DOI: 10.1080/17565529.2021.1964937

Singh, N.P., B. Anand and M. A. Khan, 2018: Micro-level perception to climate change and adaptation issues: a prelude to mainstreaming climate adaptation into developmental landscape in India. *Nat. Hazards*, **92**(3), 1287–1304.

Skeie, R.B., et al., 2017: Perspective has a strong effect on the calculation of historical contributions to global warming. *Environ. Res. Lett.*, **12**(2), 24022.

Slater, S.M., R.J. Twitchett, S. Danise and V. Vajda, 2019: Substantial vegetation response to Early Jurassic global warming with impacts on oceanic anoxia. *Nat. Geosci.*, **12**(6), 462–467.

Smith, A., J.-P. Voß and J. Grin, 2010: Innovation studies and sustainability transitions: the allure of the multi-level perspective and its challenges. *Res. Policy*, **39**(4), 435–448.

Smith, R. and J. Botha, 2005: The recovery of terrestrial vertebrate diversity in the South African Karoo Basin after the end-Permian extinction. *C. R. Palevol*, **4**(6), 623–636.

Smithers, J. and B. Smit, 1997: Human adaptation to climatic variability and change. *Glob. Environ. Change*, **7**(2), 129–146.

Solecki, W., M. Pelling and M. Garschagen, 2017: A framework for urban risk management regime shifts. *Ecol. Soc.*, **22**(2), 38.

Song, H., et al., 2021: Thresholds of temperature change for mass extinctions. *Nat. Commun.*, **12**(1), 4694.

Spielman, S.E., et al., 2020: Evaluating social vulnerability indicators: criteria and their application to the Social Vulnerability Index. *Nat. Hazards*, **100**(1), 417–436.

Stanley, S.M., 2016: Estimates of the magnitudes of major marine mass extinctions in earth history. *Proc. Natl. Acad. Sci.*, **113**(42), E6325–E6334.

Stockholm Resilience Center, 2015: *Principles for Building Resilience: Sustaining Ecosystem Services in Social-Ecological Systems*. Cambridge University Press.

Stone, D., et al., 2013: The challenge to detect and attribute effects of climate change on human and natural systems. *Clim. Change*, **121**(2), 381–395.

Stone, D.A., S.M. Rosier and D.J. Frame, 2021: The question of life, the universe and event attribution. *Nat. Clim. Change*, **11**(4), 276–278.

Storch, H.V., 2018: The temporal dimension of coastal adaptation to climate change. In: *The 9th Chinese-German Joint Symposium on Hydraulic and Ocean Engineering (CGJOINT 2018)*. National Cheng Kung University, Tainan, Taiwan, pp. 53–58.

Stott, P.A., et al., 2016: Attribution of extreme weather and climate-related events. *WIREs Clim. Change*, **7**(1), 23–41.

Suding, K.N. and R.J. Hobbs, 2009: Threshold models in restoration and conservation: a developing framework. *Trends Ecol. Evol.*, **24**(5), 271–279.

Sukumar, R., J.K. Sharma, R.K. Chaturvedi and N. Ravindranath, 2016: The impacts of climate change on biodiversity and ecosystems in India. In: *Tropical Conservation: Perspectives on Local and Global Priorities*, (Eds. A.A. Aguirre and R. Sukumar), 7, 89–102. Oxford University Press, New York.

Sun, J. and K. Yang, 2016: The wicked problem of climate change: a new approach based on social mess and fragmentation. *Sustainability*, **8**(12), 1312.

Surminski, S. and A. Lopez, 2015: Concept of loss and damage of climate change—a new challenge for climate decision-making? A climate science perspective. *Clim. Dev.*, **7**(3), 267–277.

Sutton, R.T., 2018: ESD Ideas: a simple proposal to improve the contribution of IPCC WGI to the assessment and communication of climate change risks. *Earth Syst. Dyn.*, **9**(4), 1155–1158.

Svarstad, H. and T.A. Benjaminsen, 2020: Reading radical environmental justice through a political ecology lens. *Geoforum*, **108**, 1–11.

Swart, R., R. Biesbroek and L. Ão, 2014: Science of adaptation to climate change and science for adaptation. *Front. Environ. Sci.*, **2**. DOI: 10.3389/fenvs.2014.00029/full.

Szopa, S., V. Naik, B. Adhikary, P. Artaxo, T. Berntsen, W.D. Collins, S. Fuzzi, L. Gallardo, A. Kiendler Scharr, Z. Klimont, H. Liao, N. Unger, and P. Zanis, 2021: Short-Lived Climate Forcers. In *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press. In Press.

Tàbara, J.D., et al., 2018: Positive tipping points in a rapidly warming world. *Curr. Opin. Environ. Sustain.*, **31**, 120–129.

Taberna, A., T. Filatova, D. Roy and B. Noll, 2020: Tracing resilience, social dynamics and behavioral change: a review of agent-based flood risk models. *Socio-Environ. Syst. Model.*, **2**, 17938.

Taillardat, P., D.A. Friess and M. Lupascu, 2018: Mangrove blue carbon strategies for climate change mitigation are most effective at the national scale. *Biol. Lett.*, **14**(10), 20180251.

Tanner, T., et al., 2015: Livelihood resilience in the face of climate change. *Nat. Clim. Change*, **5**(1), 23–26.

Taylor, A.L., S. Dessai and W.B. de Bruin, 2014: Public perception of climate risk and adaptation in the UK: a review of the literature. *Clim. Risk Manag.*, **4**, 1–16.

Termeer, C.J.A.M., A. Dewulf and G.R. Biesbroek, 2016: Transformational change: governance interventions for climate change adaptation from a continuous change perspective. *J. Environ. Plan. Manag.*, **60**(4), 558–576.

Thackeray, S.J., et al., 2020: Civil disobedience movements such as School Strike for the Climate are raising public awareness of the climate change emergency. *Glob. Change Biol.*, **26**(3), 1042–1044.

Thaler, T., et al., 2019: Drivers and barriers of adaptation initiatives–How societal transformation affects natural hazard management and risk mitigation in Europe. *Sci. Total Environ.*, **650**, 1073–1082.

Theys, J. and P. Cornu, 2019: Temps de la nature, temps de la société, temps scientifique à l'heure du changement global. Pour une approche interdisciplinaire de la crise de la temporalité. *Nat. Sci. Soc.*, **27**(4), 381–389.

Thiery, W., et al., 2020: Warming of hot extremes alleviated by expanding irrigation. *Nat. Commun.*, **11**(1), 290.

Thompson, M. and S. Rayner, 1998: Risk and governance part I: the discourses of climate change. *Gov. Oppos.*, **33**(2), 139–166.

Tierney, J.E., P.B. deMenocal and P.D. Zander, 2017: A climatic context for the out-of-Africa migration. *Geology*, **45**(11), 1023–1026.

Timmermann, A. and T. Friedrich, 2016: Late Pleistocene climate drivers of early human migration. *Nature*, **538**(7623), 92–95.

Tompkins, E.L., et al., 2010: Observed adaptation to climate change: UK evidence of transition to a well-adapting society. *Glob. Environ. Change*, **20**(4), 627–635.

Tompkins, E.L., K. Vincent, R.J. Nicholls and N. Suckall, 2018: Documenting the state of adaptation for the global stocktake of the Paris Agreement. *Wiley Interdiscip. Rev. Clim. Change*, **9**(5), e545.

Tozier de la Poterie, A. and M.-A. Baudoin, 2015: From Yokohama to Sendai: approaches to participation in international disaster risk reduction frameworks. *Int. J. Disaster Risk Sci.*, **6**(2), 128–139.

Tschakert, P., et al., 2017: Climate change and loss, as if people mattered: values, places, and experiences. *Wiley Interdiscip. Rev. Clim. Change*, **8**(5), e476.

Tschakert, P., N.R. Ellis, C. Anderson, A. Kelly and J. Obeng, 2019: One thousand ways to experience loss: a systematic analysis of climate-related intangible harm from around the world. *Glob. Environ. Change Hum. Policy Dimens.*, **55**, 58–72.

Tschakert, P., B. van Oort, A.L. St. Clair and A. LaMadrid, 2013: Inequality and transformation analyses: a complementary lens for addressing vulnerability to climate change. *Clim. Dev.*, **5**(4), 340–350.

Turney, C.S.M. and H. Brown, 2007: Catastrophic early Holocene sea level rise, human migration and the Neolithic transition in Europe. *Quat. Sci. Rev.*, **26**(17), 2036–2041.

UN, 2007: *United Nations Declaration on the Rights of Indigenous Peoples*. Vol. 12. UN, Wash, 1–18.

UN, 2015: *Addis Ababa Action Agenda of the Third International Conference on Financing for Development*. United Nations, New York.

UN, 2017: *New Urban Agenda, United Nations Conference on Housing and Sustainable Urban Development (Habitat III)*, 1–66. UN, Quito, Equador.

UN, 2020: Building an inclusive, sustainable and resilient future with indigenous peoples: a call to action. [United Nations System Chief Executives Board for Coordination (CEB), New York, NY, USA.

UN Commission on Human Rights, 1992: *Rio Declaration on Environment and Development*. UN Commission on Human Rights, Geneva. 50th sess.: 1994.

UN Department of Economic and Social Affairs, 2020: *World Social Report 2020: Inequality in a Rapidly Changing World*. UN.

UN Inter-agency Task Force on Financing for Development, 2019: *Financing for Sustainable Development 2019*. UN, New York, NY.

Undorf, S., et al., 2018: Detectable impact of local and remote Anthropogenic aerosols on the 20th century changes of West African and South Asian monsoon precipitation. *J. Geophys. Res. Atmos.*, **123**(10), 4871–4889.

UNDP, 2018: *Inequality-adjusted Human Development Index (IHDI)*. UNDP, New York, NY, USA.

UNDRR, 2019: Integration between disaster risk reduction and national climate change adaptation strategies and plans. In: *Global Assessment Report*, pp. 335–362.

UNEP, 2011: *Towards a Green Economy: Pathways to Sustainable Development and Poverty Eradication*. UNEP, Nairobi, Kenya.

UNEP, 2014: *Adaptation Gap Report 2014*. UNEP, Nairobi, Kenya.

UNEP, 2018: *Adaptation Gap Report*. UNEP, Nairobi, Kenya.

UNEP, UNEP DTU Partnership, and World Adaptation Science Programme (WASP), 2021: *Adaptation Gap Report 2020*. UNEP, Nairobi, Kenya.

UNESCO, 2018a: *Local and Indigenous Knowledge Systems*. United Nations Educational, Scientific and Cultural Organization, Paris, France.

UNESCO, 2018b: *Report of the UNESCO Expert Meeting on Indigenous Knowledge and Climate Change in Africa*. 27–28 June 2018. UNESCO, Nairobi, Kenya.

UNFCCC, 2013: Warsaw international mechanism. In: *COP 19* [UNFCCC(ed.)]. UNFCCC, Warsaw, Poland.

UNFCCC, 2015a: *Decision 1/CP.21, Conference of the Parties*. UNFCCC, Paris, France.

UNFCCC, 2015b: *Paris Agreement, COP 21*. UNFCCC, Paris, France.

UNFCCC, 2016: *Paris Agreement, COP 21*. UNFCCC, Paris, France.

UNFCCC, 2018a: Addendum 1. Decisions 1–12. In: *Report of the Conference of the Parties serving as the Meeting of the Parties to the Paris Agreement on the Third Part of its First Session, Held in Katowice from 2 to 15 December 2018* (FCCC/PA/CMA/2018/3/Add.2). UNFCCC, Paris, France.

UNFCCC, 2018b: Addendum 2. Decisions 13–20. In: *Report of the Conference of the Parties serving as the Meeting of the Parties to the Paris Agreement on the Third Part of its First Session, Held in Katowice from 2 to 15 December 2018* (FCCC/PA/CMA/2018/3/Add.2). UNFCCC, Paris, France.

UNFCCC, 2021: *Action for Climate Empowerment Guidelines*. UNFCCC, Rio de Janeiro, Brazil and New York, NY, USA.

UNISDR, 2015: Sendai framework for disaster risk reduction 2015–2030. In: *Proceedings of the 3rd United Nations World Conference on DRR*. UNISDR, Sendai, Japan. pp. 14–18.

United Nations; Department of Economic and Social Affairs; Population Division, 2019: *World Population Prospects 2019: Highlights (ST/ESA/SER.A/423)*. UN DESA, New York, NY, USA.

United Nations, 1997: *Kyoto Protocol to the United Nations Framework Convention on Climate Change*. United Nations, Kyoto, Japan.

USEPA, 2016: *Climate Change Indicators in the United States 2016*, 4. United States Environmental Protection Agency, Washington, DC, USA.

USGCRP, 2018: *Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment*. U.S. Global Change Research Program, Washington, DC, USA.

van Ginkel, K.C., et al., 2020: Climate change induced socio-economic tipping points: review and stakeholder consultation for policy relevant research. *Environ. Res. Lett.*, **15**(2), 23001.

Van Valkengoed, A.M. and L. Steg, 2019: Meta-analyses of factors motivating climate change adaptation behaviour. *Nat. Clim. Change*, **9**(2), 158.

van Vliet, J., D.A. Eitelberg and P.H. Verburg, 2017: A global analysis of land take in cropland areas and production displacement from urbanization. *Glob. Environ. Change*, **43**, 107–115.

Vautard, R., et al., 2019: Evaluation of the HadGEM3-A simulations in view of detection and attribution of human influence on extreme events in Europe. *Clim. Dyn.*, **52**(1), 1187–1210.

Veldkamp, T., et al., 2017: Water scarcity hotspots travel downstream due to human interventions in the 20th and 21st century. *Nat. Commun.*, **8**(1), 1–12.

Veldman, J.W., et al., 2015: Where tree planting and forest expansion are bad for biodiversity and ecosystem services. *BioScience*, **65**(10), 1011–1018.

Vermeulen, S.J., D. Dinesh, S.M. Howden, L. Cramer and P.K. Thornton, 2018: Transformation in practice: a review of empirical cases of transformational adaptation in agriculture under climate change. *Front. Sustain. Food Syst.*, **2**. DOI: 10.3389/fsufs.2018.00065/full.

Verschuur, J., S. Li, P. Wolski and F.E.L. Otto, 2021: Climate change as a driver of food insecurity in the 2007 Lesotho-South Africa drought. *Sci. Rep.*, **11**(1), 3852.

Vervoort, J. and A. Gupta, 2018: Anticipating climate futures in a 1.5°C era: the link between foresight and governance. *Curr. Opin. Environ. Sustain.*, **31**, 104–111.

Vicedo-Cabrera, A.M., et al., 2018: A multi-country analysis on potential adaptive mechanisms to cold and heat in a changing climate. *Environ. Int.*, **111**, 239–246.

Vignola, R., G. Leclerc, M. Morales and J. Gonzalez, 2017: Leadership for moving the climate change adaptation agenda from planning to action. *Curr. Opin. Environ. Sustain.*, **26–27**, 84–89.

Vij, S., R. Biesbroek, A. Groot and K. Termeer, 2018: Changing climate policy paradigms in Bangladesh and Nepal. *Environ. Sci. Policy*, **81**, 77–85.

Vincent, K. and G. Cundill, 2021: The evolution of empirical adaptation research in the global South from 2010 to 2020. *Clim. Dev.*, 1–14. DOI: 10.1080/17565529.2021.1877104.

Viner, D., et al., 2020: Understanding the dynamic nature of risk in climate change assessments—A new starting point for discussion. *Atmosp. Sci. Lett.*, **21**(4). DOI: 10.1002/asl.958.

Vogel, M.M., J. Zscheischler, R. Wartenburger, D. Dee and S.I. Seneviratne, 2019: Concurrent 2018 hot extremes across northern hemisphere due to human-induced climate change. *Earth's Future*, **7**(7), 692–703.

Vos, C.C., et al., 2008: Adapting landscapes to climate change: examples of climate-proof ecosystem networks and priority adaptation zones. *J. Appl. Ecol.*, 1722–1731. DOI: 10.1111/j.1365-2664.2008.01569.x.

Walker, B. and J. Meyers, 2004: Thresholds in ecological and social–ecological systems: a developing database. *Ecol. Soc.*, **9**(2), 3. Retrieved March 16, 2022: http://www.ecologyandsociety.org/vol9/iss2/art3/

Wan, X. and Z. Zhang, 2017: Climate warming and humans played different roles in triggering Late Quaternary extinctions in east and west Eurasia. *Proc. R. Soc. B*, **284**(1851), 20162438.

Wang, H., et al., 2020: Aerosols in the E3SM version 1: new developments and their impacts on radiative forcing. *J. Adv. Model. Earth Syst.*, **12**(1), e2019MS001851.

Ward, J.D., et al., 2016: Is decoupling GDP growth from environmental impact possible? *PLoS ONE*, **11**(10). DOI: 10.1371/journal.pone.0164733.

Watkiss, P., A. Hunt, J. Dyszynski and J. Dyszynski, 2015: The use of new economic decision support tools for adaptation assessment: a review of methods and applications, towards guidance on applicability. *Clim. Change*, **132**(3), 401–416.

Webb, N.P., et al., 2017: Land degradation and climate change: building climate resilience in agriculture. *Front. Ecol. Environ.*, **15**(8), 450–459.

Webber, S., 2016: Climate change adaptation as a growing development priority: towards critical adaptation scholarship. *Geogr. Compass*, **10**(10), 401–413.

Wehner, M.F., C. Zarzycki and C. Patricola, 2019: Estimating the human influence on tropical cyclone intensity as the climate changes. In: *Hurricane Risk* [Collins, J.M. and K. Walsh(eds.)]. Springer International Publishing, New York, NY, USA, Cham, pp. 235–260.

Weiss, H. (ed.), 2017: *Megadrought and collapse: from early agriculture to Angkor*. Oxford University Press. Oxford, UK.

Welch, J.R., E.S. Brondízio, S.S. Hetrick and C.E. Coimbra Jr, 2013: Indigenous burning as conservation practice: neotropical savanna recovery amid agribusiness deforestation in Central Brazil. *Plos One*, **8**(12), e81226.

Westaway, M.C., J. Olley and R. Grün, 2017: At least 17,000 years of coexistence: modern humans and megafauna at the Willandra Lakes, South-Eastern Australia. *Quat. Sci. Rev.*, **157**, 206–211.

Westoby, R., K.E. McNamara, R. Kumar and P.D. Nunn, 2020: From community-based to locally led adaptation: evidence from Vanuatu. *Ambio*, **49**(9), 1466–1473.

Williams, A.N., S. Ulm, T. Sapienza, S. Lewis and C.S.M. Turney, 2018: Sea-level change and demography during the last glacial termination and early Holocene across the Australian continent. *Quat. Sci. Rev.*, **182**, 144–154.

Willox, A.C., et al., 2015: Examining relationships between climate change and mental health in the Circumpolar North. *Reg. Environ. Change*, **15**(1), 169–182.

Wilson, A.J. and B. Orlove, 2019: *What do we mean when we say climate change is urgent?* Center for Research on Environmental Decisions Working Paper. Earth Institute, Columbia University, New York, NY, USA.

Wilson, R.S., A. Herziger, M. Hamilton and J.S. Brooks, 2020: From incremental to transformative adaptation in individual responses to climate-exacerbated hazards. *Nat. Clim. Change*, **10**(3), 200–208.

Wise, R.M., et al., 2014: Reconceptualising adaptation to climate change as part of pathways of change and response. *Glob. Environ. Change*, **28**, 325–336.

Wisner, B., 2016: *Vulnerability as Concept, Model, Metric, and Tool, Oxford Research Encyclopedia of Natural Hazard Science*. Oxford University Press, Oxford, UK.

Woodruff, S.C., S. Meerow, M. Stults and C. Wilkins, 2018: Adaptation to resilience planning: alternative pathways to prepare for climate change. *J. Plan. Educ. Res.* DOI: 10.1177/0739456X18801057

Woodruff, S.C. and P. Regan, 2019: Quality of national adaptation plans and opportunities for improvement. *Mitig. Adapt. Strateg. Glob. Change*, **24**(1), 53–71.

World Economic Forum, 2021: *The Global Risks Report 2021: Insight Report*. World Economic Forum.

Woroniecki, S., et al., 2019: The framing of power in climate change adaptation research. *WIREs Clim. Change*, **10**(6). DOI: 10.1002/wcc.617.

Wright, H., et al., 2014: Farmers, food and climate change: ensuring community-based adaptation is mainstreamed into agricultural programmes. *Clim. Dev.*, **6**(4), 318–328.

Xu, C., T.A. Kohler, T.M. Lenton, J.-C. Svenning and M. Scheffer, 2020: Future of the human climate niche. *Proc. Natl. Acad. Sci.*, **117**(21), 11350–11355.

Yasuhara, M., et al., 2020: Past and future decline of tropical pelagic biodiversity. *Proc. Natl. Acad. Sci.*, **117**(23), 12891–12896.

Yeh, E.T., 2016: 'How can experience of local residents be 'knowledge'?' Challenges in interdisciplinary climate change research. *Area*, **48**(1), 34–40.

Yokohata, T., et al., 2019: Visualizing the interconnections among climate risks. *Earth's Future*, **7**(2), 85–100.

Young, O.R., 2017: Beyond regulation: Innovative strategies for governing large complex systems. *Sustainability*, **9**(6), 938.

Yu, J., et al., 2015: Vegetation changeover across the Permian–Triassic Boundary in Southwest China: extinction, survival, recovery and palaeoclimate: a critical review. *Earth Sci. Rev.*, **149**, 203–224.

Yumagulova, L., et al., 2019: The role of disaster volunteering in Indigenous communities. *Environ. Hazards*, 1–18. DOI: 10.1080/17477891.2019.1657791.

Zimmermann, A., J. Benda, H. Webber and Y. Jafari, 2018: *Trade, Food Security, and Climate Change: Conceptual Linkages and Policy Implications*. Food and Agricultural Organization, Rome, Italy.

Zommers, Z., et al., 2020: Burning embers: towards more transparent and robust climate-change risk assessments. *Nat. Rev. Earth Environ.*, **1**(10), 516–529.