3 Climate change impacts and their cascading effects: implications for losses and damages

This chapter characterises observed and projected physical and socio-economic losses and damages, highlighting the interconnectedness of risks across societies. It aims at elucidating the potential cascading effects of impacts from climate change and how these add complexity to the evaluation of risks. The nature and potential scale of climate risks are illustrated by analysis of impacts of sea-level rise in Small Island Developing States; the potential impact of and attribution of extreme events to human-made climate change; and the implications of crossing a tipping threshold for the Atlantic Meridional Overturning Circulation.

In Brief

Climate-related hazards are widespread and intensifying rapidly, leading to cascading impacts across sectors and international borders.

This chapter analyses three broad categories of physical climate hazard: i) ***extreme weather events*****,** including higher frequency and severity of heatwaves, droughts, extreme rainfall and floods; ii) ***slow-onset events***, including sea-level rise, ocean acidification, glacial retreat, loss of biodiversity and desertification; and iii) ***tipping points*****,** including Atlantic Meridional Overturning Circulation (AMOC) collapse and the Amazon rainforest dieback.

Natural, social and economic systems around the world are interconnected and interdependent. Consequently, climate change impacts may propagate internationally through, for example, global trade, financial flows and supply networks. These cascading effects of climate change across sectors and international borders pose particular challenge to risk assessments.

This chapter provides a discussion and novel analysis of three specific instances of climate-related hazards, one from each of the three broad categories above. These hazards pose serious threats to human and natural systems, leading to losses and damages already today for extreme and slow-onset events. The severity of these hazards, summarised below, is projected to increase.

Sea-level rise in Small Island Developing States

- Small Island Developing States (SIDS) comprise a heterogeneous group of island territories most of which are situated in the Caribbean, the Pacific and the Indian Ocean. Irrespective of this diversity, all SIDS are vulnerable to climate change, and in particular sea-level rise (SLR) for four reasons: i) the most habitable area of SIDS is the low-lying coastal zone; ii) SIDS are disproportionally affected by weather-related disasters; iii) SIDS have fragile economies and a limited range of natural resources; and iv) many are far away from markets.
- Impacts, losses and damages in SIDS as a result of SLR are manifold: coastal flooding; coastal erosion and loss of land; loss of ecosystems, which enhances coastal flooding and erosion; and loss of freshwater resources.

Quantifying the adverse impacts of climate change with extreme event attribution

- Assessing and quantifying the real-world impacts of climate change as they manifest themselves represents an enduring challenge for scientists. “Attribution science” represents a “bottom-up” methodology to disentangle the different physical drivers of these costly disasters. It also helps quantify the exacerbating effect of climate change on individual extreme weather events.
- Novel analysis reveals that heat-related extremes are becoming more frequent and severe by orders of magnitude more rapidly than any other type of extreme weather. It also shows tropical oceans are, by far, witnessing the most rapid relative changes in high-temperature extremes. The next most rapid changes occur in North African and Middle East arid regions, and then other tropical land areas. In addition, the average relative change in extreme heat is 50% higher for a person in a Least Developed Country (LDC) compared to global average increase. Meanwhile, OECD members experience relative changes in extreme heat slower than the global average.
- The severity of a climate-related hazard is an imperfect proxy for the severity of impacts; vulnerability and exposure also play a crucial role in determining the magnitude of losses and

damages. Indeed, relatively common and/or frequent weather hazards can still cause significant and detrimental impacts if they strike vulnerable, exposed communities. The opportunities to reduce vulnerability are largest in poorer countries.

- Attribution science offers many benefits, particularly a method to causally link the recent extreme weather events with climate change. However, it too often produces an inconclusive result when considering weather extremes that impact lower income countries. Specific impediments to raising the quality and quantity of event attribution studies for lower income countries have been identified. These include poor observational records, the inadequacy of lower-resolution climate models and differences in extreme event impact reporting mechanisms.
- There is an urgent need to develop a quantitative inventory of the impacts of extreme weather due to anthropogenic climate change. This chapter proposes a preliminary framework for an inventory of the impacts of climate change from extreme weather.

Tipping points

- The abrupt weakening or collapse of the AMOC would result in a climatic shift with profound regional, and even global, implications. Europe would become colder and drier, which would reduce agricultural productivity and render most land unsuitable for arable farming. Boreal forests in northern Europe and Asia would likely die back, mostly due to regional drying. Conversely, boreal forests in North America could benefit from increased precipitation and cooler summers.
- The reorganisation of the climate system induced by the AMOC collapse would affect ecosystems, as well as human health, livelihoods, food security, water supply and economic growth at a global scale. Changes in sea-surface temperature and rainfall patterns in the tropical Atlantic would impact the stability of the Amazon. The future climate of the Amazon region after an AMOC shutdown would resemble the climate of African regions where savannah and grasslands are the dominant biome, suggesting the loss of the rainforest. Even without the AMOC collapse, northern Africa is projected to experience the largest decrease in rainfall on the planet due to climate change. A collapse of the AMOC would disrupt the West African monsoon, leading to further reduction in precipitation.
- The AMOC collapse explored in depth in this report is just one of the many parts of the Earth system that have the potential to display a tipping point. The Intergovernmental Panel on Climate Change (IPCC) assesses the shutdown of the AMOC as “very unlikely” within this century i.e. 0-10% likelihood. However, such a collapse cannot be ruled out. Recent research shows the AMOC is at its weakest in a millennium and that this slowdown will likely continue. Given the potentially far-reaching cascading impacts, such high-impact low-likelihood events must be included in risk assessments, as the IPCC recommends.
- Climate change continues to reshape the global socio-economic structure. This is likely to impact on progress towards Sustainable Development Goals, disrupt global trade and amplify social conflict, inequalities and human security. As well as rapid and deep reductions in greenhouse gas emissions, measuring and monitoring of key tipping elements, such as the AMOC, will provide countries with time to develop strategies (including through adaptation and preventive measures) to deal with the consequences of these abrupt changes of the climate systems.

3.1. Introduction

Losses and damages are the outcome of complex and linked physical and socio-economic processes over many decades and even centuries. As highlighted in Chapter 1, it is useful to think about climate risks in terms of climate-related ***hazards*** of a given intensity, ***exposure*** and ***vulnerability*** to that hazard (IPCC, 2014[1]). This means that risk depends on the scale of anthropogenic climate change at a global level. Together with the geographical location of the country, this anthropogenic change determines the nature and intensity of the climate-related hazards it faces. The risk also depends on exposure of human and natural systems to that hazard. Finally, it depends on vulnerability to the different hazards to which the country is subjected.

The interaction of these three elements acting on interconnected systems may lead to key risks cascading through sectors and regions. Storm surges, coastal flooding or sea-level rise (SLR), for example, may disrupt livelihoods. Systemic risks due to extreme weather events may also lead to breakdown of infrastructure networks and critical services; risk of food and water insecurity; and loss of rural livelihoods and income, particularly for poorer populations (IPCC, 2014[2]).

Chapter 1 highlighted, among others, that climate change leads to significant changes in natural and human systems on all continents and across oceans. Chapter 2 examined in detail the different types and levels of uncertainties in all three elements of risk, namely hazards, exposure and vulnerability. These uncertainties must be considered when formulating approaches to reducing and managing the risks of losses and damages from climate change. Chapter 3 provides in-depth analysis of three types of climate-related hazards as well their associated impacts. Section 3.2 provides a summary description of climate-related hazards, including extreme weather events, slow-onset events and tipping points. Section 3.3 discusses the potential for cascading impacts spanning over different sectors and regions. The chapter then discusses three specific types of climate-related hazards likely to give rise to losses and damages. First, it looks at sea-level rise (SLR) with a specific focus on the situation of Small Island Developing States (SIDS) (Section 3.4). Second, it examines extreme events and their attribution to anthropogenic climate change, with a specific focus on heatwaves (Section 3.5). Finally, the chapter discusses the implications of climatic tipping points for losses and damages (Section 3.6). It takes a deep dive on one specific tipping point, the weakening of the Atlantic Meridional Overturning Circulation (AMOC) that transfers heat from the equator to high latitudes in the Atlantic. These three types of hazards pose serious threats to human and natural systems. They have already led to losses and damages; the severity of these hazards are projected to increase in the future.

3.2. Climate change impacts: From climate-related hazards to economic losses

3.2.1. Climate-related hazards

The accumulation of greenhouse gas (GHG) emissions in the atmosphere will cause further warming and long-lasting changes in many components of the Earth system, amplifying current risks and creating new ones. The Intergovernmental Panel on Climate Change (IPCC) is the most authoritative source on projections of climate-related hazards from climate change. It projects with confidence that impacts of climate change will increase in severity, frequency and magnitude with continued global warming and that these impacts may become irreversible. These climate-related hazards are diverse, occur at different timescales and manifest at different speeds (IPCC, 2014[2]). Article 8 of the Paris Agreement recognises these distinct temporal scales and their potential different consequences for losses and damages. It states that “Parties recognize the importance of averting, minimising and addressing loss and damage associated with the adverse effects of climate change, including extreme weather events and slow-onset events” (Paris Agreement, 2015[3]).

In addition to extreme weather events and slow-onset events, climate change also has the potential to push components of the Earth system past critical thresholds – the “climate tipping points”. This will lead to qualitatively new climatic states with potentially large-scale impacts on human and ecological systems (Lenton et al., 2008[4]). Based on a range of definitions accepted by Parties to the United Nations

Framework Convention on Climate Change (UNFCCC) or provided by the IPCC and the body of climate science literature, this chapter considers three broad categories of climate-related hazards for characterising the impacts of climate change:

- ***Extreme weather events***: IPCC defines an extreme weather event as "an event that is rare at a particular place and time of year. […] By definition, the characteristics of what is called extreme weather may vary from place to place in an absolute sense" (IPCC, 2018[5]). Typically, an extreme weather event is associated with timeframes of less than a day to a few weeks[1] (Seneviratne et al., 2012[6]). Extreme weather events include higher frequency and severity of heatwaves, droughts, cyclones, extreme rainfall, extreme sea levels (surges, waves; Box 3.2), flooding (resulting from extreme rainfall, extreme sea levels and glacier melting) and wildfires (resulting from multivariate drivers, including heat, lack of rainfall and winds), for example.
- ***Slow-onset events***: At the time of writing, there was no official definition of slow-onset event under the IPCC. Schäfer et al. (2021[7]) define slow-onset processes "as phenomena caused or intensified by anthropogenic climate change that take place over prolonged periods of time – typically decades, or even centuries – without a clear start or end point." The UNFCCC, in its Cancun Agreements, acknowledges that slow-onset events include SLR, increasing temperatures, ocean acidification, glacial retreat and related impacts, salinisation, land and forest degradation, loss of biodiversity and desertification (UNFCCC, 2010[8]).
- ***Tipping points***: The IPCC defines tipping point as a "level of change in system properties beyond which a system reorganises, often in a nonlinear manner, and does not return to the initial state even if the drivers of the change are abated. For the climate system, the term refers to a critical threshold when global or regional climate changes from one stable state to another stable state." The IPCC introduced the idea of climate tipping points about two decades ago when they were considered likely only at high rates and magnitudes of warming between 5-6ºC by 2100 (IPCC, 2001[9]). More recent IPCC reports recognise the risk of crossing tipping points at much lower levels of warming (IPCC, 2018[10]; IPCC, 2019[11]). Examples of climate tipping elements are collapse of the West Antarctic ice sheet, the AMOC collapse, coral reef die-off and Amazon rainforest dieback.

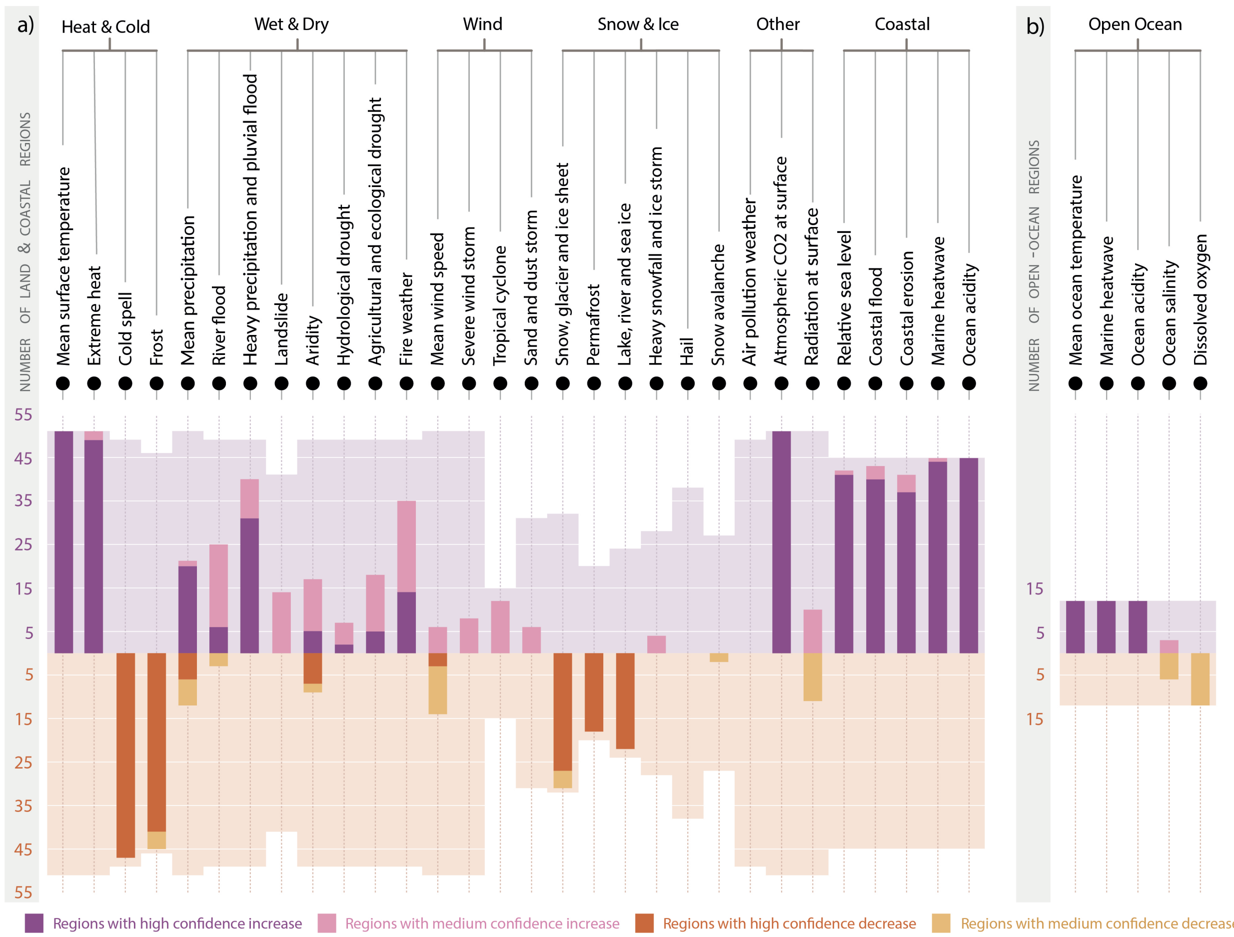
The following sub-sections briefly analyse the most recent literature on these three distinct phenomena. As much as possible, they assess the likelihood of human influence on observed past changes (e.g. of the occurrence of different types of extreme weather events) or of the crossing of a tipping point in different potential warming futures. These likelihood assessments are based on the IPCC's well-established likelihood scale and terms as described in Chapter 2. That chapter also discussed how a risk management strategy needs to avoid the possibility of overestimating or underestimating the risk of an event (Shepherd, 2019[12]). Climate change is a problem of risk management for policy makers in national contexts (see also Chapter 2). Sutton (2019[13]), for example, considers the focus of climate science on likelihoods unhelpful as likelihoods are not the same as risk. The likelihoods presented here for projected changes therefore need to be considered critically from a policy-making perspective and when formulating risk management strategies.

Additionally, the risk of a certain event is determined by more than its likelihood. Other key factors are where and when it will occur, the levels of vulnerability and exposure of the systems impacted, as well as the severity of the hazard itself. Large singular disasters may only occur once in a few years. However, hazardous events of smaller intensity may occur far more frequently. Indeed, the cumulative impact of such high frequency, low impact events can be as or more devastating than major disasters (refer to Chapter 5 for a discussion on the impact of recurring impacts on fiscal sustainability of countries).

Extreme weather events

Climate change leads to changes in the frequency, intensity, spatial extent, duration and timing of weather extremes, potentially resulting in unprecedented extremes (IPCC, 2021[14]). Changes in many extreme weather events have been observed since the mid-20th century. Every increment of global warming causes clearly discernible increases in the intensity and frequency of hot extremes, including heatwaves, heavy precipitation and marine heatwaves. It also includes increases in the proportion of intense tropical cyclones (IPCC, 2021[14]). Figure 3.1 displays a synthesis of the number of regions where climatic impact-drivers are projected to change between 1.5-2ºC. “Change” is understood as physical climate system conditions, such as means, events and extremes, that affect an element of society or ecosystems. The figure shows that changes in several climatic impact-drivers would be more widespread at 2°C relative to 1.5°C. This trend would be even more pronounced globally for higher warming levels.

Figure 3.1. Synthesis of the number of regions where climatic impact-drivers are projected to change



Note: Number of land and coastal regions (a) and open-ocean regions (b) where each climatic impact-driver is projected to increase or decrease with high confidence (dark shade) or medium confidence (light shade). The height of the lighter shaded “envelope” behind each bar represents the maximum number of regions for which each climatic impact-driver is relevant. The envelope is symmetrical about the x-axis showing the maximum possible number of relevant regions for climatic impact-driver increase (upper part) or decrease (lower part).
Source: Figure SPM.9 from (IPCC, 2021[14]).

Rising temperatures and more frequent heatwaves and droughts are expected to extend fire weather seasons i.e. periods of time where weather conditions are conducive to the outbreak of wildfires. The extension of fire weather seasons therefore increases the potential for wildfires (Jolly et al., 2015[15]; Ross, 6 August 2020[16]; Gomes Da Costa et al., 2020[17]).

In recent years, several major wildfires have occurred around the world. In 2017, extreme wildfires burned 1.4 million acres in Chile, which represented a cost of USD 362.2 million, including combat of wildfires, housing reconstruction and support for productive sectors, among others (González et al., 2020[18]). Extreme bushfires burned more than 46 million acres [18.6 million hectares (ha)] in Australia during the 2019-20 season, with losses estimated at about USD 1.3 billion (CDP, 2020[19]). The extreme heat in the eastern Mediterranean in early August 2021 led to severe wildfires in Greece and Turkey. Later in the month, the heatwave extended farther west, leading to fires in other European and African countries, such as Italy, France and Algeria (Frost, 2021[20]; Mezahi, 2021[21]; Frost, 2021[22]). In 2020, California wildfires burned a record-breaking 4.2 million acres (1.7 million ha). At the time of writing, fires in the 2021 season had already burned 2.2 million acres (0.9 million ha). This posed a threat to the Giant Forest, which harbours more than 2 000 Sequoia trees (Reuters, 2021[23]; Keeley and Syphard, 2021[24]). Box 3.1 describes recent impacts from record temperatures experience in the Pacific coast areas of the United States and Canada and their relation with climate change.

Peak wind speeds of the most intense tropical cyclones, as well as the proportion of intense tropical cyclones (categories 4-5), are projected to increase globally with increasing global warming (IPCC, 2021[14]). More frequent or more intense cyclonic or convective storms will also increase the frequency of extreme precipitation events (Witze, 2018[25]). Coastal flooding risk is likely to increase as a result of rising sea levels, which can lead to increased tidal flooding. This, in turn, can increase erosion rates, as well as lead to greater inundation (and salt water intrusion) as a result of storm surge.

Section 3.5 presents an in-depth analysis of the quantification of the impacts of climate change using extreme event attribution. The chapter focuses on methods and uncertainties in attribution science. It reflects on how to improve current and future estimates of the impacts of climate change from extreme weather. Extreme event attribution has evolved primarily to assess changes in the likelihood of witnessing a specific extreme weather event. It aims to provide understanding of how today’s extreme weather events might be worsening due to anthropogenic climate change. Section 3.5.3 considers how the vulnerability of exposed communities to past extreme events containing a strong climate-change signal influences the risk of losses and damages associated with these events (Philip et al., 2021[26]).

Box 3.1. Recent heatwaves in the Pacific coast areas of the United States and Canada

The 2021 Pacific Northwest heat wave impacted the United States and western Canada for a four-day period, June 26-29. A large mass of high pressure air called a "heat dome" settled over regions not known for extreme heat, including Portland, Oregon and Seattle, Washington in the United States, and Vancouver, British Columbia in Canada. Temperatures rose far above 40ºC in many regions. Moreover, they occurred one whole month before the climatologically warmest part of the year, normally occurring at end of July or early August (Philip et al., 2021[26]) The region's peak temperature was recorded in Lytton, British Columbia at 49.6ºC, setting a new record for the entire country (Di Liberto, 2021[27]). Shortly after setting the record, wildfire spread across Lytton.

According to the National Center for Environmental Information Climate Extreme Index, the Pacific Northwest has experienced more extreme temperatures over the last 20 years (Di Liberto, 2021[27]). A study in a growing body of research termed "rapid attribution" analysis predicted the heat wave would have been extremely unlikely without human-induced climate change: the event was statistically estimated to be about a 1 in 1 000 year event in the current climate (Philip et al., 2021[26]).

The high temperatures were particularly harmful for the region as it is not adapted to this type of extreme heat. More than 500 reported deaths and 180 wildfires were recorded in British Columbia (Schiermeier, 2021[28]) and about 200 related deaths in Oregon and Washington (Popovich and Choi-Schagrin, 2021[29]). An analysis reported a sharp rise in emergency department visits. Nearly 3 000 in the Pacific Northwest visited an emergency department between June 25-30 for heat-related illness – seven times higher than in June 2019 (Schramm et al., 2021[30]).

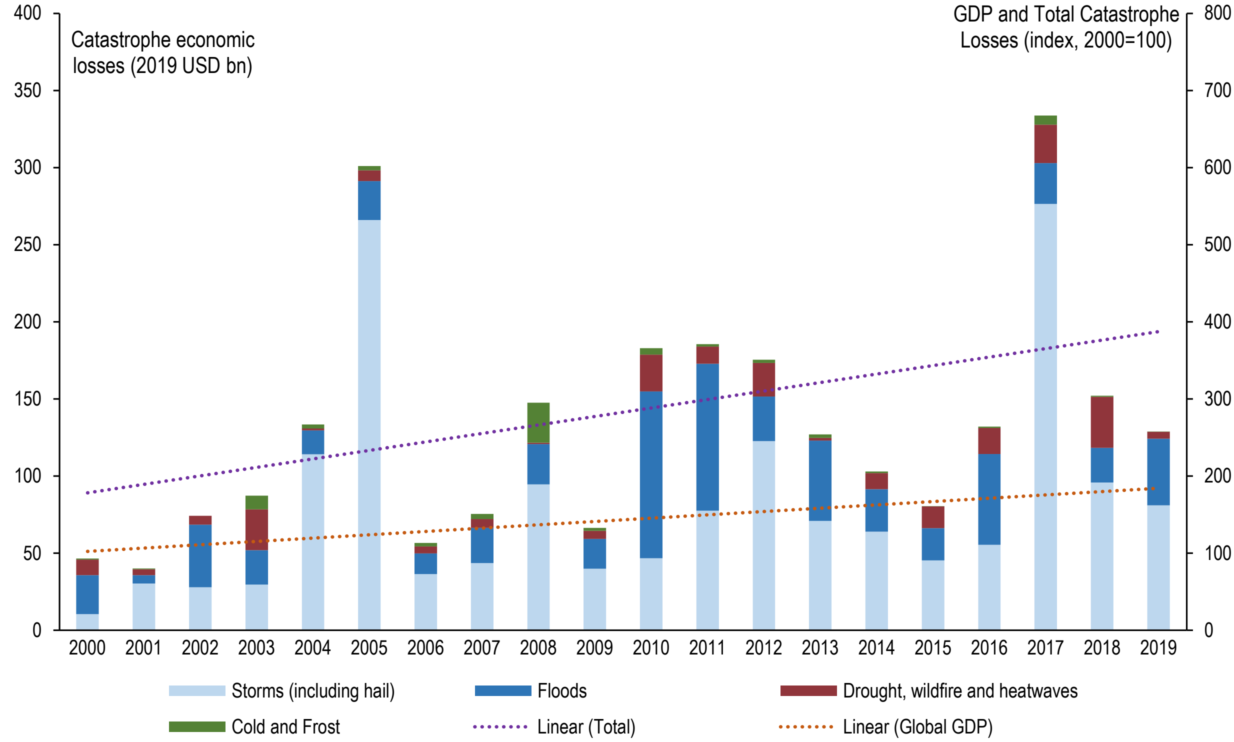
The 2021 heat wave caused shoreline temperatures to rise above 50ºC, leading to mass deaths of marine life and restructuring of entire marine ecosystems. Preliminary estimates show that billions of marine animals died from the extreme heat. These included mussels that live on the shoreline and sea creatures that live in the mussel beds. This loss can lead to cascading effects to other animals. Sea stars, for example, feed on mussels; sea ducks also feast on mussels before migrating to their summer breeding grounds in the Arctic (Einhorn, 2021[31]).

Examples of economic losses from extreme weather events

This sub-section provides data on economic losses and damages from past extreme weather events. Non-economic losses and damages are equally important albeit less easily quantifiable. These are discussed in Chapter 1 and further explored in terms of their uncertainties in Chapter 2.

Extreme weather events, especially storms, floods, droughts, wildfires, heatwaves, and cold and frost,[2] can result in economic losses; significant damage; and loss of income and livelihoods. These losses touch both private and public spheres. They can damage privately-owned buildings and infrastructure, such as homes and businesses. Publicly-owned buildings and infrastructure at risk include schools, hospitals, roads and power generation and distribution infrastructure. Reported economic losses from climate-related events are highly volatile from year-to-year. However, they have been increasing on a global basis since 2000 at a much faster rate than gross domestic product (GDP) (see Figure 3.2).[3]

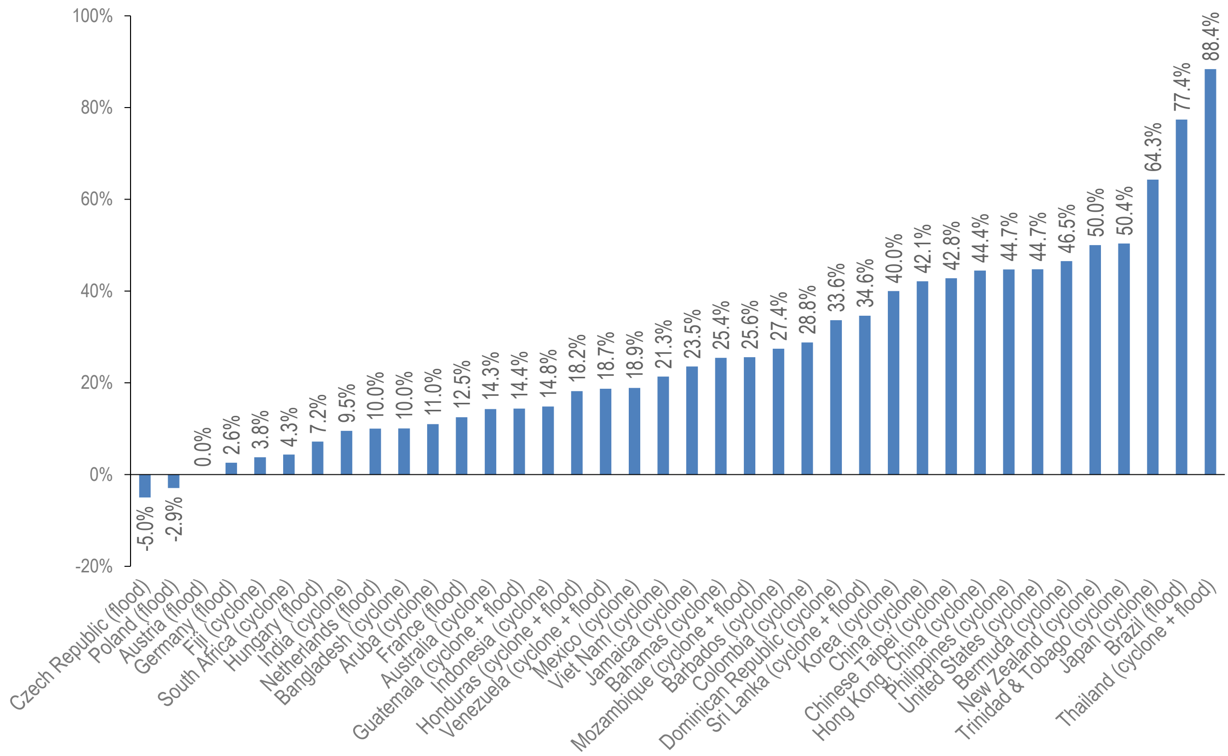
Figure 3.2. Economic losses from climate-related catastrophes by type (USD bn)



Source*:* OECD calculations based on data on economic losses provided by Swiss Re sigma and data on gross domestic product from *World Economic Outlook* (database) (April 2021).

There is significant uncertainty about the trajectory of future climate changes and the impact of these changes on economic losses in specific countries or locations. Nevertheless, several analyses have examined potential impacts. For example, S&P Global Ratings (2015[32]) with support from Swiss Re estimated the level of damage from a 1-in-250 year (i.e. an event with 0.4% likelihood of occurring in any given year) flood or cyclone would increase significantly in many countries by 2050 (see Figure 3.3). Increasing severity of extreme weather events, along with continued development in hazard-prone locations, will almost certainly lead to rising climate-related catastrophe losses in the future.

Figure 3.3. Increase in expected damage from a 1-in-250 year cyclone or flood in 2050 (percentage)



Note*:* The S&P Global Ratings estimates for future tropical cyclone damage are based on: i) an increase in maximum wind speed of 1% to 5%; ii) no change in frequency of cyclone formation; iii) sea-level rise of +25 cm to +40 cm across different basins; and iv) increased cyclone-related precipitation. The estimates for flood are based on estimates of changes in return periods for a 100-year flood developed by Hirabayashi et al. (2013[33]).
Source*:* OECD calculations based on estimates of direct damage from a 1-in-250 year flood (14 sovereign issuers) or cyclone (30 sovereign issuers) provided by S&P Global Ratings (2015[32]).

Slow-onset events

The Cancun Agreements (dating from UNFCCC COP16) include the following different types of climate-related hazards under the category of "slow-onset events": SLR, increasing temperatures, ocean acidification, glacial retreat and related impacts, salinisation, land and forest degradation, loss of biodiversity and desertification (UNFCCC, 2010[8]). As opposed to extreme weather events, slow-onset events unfold over decades or centuries. This sub-section provides a short overview of the state-of-art knowledge on slow-onset events, based on IPCC's Special Report on Climate Change and Land (IPCC, 2019[34]), the Special Report on the Ocean and Cryosphere in a Changing Climate (IPCC, 2019[35]), their review and summary provided in van der Geest and van den Berg (2021[36]) and the contribution of Working Group I to the IPCC Sixth Assessment Report (IPCC, 2021[14]).

- ***Increasing temperatures***: The global surface temperature was 1.09°C higher in 2011-20 than 1850-1900[4], but not all areas experience the average amount of warming. Over land, significantly greater rises in temperature have been measured (1.59°C on average) than over the ocean (0.88ºC on average). Polar regions also experience greater warming than tropical zones, with Arctic temperatures rising by more than double the global average. Changes due to higher temperatures include heatwaves and changes to ecosystem functioning (especially in high latitudes).
- ***Sea-level rise***: Current levels of human-induced SLR are mainly from thermal expansion of seawater due to higher temperatures with increasing contributions from glacier and ice sheet melt.

Over the 20th century, SLR amounted to 1-2 millimetres (mm) per year in most regions; this rate has now accelerated to 3.7 mm per year (from 2006 to 2018). Projections of annual SLR by the end of the 21st century are of 4-9 mm and 10-20 mm per year under a low-(RCP2.6) and high-(RCP 8.5) GHG emissions scenario, respectively. Adverse effects of SLR include the exacerbation of extreme sea-level events such as storm surge and waves, and associated coastal flooding. Under high existential risk to SLR are, of course, SIDS and low-lying coastal deltas such as southern Bangladesh. Risks and uncertainties of mean SLR and extreme sea-level rise events are discussed in Box 3.2. Section 3.4 explores the potential impacts and associated losses and damages of SLR and sea-level extremes, with a particular focus on SIDS.

- ***Salinisation***: In salinisation, non-saline soil becomes saline enough to negatively affect plant growth, mainly driven by SLR and irrigation. Main impacts of salinisation include land degradation and desertification, biodiversity loss and adverse effects on agricultural production, freshwater resources and health. It is estimated that salt affects 7.4% of land globally.
- ***Ocean acidification***: Carbon dioxide (CO_2) in the atmosphere forms a weak acid as it dissolves in seawater. This leads to a decrease in pH as atmospheric CO_2 concentrations increase, with negative consequences for marine life. One notable consequence of ocean acidification is coral bleaching. Over the past three decades, seawater pH declined by 0.017-0.027 per decade as a result of rising concentrations of CO_2 in the atmosphere, a change assessed by the IPCC as "unusual in the last 2 million years"; such a decline could be up to 90% faster under an extremely high-emissions scenario (RCP8.5). Impacts of ocean acidification include loss of biodiversity, for example, by reducing the calcification of organisms and by affecting fish species, invertebrates and corals.
- ***Glacial retreat***: Glacial retreat occurs when the snow and ice mass of glaciers melt at a faster rate than they accumulate. This leads to the alteration of the flow of meltwater rivers, with adverse effects on water availability for irrigation and contributing to SLR. Ice loss on land, particularly the vast Greenland and Antarctic Ice Sheets and high mountain areas in the Andes, Himalayas and Alps, contribute with about 1.81 mm to SLR each year. Glacial retreat can lead to local and regional impacts involving river and stream flow, ecosystems and agricultural livelihoods. A loss of 36% of glacier mass is projected to occur under an extremely high-emission scenario (RCP8.5) by 2100, in comparison to 18% in a low-emission scenario (RCP2.6).
- ***Land and forest degradation***: Land degradation consists of a negative trend in land properties and conditions, often expressed as reduction or loss of biological productivity, ecological integrity and/or value to humans. Land degradation affects about 3.2 billion people worldwide. Land and forest degradation can have a wide range of impacts on the natural environment and society (e.g. loss of ecosystem services).
- ***Desertification***: This consists in degradation of land into arid, semi-arid and dry-subhumid areas and results from the interaction of different human and environmental processes, notably drought. Main impacts are related to the loss of ecosystem services and resulting implications for livelihoods of natural resource-dependent populations.
- ***Loss of biodiversity***: Biodiversity is the variability among living organisms from terrestrial, marine, and other aquatic ecosystems. Biodiversity includes variability at the genetic, species and ecosystem levels (CBD, 1992[37]). Biodiversity declines when the variability in any one of these levels decreases. Loss of biodiversity can lead to the loss of ecosystem functions. This, in turn, leads to declined ecosystem services, such as carbon sequestration and the capacity to adapt to further climate change. The main drivers of biodiversity loss are land-use change, over-exploitation of animals and plants (including illegal trade), pollution, invasive non-native species and, increasingly, climate change (Pecl et al., 2017[38]). Indeed, approaches to deal with biodiversity loss have many synergies with approaches considered by the climate agenda worldwide (See Chapter 1).

Box 3.2. Uncertainty in sea-level rise and extreme sea-level events

The Sixth Assessment Report of the IPCC (AR6) projects a ***mean sea level*** to rise by *likely* 0.6-1.0 m by 2100 if GHG emissions rise unabated (i.e. under the very high-emissions scenario RCP8.5) (Oppenheimer et al., 2019[39]; Fox-Kemper et al., 2021[40]). If emissions are reduced to meet the goal of the Paris Agreement to limit global warming "well below 2°C" (i.e. under the low-emissions scenario RCP2.6), global mean sea level would likely rise by 0.3-0.6m in 2100 (Oppenheimer et al., 2019[39]; Fox-Kemper et al., 2021[40]).

Four aspects are important for managing risks of losses and damages from sea-level rise (SLR) (Chapter 4). First, the above-named sea-level ranges are *likely ranges*, which means a 17% chance of SLR exceeding this range for a given emission scenario. The scientific uncertainty about such potential ***high-end mean SLR*** is higher than about the likely range due to ***deep uncertainty*** (Chapter 4, Section 4.2) about the possible, but unlikely, rapid melting of the ice sheets of Greenland and Antarctica. Under RCP8.5, an SLR of 2 m by 2100 cannot be ruled out (Fox-Kemper et al., 2021[40]).

Second, SLR will continue for centuries to millennia, even when GHG concentrations are stabilised due to continued ocean warming and ice sheet melt. IPCC AR6 projects that global mean sea levels will rise by 2-6 m if warming is limited to 2°C and 19-22 m with 5°C warming over the next 2 000 years.

Third, sea levels do not rise uniformly across the globe but are regionally differentiated mainly due to three factors: i) changes in ocean circulation and regionally differentiated rates of thermal expansion; ii) redistribution of mass within the cryosphere (due to the melting of the ice sheets) and hydrosphere (due to changes in land water storage); and iii) vertical land movement (Lowe et al., 2009[41]; Nicholls et al., 2013[42]; Bamber et al., 2019[43]; Hinkel et al., 2019[44]; Stammer et al., 2019[45]).

Fourth, mean SLR is a slow-onset hazard, but most impacts of mean SLR will not be felt directly. Instead, gradual mean SLR will raise the heights of ***extreme sea-level events*** such as tides, surges and waves (Oppenheimer et al., 2019[39]; Wahl et al., 2017[46]; Woodroffe, 2008[47]). Through this effect, extreme sea-level events that are rare (e.g. once per century) will become common by 2100 (e.g. annual) under every emission scenario (Menéndez and Woodworth, 2010[48]; Oppenheimer et al., 2021[49]).

The uncertainties in today's extreme sea level are thereby often larger than those associated with 21st century climate change and SLR (Wahl et al., 2017[46]). This is mostly because sufficiently long local observation of extreme sea level is lacking (e.g. for SIDS) (Nurse et al., 2014[50]). Tide-surge and wave models can provide the missing information. For example, global datasets of extreme sea level produced with numeric models are increasingly becoming available (Muis et al., 2020[51]; Muis et al., 2016[52]; Vousdoukas et al., 2017[53]). These data can be used for local analysis in SIDS if local data are lacking. While these models can generally reproduce observed extreme sea level reasonably well, they often perform badly in areas threatened by tropical cyclones. This is because climate model input data lack the spatial/temporal resolution necessary to fully include the strong winds of tropical cyclones. They also lack a sufficient number of tropical cyclones for reliable statistics of extreme values (Appendini et al., 2017[54]; Hodges, Cobb and Vidale, 2017[55]; Mentaschi et al., 2020[56]; Mentaschi, 2018[57]; Muis et al., 2020[51]).

For wave modelling, another major uncertainty is the lack of high resolution bathymetry data. These are necessary to assess how offshore waves propagate onto the shore and cause damage (Athanasiou et al., 2019[58]).

Note: In IPCC terms, *likely* means a 66% chance. Here and in the context of SLR science, likely range refers to the 17th to 83rd percentiles of the probability distribution of future SLR. This means that experts judge a 66% chance that sea levels will be within the likely range and a 17% chance that sea levels will be above this likely range.

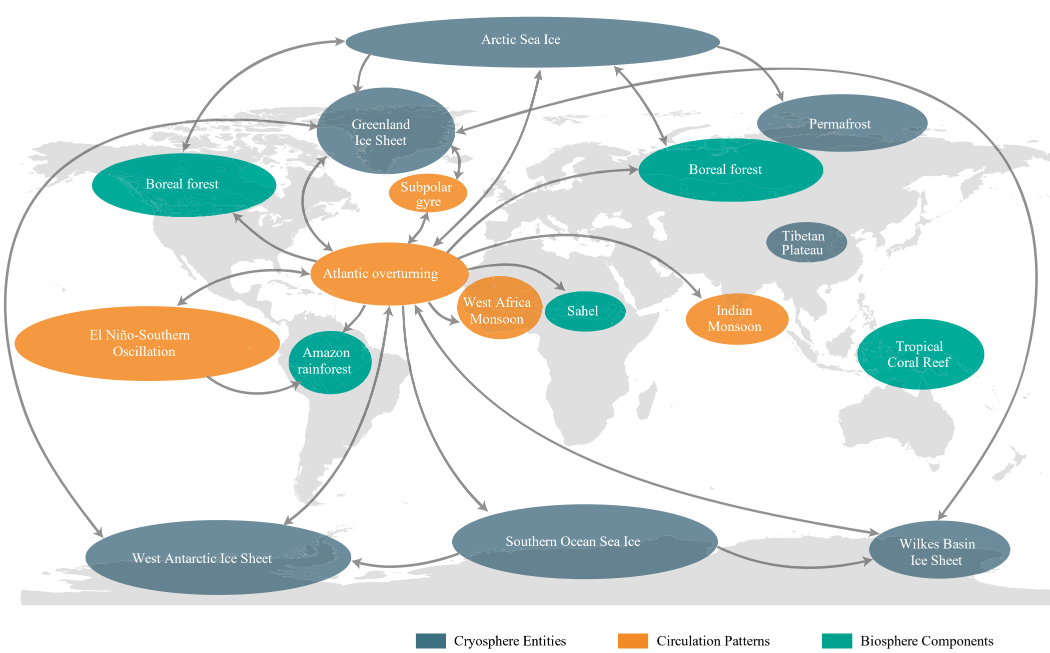
Tipping points

In popular understanding, a “tipping point” is where a small change makes a big difference to the future state of a system (Gladwell, 2000[59]). In the context of climate change, a “climate tipping point” is where a small change in climate (e.g. global temperature) makes a big difference to a large part of the climate system, changing its future state (Lenton et al., 2008[4]). The crossing of tipping points typically triggers accelerating change and is usually inherently hard to reverse. The resulting transition to a different state can appear fast or slow from a human perspective. This perception occurs because its rate depends on the system in question (e.g. the atmosphere changes fast, the biosphere at an intermediate rate, and ice sheets typically change slowly).

Crucial to the existence of a tipping point is the presence of strongly reinforcing positive feedback within a system (Levermann et al., 2011[60]). This can amplify a small initial change and turn it into a large consequence. It can also be self-propelled without further forcing once tipped (Scheffer et al., 2012[61]). Essentially, the relative strength of positive (amplifying) and negative (damping) feedback loops within some part of the climate system can change as the overall climate changes and affects that sub-system. Climate tipping points arise when the balance of feedback loops within a part of the climate system shifts. In such a shift, positive (amplifying) feedback loops dominate over negative (damping) feedback loops. This supports self-propelling change within that part of the climate system (Lenton and Williams, 2013[62]). The relevant positive feedback loops may also act to amplify global temperature change. However, they do not have to do so for a tipping point to occur.

Climate “tipping elements” (Figure 3.4) are defined as at least sub-continental scale parts (or subsystems) of the climate system that can pass a climate tipping point (Lenton et al., 2008[4]). When near a tipping point, these elements can be tipped into a qualitatively different state by small external perturbations or by internal climate variability (Lenton, 2011[63]). However, to bring them near to a tipping point usually requires significant forcing of the climate. Policy-relevant tipping elements are defined here as those that may pass a tipping point this century due to anthropogenic climate forcing.

Figure 3.4. Candidate tipping elements in the climate system



Note*:* Global map of candidate tipping elements of the climate systems and potential tipping cascades. Arrows show the potential interactions among the tipping elements that could generate tipping cascades, based on expert elicitation.
Source*:* World map obtained from Peel, M. C., Finlyson, B. L., and McMahon, T. A. (University of Melbourne).

Recently, evidence that climate tipping points may be approaching – and at least one in West Antarctica may have been crossed – has underpinned declarations of a climate and ecological emergency (Lenton et al., 2019[64]). Table 3.1 summarises different policy-relevant climate tipping points and assesses the likelihood of crossing them at different levels of global warming (above pre-industrial). The assessment is based on paleo-climate and observational evidence, future projections from different models [e.g. (Drijfhout, 2015[65])], and expert elicitation of probabilities at different levels of warming (Kriegler et al., 2009[66]). Once a threshold is crossed, the speed at which the implications unfold will be different for different tipping elements (Ritchie et al., 2021[67]). Some might impact within decades, others only over centuries.

Table 3.1. Likelihood of crossing climate tipping points at different levels of global warming

	Global warming (above pre-industrial)				
Tipping point	≤1.5°C	>1.5°C to <2°C	2°C to <3°C	3°C to 5°C	>5°C
Greenland ice sheet meltdown	Unlikely	As likely as not	Likely	Very likely	Virtually certain
West Antarctic ice sheet collapse	Unlikely	As likely as not	Likely	Very likely	Virtually certain
Wilkes Basin ice sheet collapse	Exceptionally unlikely	Exceptionally unlikely	As likely as not	Likely	Virtually certain
Arctic summer sea-ice loss	Very unlikely	As likely as not	Virtually certain		
Year-round loss of Arctic sea ice	Exceptionally unlikely	Exceptionally unlikely	Exceptionally unlikely	Very unlikely	Likely
Southern Ocean sea-ice abrupt loss	Very unlikely		Unlikely		
Subpolar gyre convection collapse	Unlikely	As likely as not	As likely as not	Likely	Likely
Atlantic overturning (AMOC) collapse	Very unlikely	Very unlikely	Unlikely	As likely as not	Likely
El Niño-Southern Oscillation shift	Exceptionally unlikely	Very unlikely	Unlikely	As likely as not	As likely as not
Tibetan plateau abrupt snow melt	Very unlikely	Unlikely	As likely as not	As likely as not	As likely as not
Permafrost abrupt collapse	Exceptionally unlikely	Exceptionally unlikely	Exceptionally unlikely	Very unlikely	Unlikely
Boreal forest dieback	Exceptionally unlikely	Very unlikely	Very unlikely	Unlikely	Unlikely
Amazon rainforest dieback	Exceptionally unlikely	Very unlikely	Unlikely	Unlikely	As likely as not
Sahel abrupt greening	Exceptionally unlikely	Exceptionally unlikely	Very unlikely	Very unlikely	Very unlikely
Tropical coral reef degradation	Very likely	Very likely	Virtually certain	Virtually certain	Virtually certain

Note: This likelihood assessment uses IPCC's well-established likelihood scale and terms (see also Chapter 2, Section 2.4): "Virtually certain"=99-100% probability; "Very likely"=90-100% probability; "Likely"=66-100% probability; "About as likely as not"=33-66% probability; "Unlikely"=0-33% probability; "Very unlikely"=0-10% probability; "Exceptionally unlikely"=0-1% probability. Probabilities are treated cumulatively with respect to temperature rise, thus for a given temperature range (e.g. >1.5°C to <2°C) the probability given for a specific tipping point is the cumulative probability of passing it at all levels of global warming up to the upper end of that range (here <2°C). The probabilities are given for each tipping point as an independent event, i.e. neglecting causal interactions between them. Overall, such contingent interactions are expected to make other tipping events more likely (although there are a few specific counterexamples) (Kriegler et al., 2009[66]; Cai, Lenton and Lontzek, 2016[68]; Wunderling et al., 2021[69]).

The tipping points probability assessment shown in Table 3.1 can be summarised as follows: Below or at 1.5°C above pre-industrial levels, it is unlikely (0-33% probability) or very unlikely (0-10% probability) that cryosphere or ocean-atmosphere tipping points will be passed. That part of the West Antarctic ice sheet may have passed a tipping point is an exception. However, between 1.5°C and 2°C above pre-industrial levels (i.e. in the Paris Agreement range) key ice sheet tipping points have a 33-66% probability of being passed. The same probability exists for complete loss of Arctic summer sea ice and a collapse of deep convection in the Labrador Sea. Between 2°C and 3°C above pre-industrial levels, it is likely (66-100% probability) that major ice sheet tipping points will be passed. It is also virtually certain (99-100% probability) that Arctic summer sea ice and tropical coral reefs will be lost. Between 3°C and 5°C above pre-industrial levels, it is very likely that major ice sheet tipping points will be passed. As likely as not (33-66% probability), there will be major reorganisations of oceanic and atmospheric circulation.

Given this probability assessment, biophysical impacts of passing particular tipping points should be assessed, as well as how these impacts translate into social impacts and economic costs. Table 3.2 summarises biophysical climate impacts for a subset of tipping points, updated from Lenton and Ciscar (2012[70]). These impacts span effects on temperature, sea level, precipitation, atmospheric circulation, ocean circulation, biogeochemical cycles, modes of climate variability and extreme weather events. In so doing, they aim to give a non-exhaustive flavour of the interconnectedness of the climate system. Effects on temperature can come both directly via changes in surface albedo (reflectivity). They can also come indirectly via changes in GHG emissions, such as CO_2 and methane (CH_4) emissions generated by permafrost thaw. Most of the listed temperature effects are positive feedback loops that will further increase global temperatures.

Table 3.2. Potential physical climate impacts of crossing different climate tipping points

Tipping event	Temperature	Sea level	Precipitation	Biogeochemical cycles	Extreme events
Greenland ice sheet meltdown	Local ↑	≤7 m global ≤0.5 m/century uneven	Local shift to rainfall, WAM disruption	Flooding of permafrost, ↑CO_2, CH_4	Storm surges, icebergs
West Antarctic ice sheet collapse	Local ↑	≤3.3 m abrupt ≤1 m/century uneven	Local shift	(as above)	Storm surges, icebergs
Wilkes Basin ice sheet collapse	Local ↑	≤4 m abrupt uneven	Local shift	(as above)	Storm surges, icebergs
Arctic summer sea-ice loss	↑Arctic & N. Hem.	(minimal effect)	Local shift snow to rainfall	↑Permafrost thawing, ↑CO_2, CH_4	Extreme European snowfall
SPG convection collapse	↓N. Atlantic	Regional shifts ↑0.3 m in parts of N. Atlantic			Amplified cold winter blocking events Europe
AMOC collapse	↓N. Hem. ↑S. Hem.	Regional shifts ↑0.8 m in parts of N. Atlantic	Sahel drying, ↓WAM, ↓ISM, ↓EAM, Amazon	↑CO_2 from ocean and land, biome changes	Cold winters in Europe, S ward hurricanes shift
ENSO shift	↑S Asia, S Australia…↓New Zealand	Regional effects	↓SE Asia, E Australia, Amazon…	↑CO_2, reduced land C storage	Droughts, floods
Boreal forest dieback	↓winter local, ↑global	–	↓regional?	↑CO_2, biodiversity loss	Fires, insect outbreaks
Amazon dieback	↑regional, ↑global	–	↓regional	↑CO_2, biodiversity loss	Droughts, fires, teleconnections

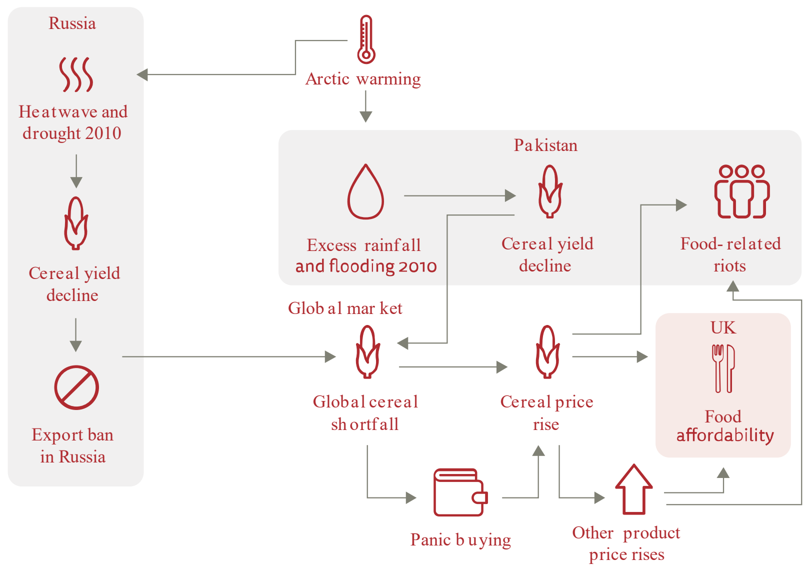
Note: WAM=West African Monsoon; ISM=Indian Summer Monsoon; EAM=East Asian Monsoon; NAO=North Atlantic Oscillation; AMO=Atlantic Multidecadal Oscillation; PDO=Pacific Decadal Oscillation; SO=Southern Oscillation.
Source: updated from (Lenton and Ciscar, 2012[70]).

3.3. Cascading impacts of climate change

The “cascading effects” of climate change are a result of the interconnectedness and interdependencies of natural, social and economic systems. Impacts propagate through international processes, such as global trade, financial flows and supply networks (Acemoglu et al., 2012[71]). These systemic climate risks pose particular challenges to risk assessment. This is especially the case when risks are transmitted in complex ways through sectors and international borders, which remain today poorly understood (Koks, 2018[72]; Challinor et al., 2018[73]).

Figure 3.5 illustrates one such complex risk transmission chain, which took place in 2010 and led to rise in food prices globally. As a result of droughts, a decline in grain yield in the Russian Federation (hereafter "Russia") led to a shortfall in cereals in the international market (also see Box 4.1). At the same time, excess rainfall in Pakistan led to a rise in food prices globally. These higher prices led to a 50% higher use of food banks in the United Kingdom. In Egypt, higher food prices became one trigger for riots leading to a change of government (Hildén et al., 2020[74]). As another example, the cascading effects of flood risk could pose global economic risks of the same order of magnitude as asset damages within and outside the affected region, due to dependencies in infrastructure systems (Koks, 2018[72]).

Figure 3.5. An example of cross-border impacts: Drought and food prices



Source: (Hildén et al., 2020[74])

A cascade takes place as a result of a significant change to a key system variable or variables. This induces the breach of "multiple thresholds across scales of space, time, social organization and across ecological, social, and economic domains" (Kinzig et al., 2006[75]). These thresholds are not easy to understand or analyse, let alone to address. The 2018 Global Risks Report acknowledges it remains a challenge for humanity to deal with "complex risks in systems characterised by feedback loops, tipping points and opaque cause-and-effect relationships that can make intervention problematic" (World Economic Forum, 2018[76]).

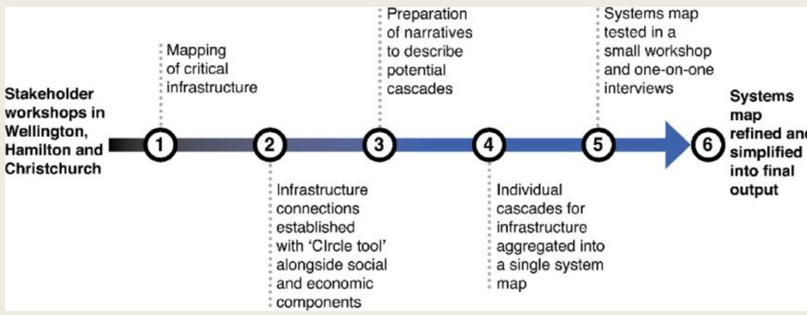
Progress on understanding cascading impacts from climate change has been evolving mainly along three axes: socio-ecological resilience, disaster risk reduction (UNDRR, 2015[77]) and systems dynamics (Lawrence, Blackett and Cradock-Henry, 2020[78]). In this sense, work relating to cascades covers a broad range of topics and thematic areas. These include human-ecosystems dynamics, ecology, natural and climate-related hazards research and systems theory.

Box 3.3 analyses the potential impacts and implications of cascades in New Zealand. It seeks to gain insight into how different types of climate change hazards (e.g. extreme events, SLR or "surprise" elements of the climate system) play concurrently across diverse linked systems and domains (Lawrence, Blackett and Cradock-Henry, 2020[78]). This highlights the importance of understanding the different types of climate-related hazards, and their potential consequences in time and space as a basis for exploring the more complex cascading impacts from climate change.

Box 3.3. Cascading climate change impacts and implications – a case study

Lawrence, Blackett and Cradock-Henry, (2020[78]) investigated cascading impacts and implications in New Zealand. According to the analysis, the framework "systematises the interaction between cascades, who and how cascades affect the system of interest, where interdependencies and co-dependencies occur, and how far impacts and implications might extend across multiple geographic locations, scales, and sectors". Figure 3.6 summarises the process of data collection and analysis.

Figure 3.6. The process of data collection and analysis



Source: (Lawrence, Blackett and Cradock-Henry, 2020[78]).

Physical climate change hazards were characterised into typologies. In this way, different types of hazards could be systematically represented for different regions. The different impacts included: i) slowly emerging and ongoing (e.g. sea-level rise and rising groundwater tables); ii) widening climate variability (e.g. increased drought, flood frequency and duration); iii) extremes (e.g. coastal storm surge and intense rainfall); iv) combined impacts (e.g. coastal and river flooding); and v) surprises (e.g. unknown impacts from atmospheric changes). A dynamic systems framework is used to examine the implications of the combination of such impacts, providing a richer assessment of the risks than traditional linear risk assessment. It analysed both the impacts on water and urban infrastructure systems and financial services, and the implications of cascading climate change impacts for governance.

The study demonstrates that close consideration of the combined effects of diverse types of linked impacts can promote better understanding of the scope and scale of climate change impacts. It examines the dependencies and feedback loops between the different systems studied, namely water and urban infrastructure and financial services. In so doing, it allows for "stress-testing" risk assumptions. The authors conclude this approach "can facilitate the design of adaptation responses that are flexible, yet robust under different future conditions, and thus avoid reaching thresholds that are beyond the ability of communities and physical systems to cope" (see also Chapter 4). For example, understanding linkages and dependencies between the financial sector and human well-being outcomes can make adaptation responses more transparent. More generally, it can inform adaptive planning and governance arrangements in delivering more effective adaptation alongside mitigation policy and practice.

Note: "The sites were: Hamilton, a landlocked city adjacent to rural areas with flood risk, and conservation and tourism demands; Wellington, a capital city constrained by geography for access and egress, and surrounded by coasts; and Christchurch, a city set around low-lying estuaries and coast, recently lowered by earthquake subsidence, with significant flood and storm water challenges."

The next sections present three separate novel studies. They focus on the impacts and, where possible, the potential cascading effects of three types of climate-related hazards: SLR, heatwaves and the tipping point resulting from the collapse of the AMOC. Using state-of-art science in these areas, the studies aim to shed light on the level of climate-related risks; reflect on how this scientific knowledge can inform policy making; and identify remaining gaps and limitations.

3.4. SLR: Impacts and associated risks of losses and damages in SIDS

SIDS comprise a heterogeneous group of island territories situated in the Caribbean, the Pacific, the Atlantic and the Indian Ocean, and the South China Sea. The UN Office of the High Representative for the Least Developed Countries, Landlocked Developing Countries, and Small Island Developing States lists 58 SIDS (UN-OHRLLS, 2021[79]), which are the territories considered in this discussion. [5]

3.4.1. While diverse in character, all SIDS are vulnerable

SIDS are diverse in terms of size, coastal characteristics, culture and geography (Nurse et al., 2014[50]; Ratter, 2018[80]; UN-OHRLLS, 2015[81]). In terms of physical geography, some SIDS are volcanic islands characterised by mountains and steep slopes. Others are tectonically raised limestone islands that generally have a flat tabular surface. Still others are coral reef islands composed of unconsolidated sediments sourced from adjacent coral reefs with elevations of usually no more than 3 m (Nunn et al., 2016[82]; Ratter, 2018[80]). Dome SIDS are archipelagos that consist of many small islands scattered across the ocean, with often large distances between them. However, not all SIDS are small islands. This category also includes Papua New Guinea, Cuba, Haiti and the Dominican Republic. Finally, not all SIDS are complete island territories, as this category also includes continental countries like Belize, Guyana, Surinam and Guinea-Bissau. SIDS are also diverse socio-economically. Island population ranges from about 1 600 (Niue) to 11 million (Cuba) (OECD, 2018[83]). Meanwhile, per capita incomes range from USD 2 300 in the Solomon Islands to USD 60 000 in Singapore (World Bank, 2021[84]).

Low elevations, exposure to hazards and fragile economies enhance vulnerability of SIDS

Irrespective of this diversity, all SIDS are vulnerable to climate change, and in particular SLR and its consequences (e.g. higher surges and waves). This vulnerability has long been recognised by international institutions such as the United Nations Agenda 21, the United Nations Framework Convention on Climate Change (UNFCCC, 1992[85]), the UN General Assembly and many subsequent policy documents including the Paris Agreement.

This recognition is mainly due to three reasons (Leatherman and Beller-Simms, 1997[86]; Nurse et al., 2014[50]; Robinson, 2020[87]; UN-OHRLLS, 2015[81]):

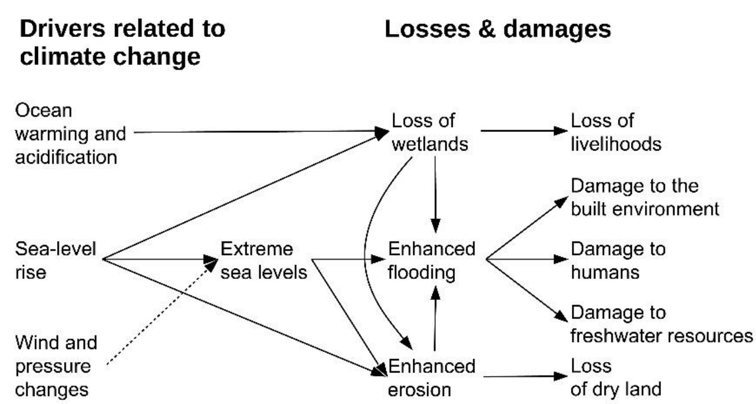
- First, the only habitable area of SIDS is the low-lying coastal zone. This includes atoll islands where the entire island is part of the coastal zone. Elevations are rarely higher than 2-3 m above mean sea levels (Woodroffe, 2008[47]). However, this also includes steep sloped volcanic islands, where the only habitable area is the narrow coastal fringe surrounding those islands. Hence, these places are highly threatened by SLR with limited on-island relocation opportunities (Nurse et al., 2014[50]; UN-OHRLLS, 2015[81]).
- Second, SIDS are disproportionally affected by weather-related disasters because of their location. SIDS are located in the oceans, which exposes them to various climate-related hazards. These include ocean-atmosphere interactions such as tropical cyclones, storm surges, wind waves and high climate variability (e.g. due to El Niño-Southern Oscillation; ENSO). For example, mean sea levels in some Pacific SIDS can be 20-30 cm higher during La Niña events (IPCC, 2014[88]). In addition, many SIDS are located near tectonically active zones. They are thus threatened by

earthquakes, volcanic eruptions and associated tsunamis. Adding to this challenge, many SIDS have long coastlines per unit area, which make protecting against ocean hazards expensive.

- Third, SIDS have fragile economies and a limited range of natural resources. The economies of many SIDS are not very diversified, relying on a few sectors such as tourism and fisheries that are vulnerable to external shocks. For example, fish export makes up nearly 60% of national GDP in Kiribati and the Marshall Islands. Meanwhile, tourism makes up between 50-80% of the national economies of the Bahamas, the Maldives, Palau, Vanuatu, the Seychelles, the Cook Islands and Antigua & Barbuda (UN-OHRLLS, 2015[81]). A low resilience of subsistence economies and the relative isolation and great distance to markets add to this socio-economic fragility.

In face of these vulnerabilities, SLR threatens SIDS with a range of impacts (see Figure 3.7). This includes enhanced coastal flooding causing damages to people, their livelihoods, their physical assets and resources, specifically the salinisation of surface and groundwater bodies. SLR also leads to enhanced coastal erosion leading to a loss of land. If this erosion affects natural or artificial coastal defences, it can also exacerbate coastal flooding. In addition, SLR can lead to a loss of coastal ecosystems and associated biodiversity. This, in turn, has adverse effects on livelihoods depending on these ecosystems. The loss of ecosystems further exacerbates coastal flooding and erosion because ecosystems such as corals and mangroves protect islands from these hazards.

Figure 3.7. Most important impacts of sea-level rise and associated climate drivers on SIDS



SLR is not the only factor driving increasing risks of losses and damages from climate change. Other climate drivers of great importance for SIDS are ocean warming and ocean acidification. These phenomena threaten the survival of coral reefs that protect SIDS against SLR and extreme sea-level events (Box 3.2).

The risks are compounded by a range of other anthropogenic pressures associated with rapid human development, urbanisation and mass tourism facing many SIDS today. This includes water pollution, reef destruction through fishing and diving, and the conversion of mangrove forest into other land uses. Finally, climate risks and potential impacts can only be understood in light of the many ongoing and possible human responses to manage SLR risks (see Chapter 4, Section 4.5).

3.4.2. Losses and damages

Coastal flooding

Extreme sea-level events such as waves and surges may lead to coastal flooding. The extent of these events is shaped by how extreme sea levels interact with the coastal profile. This profile is made up of both natural flood barriers (e.g. coral reefs, mangroves) and artificial ones (e.g. dykes, sea walls). If no barriers exist, extreme sea levels propagate inland where they exceed land elevation. If barriers exist, flooding can occur under several conditions: if waves overtop, or surges overflow, the barriers (i.e. if their heights exceed the height of the barriers); or if waves and surges destroy the barriers.

Coastal floods are among the most devastating natural disasters. They cause loss of lives; damage human health, buildings, infrastructure, freshwater systems and agricultural land; and interrupt livelihoods, economic activities and supply chains (Kron, 2012[89]). SIDS are, for reasons previously noted, vulnerable to coastal flooding. Cumulative total damages caused by tropical cyclones (due to both extreme sea level and extreme wind) from 1990 to 2013 amounted to over 10% of cumulative GDP for nine SIDS. Damages were as high as about 40% for the Maldives, 50% for Samoa, 80% for Saint Kitts and Nevis, and 90% for Grenada (UNEP, 2014[90]). Overall, Pacific SIDS have the highest per capita disaster risk globally (Edmonds and Noy, 2018[91]).

Dedicated comparative assessments of future coastal flood risks to SIDS under SLR are not available. However, several global assessments have produced results at a national level, including for SIDS (Bisaro et al., 2019[92]). Several general messages can be drawn from these studies. First, if SIDS do not adapt to SLR, the impacts will be devastating (Lincke and Hinkel, 2018[93]; Oppenheimer et al., 2019[39]; Wong et al., 2014[94]). Second, it is unlikely or even implausible to assume that SIDS will not adapt to SLR (Hinkel et al., 2014[95]) because coastal adaptation is widespread today. It also has a long history (Charlier, Chaineux and Morcos, 2005[96]), including in SIDS (Klöck and Nunn, 2019[97]). Third, in densely populated areas, also including those on SIDS, adaptation is generally cost-efficient. In other words, it costs much less than the losses and damages experienced without adaptation (Aerts et al., 2014[98]; Hallegatte et al., 2013[99]; Hinkel et al., 2018[100]; Lincke and Hinkel, 2018[93]; Oppenheimer et al., 2019[39]; Bisaro et al., 2019[92]). However, adaptation is also costly, amounting to several percent of national GDP for many SIDS towards the end of the century. Hence, it may not by affordable, highlighting the existential risk that SLR poses for SIDS (Wong et al., 2014[94]; Oppenheimer et al., 2019[39]).

Coastal erosion and loss of land

Independent of SLR, erosion of land at coasts is widespread. Erosion is influenced by a range of natural and anthropogenic drivers. Natural drivers of coastal erosion include currents, tides, waves, surges and natural relative sea-level change (due to vertical land movements). These induce a permanent loss of land, usually associated with a gain of land where the eroded sediment is deposited.

Widespread human modifications of the coast have altered these natural erosion, sediment transport and sediment accretion processes. It is not possible to attribute erosion to precise natural or human drivers. However, it is estimated about 24% of the world’s sandy coastline is eroding, 28% is accreting (gaining land) and the rest is stable (Luijendijk et al., 2018[101]).

Rises in mean sea levels are expected to lead to enhanced erosion. The same is true for higher surges and waves as they bring more energy onto the shore (Ranasinghe, 2016[102]; Wong et al., 2014[94]). In absolute terms, global modelling efforts have found that Caribbean SIDS are the most affected by coastal retreat due to erosion (without protective measures). They have a median shoreline recession of 300 m until 2100 under RCP8.5, about 70% of which is caused by SLR (Vousdoukas et al., 2020[103]).

Processes of eroding and accreting land are specifically pronounced in coral islands. Unconsolidated biogenic material from coral reefs are deposited by currents and waves onto coral islands and their lagoons (Duvat, 2018[104]; Holdaway, Ford and Owen, 2021[105]; Kench, 2012[106]; Kumar et al., 2018[107]). This has led to the concern that SLR may soon lead to the disappearance of coral islands.

Recent studies have somewhat alleviated concerns about the disappearance of coral islands. Studies have looked at a large number of coral islands in the Pacific and Indian Oceans, either by meta-analysing case studies or through analysing satellite images. These studies found about 90% of these islands were either stable or have increased in area over the last decades of SLR (Duvat, 2018[104]; Holdaway, Ford and Owen, 2021[105]). This includes islands in regions where sea level rose by over three to four times the global average (McLean and Kench, 2015[108]).

These studies also highlight diverse drivers that are contributing to change on the islands. These drivers include natural currents, variability and extreme sea-level events. In addition, humans alter sediment transport patterns by destroying coral reefs and constructing coastal infrastructure such as sea walls, harbours and breakwaters. Anthropogenic SLR plays a minor role (McLean and Kench, 2015[108]).

While the findings are encouraging, SLR may well threaten these islands in the future. This underscores the importance of one aspect for adaptation: coral islands can withstand and grow with SLR under several conditions. First, the reef needs to produce sufficient sediment. Second, natural sediment transportation dynamics must be kept alive. Third, islands must be allowed to be flooded episodically so they can grow vertically through the sediment deposited by the flood. This ability to adapt, however, is threatened by other climate drivers as discussed further below.

Loss of ecosystems

In combination with other drivers, SLR also threatens coastal ecosystems such as corals and mangroves. These ecosystems naturally protect coasts from extreme sea level that erodes shores and causes floods. Loss of these ecosystems, then, exacerbates erosion and flooding impacts.

Coral reefs are particularly important for protecting coasts from extreme waves – the main coastal hazard for many Pacific and Indian Ocean SIDS. The reef crest and reef flat both dissipate wave energy. As a result, the wave arriving at the coastline is smaller than outside of the reef. On global average, it has been estimated that coral reefs reduce wave energy by 97% (Ferrario et al., 2014[109]). This, in turn, means that taking away the corals has a disastrous effect on these coasts in terms of enhancing coastal flooding. Furthermore, corals support local livelihoods in many ways. For example, they provide the basis for tourism (which is the biggest economic sector in many SIDS). They also serve as an important habitat for local fisheries. Globally, the value of corals for tourism has been estimated to USD 36 billion (Spalding et al., 2017[110]).

The main climate driver of coral loss is not SLR but rather ocean warming. To some extent, corals can even grow upwards with SLR. However, warmer than normal temperatures can lead to mass coral bleaching and subsequent dieback (Hughes et al., 2017[111]). Corals throughout the world are already severely stressed under today's level of global warming (Hughes et al., 2018[112]). By 2070, more than 75% of corals are expected to be experiencing annual severe bleaching even under intermediate levels of global warming (i.e. RCP4.5) (van Hooidonk et al., 2016[113]). Ocean acidification adds to the challenge facing corals. Acidification can reduce the rate at which corals build up their calcareous structures. However, the long-term effects of this process are only beginning to be understood (Kroeker et al., 2013[114]).

The loss of corals significantly increases risk of both erosion and floods. Unhealthy or dead reefs cannot produce the sediment required for coral islands to grow and keep up with SLR. Similar to corals, mangroves protect the coastline of SIDS from extreme sea-level events. They provide a number of important ecosystem services such as support for fisheries and carbon sequestration. Generally, mangroves can keep up with high rates of SLR by migrating inland and upwards the coastal slope if sufficient accommodation space and sediment supply are available (Lovelock et al., 2015[115]; Schuerch et al., 2018[116]).

Accommodation space refers to the inland migration not prohibited by steep coastal slopes or human infrastructures (e.g. dykes, roads, human settlements, etc.). However, the coastal zone is small, and/or heavily used by humans (Sasmito et al., 2015[117]). This can often limit the availability of such accommodation space in SIDS. Similarly, the availability of sediment that mangroves need to grow upwards with SLR is heavily constrained. Anthropogenic pressures such as the damming of rivers, for example, bring sediment to the coast. This process is expected to worsen over the 21st century (Dunn et al., 2019[118]). A comparative analysis in 2015 looked at mangrove sites, including on SIDS in the Indo-Pacific region. In about 70% of the study sites, sediment unavailability already constrains mangroves' ability to adjust to SLR today (Lovelock et al., 2015[115]).

Loss of freshwater resources

Many SIDS are already characterised by limited fresh water supply and SLR. Extreme sea-level events and associated enhanced coastal flooding and coastal erosion put additional pressures on these limits (Nurse et al., 2014[50]). Many studies have found that SLR alone does not necessarily threaten freshwater lenses. Two conditions protect against this threat. First, sufficient vertical accommodation space must allow the freshwater lenses to move upwards with SLR. Second, coastal erosion must not reduce island size (Falkland and White, 2020[119]).

SLR that leads to more frequent surge or wave flooding of islands, however, has adverse consequences for freshwater availability on SIDS. This is particularly true for coral islands, which have a freshwater lens that is only a few metres thick. With such a thin lens, small amounts of salt water intrusion from above can render the freshwater not potable for months to years (Gingerich, Voss and Johnson, 2017[120]; Holding and Allen, 2015[121]).

With SLR, wave-induced flooding will become more intense and frequent. This increases the recovery time of freshwater lenses. This, in turn, can lead to freshwater no longer being potable. Some studies argue the risk of losing potable water is inevitable in some cases. Storlazzi et al. (2018[122]) suggest the coral islands of Roi-Namur in the Republic of Marshall Islands will lose potable water in 2030-40 under RCP8.5 and 2055-65 under RCP4.5. This leads the authors to conclude that "most atolls will be uninhabitable by the mid-21st century."

The conclusions of Storlazzi et al. (2018[122]) fail to consider human adaptation. Many atolls are already heavily threatened by water stress. Hence, they de-salinate sea water for potable water, or import and use brackish groundwater for non-potable water needs (Falkland and White, 2020[119]). While de-salinisation is technically feasible in most cases, it is also an expensive and technologically complex option. It requires effective operation and maintenance (Falkland and White, 2020[119]).

3.5. Quantifying the impacts of climate change with extreme event attribution

The costs of extreme weather are rising (Barthel and Neumayer, 2012[123]; Smith and Katz, 2013[124]; Smith and Matthews, 2015[125]; NOAA National Centers for Environmental Information (NCEI), 2021[126]). Examples of these increasing costs, like the frequency of "billion-dollar disasters" in the United States, are frequently cited in public discourse as evidence of anthropogenic climate change. For many, such anecdotes represent "real-world impacts of climate change". However, such claims could be considered premature. Other factors unrelated to climate change also drive increases in event damages. These include the increasing exposure of physical assets or improvements in reporting event-related costs (Smith and Katz, 2013[124]). A more rounded assessment of the costs of human-caused climate change instead requires a disentangling of these different factors. Notably, it should identify the role of exposure and vulnerability in the context of the extreme event. It also isolates the role of climate change in the extreme event itself.

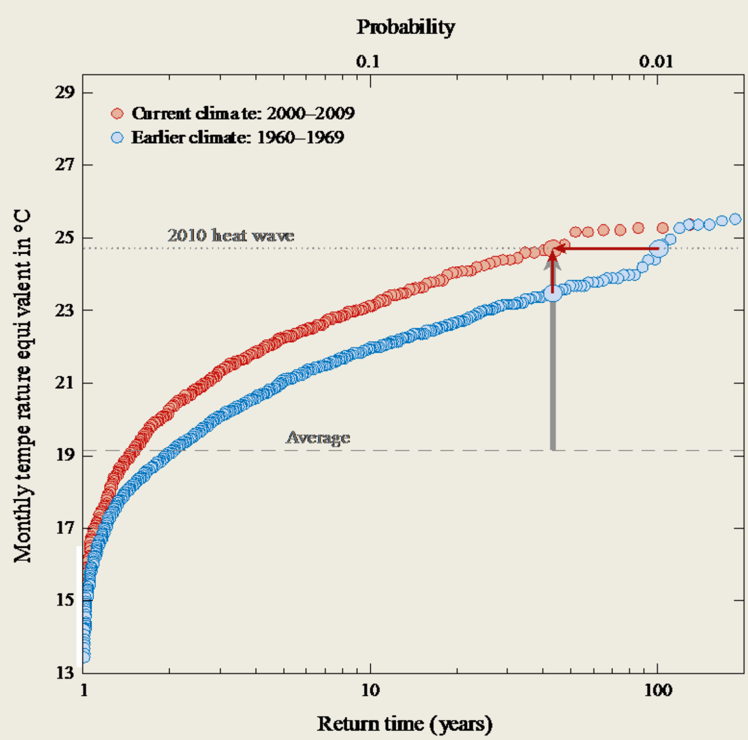
While deemed impossible by scientists themselves for decades, the advent of the science of extreme event attribution offers a quantitative method to answer the question of whether and to what extent climate change is responsible for worsening the impacts of individual extreme weather events today. Extreme event attribution therefore represents a critical conceptual bridge. It links today's extreme weather with long-term increases in global-mean temperatures that are driven by human-induced climate change (see Box 3.4).

Box 3.4. What is extreme event attribution?

Event attribution literature is rapidly growing. In so doing, it is providing a deeper understanding of how climate change is impacting natural and human systems at the local level. It is also indicating how higher levels of greenhouse gas emissions, combined with other pollutants and a changing land surface, alter the likelihood and intensity of extreme events (Stott et al., 2015[127]; Otto, 2017[128]). Climate change not only affects the overall temperature of the planet but also the atmospheric circulation (Vautard et al., 2016[129]). Hence, climate change can affect extreme weather in three possible ways. It can i) increase the likelihood of an event occurring; ii) it can decrease the likelihood of an event occurring; or iii) it can have no effect on the likelihood of an event occurring.

The approach most widely used, illustrated in Figure 3.8, uses the example of the 2010 Russian heat wave (Otto et al., 2012[130]). First, it assesses the probability of the observed intensity of the extreme event in question (horizontal dotted line) to occur in the current climate (red dots), all human-induced (non-climate) drivers included. It then compares it with the probability of its occurrence in a world without human-induced climate change (blue dots). This enables the isolation and quantification of the effect of climate change (horizontal arrow) on the probability of occurrence of an event of a given magnitude, as well as the change in intensity of an event of an observed likelihood (small vertical arrow).

Figure 3.8. Attribution analysis of the 2010 Russia heatwave



Note: Return time of extremely high monthly mean temperatures in Western Russia in the current climate (red) and an earlier climate (blue). The dashed line shows monthly average temperatures, and the dotted line shows the magnitude of the heat wave in 2010. The grey arrow shows the departure from the average in the magnitude, and the red vertical arrow depicts the role of climate change in that departure. The red horizontal arrow shows the increase in frequency of a 2010-like heat wave due to anthropogenic climate change.
Source: (Otto, 2017[128]).

For today's climate, observations of weather and climate can help estimate the likelihood of an event. Observations of a hypothetical, counterfactual world without anthropogenic climate change do not exist. Furthermore, only weather that has *occurred* can be observed; it is not possible to observe all weather events possible in a given climate. Event attribution thus relies on climate models to simulate possible weather, including the extreme event in question, in a given region and season accurately enough to draw conclusions on the role of climate change. Early studies applying the probabilistic event attribution approach employed a single climate model (Stott, Stone and Allen, 2004[131]); thus, the results depend heavily on that model's reliability (Bellprat and Doblas-Reyes, 2016[132]; Otto et al., 2020[133]). A more robust approach has since been developed that includes both observation-based statistical analysis and multiple models of varying complexity. A whole new field of climate science has thus emerged, and the methods are constantly improving (Philip et al., 2020[134]; van Oldenborgh et al., 2021[135]).

Two aspects of the methodology are important. First, the definition of an extreme event is a crucial part of the analysis and determines the outcome. In the most commonly used approach, the event is always defined as a type of weather that leads to an impact. This could be, for example, extreme rainfall above a certain threshold in a particular area or season that causes flooding. Other methodologies favour highly-conditioned (or storyline) approaches, which are not probabilistic and consider a much narrower event definition [(Shepherd et al., 2018[136]; Hegdahl et al., 2020[137]) and Box 4.2]. Second, attribution of extreme events relies on the availability of climate models realistically simulating the type of event. For example, the impacts of extreme tornado or hailstorm events will remain unassessed while current-generation models fail to meaningfully simulate the relevant physical processes.

In addition, the best available impact data relating to a given class of extreme weather affecting a specific region are often only one single data point – the impacts of that recently-observed event. Consequently, attribution statements work within the constraints of one impact observation. In the context of framing attribution statements, scientists have a limited understanding of the specific shape of the hazard-impact relationship. In other words, they are often unable to quantitatively resolve whether a slightly less-intense event would have resulted in slightly fewer impacts, or perhaps no impacts whatsoever. Climate models can look at the probability of witnessing meteorological characteristics equal to or worse than the recently-observed, knowingly-impactful event. They can quantify what fraction of this probability would not have occurred in a pre-industrial climate. In this way, the attribution methodology sidesteps the need to resolve other details in the hazard-impact relationship. Instead, it frames the estimated attributable change in impacts solely around the one observed data point. There must be confidence in this point being directly relevant to the communities who suffered from that event (Frame et al., 2020[138]; Clarke, E. L. Otto and Jones, 2021[139]).

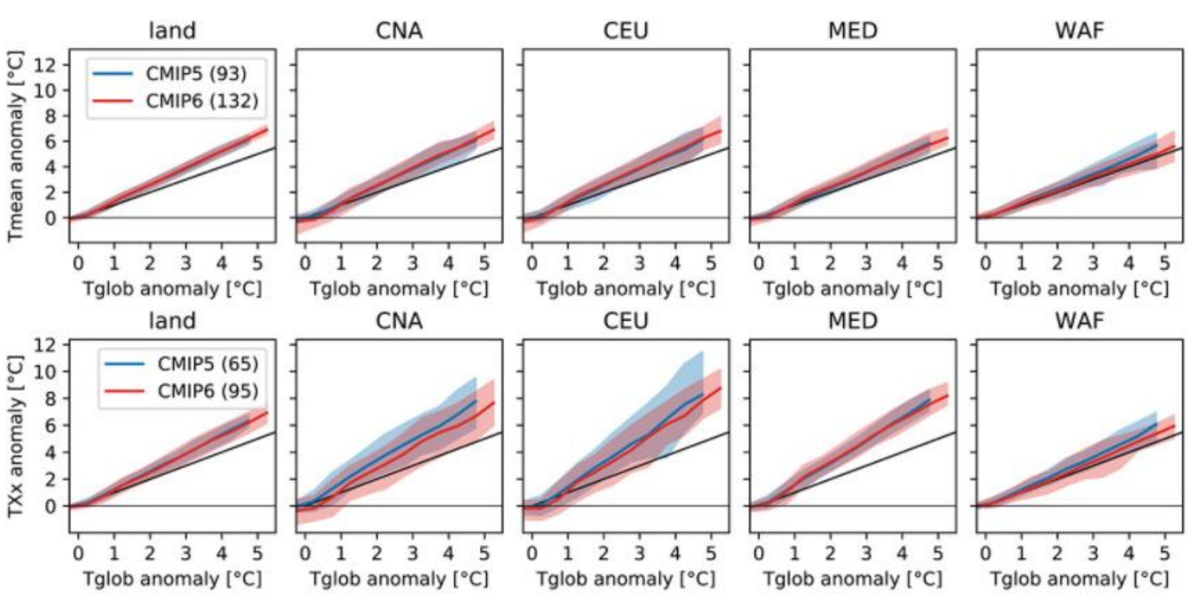
The science of extreme event attribution has received high scrutiny by peers. Some claim that scientists are too confident in their attribution statements (Bellprat and Doblas-Reyes, 2016[132]). Others argue they are too cautious (Lloyd and Oreskes, 2018[140]; Lloyd et al., 2021[141]). Within the probabilistic attribution community, this scrutiny led to a rather fast development of transparent and more robust methods of estimating changing hazards. These methods are detailed in van Oldenborgh et al. (2021[135]). They consist of careful considerations of the event definition; a standardised evaluation of whether to include climate models in a study; and assessment of structural uncertainties in climate models and due to observational data constraints.

3.5.1. Robust features of worsening extreme weather due to climate change

Attribution science has helped to identify many robust features of worsening extreme weather due to climate change (despite the methodological challenges and uncertainties discussed in Box 3.4 and Box 3.5 respectively). First and foremost, there is high confidence that heat-related extremes are becoming more frequent and severe by orders of magnitude more rapidly than any other type of extreme weather (Fischer and Knutti, 2015[142]), and that changes in marine heatwaves emerge even faster than land-based heatwaves (Oliver et al., 2017[143]; Frölicher, Fischer and Gruber, 2018[144])[6]. This is important to emphasise, as significant differences around future risk management exist when one class of extreme weather is *only* being made twice as likely due to current levels of warming (e.g. flooding in the UK (Otto et al., 2018[145]), while another class of event might be becoming hundreds of times more common (like heatwaves in the Tropics (Perkins-Kirkpatrick and Gibson, 2017[146]). This is especially true when risk assessments on national levels are primarily driven by the insurance industry, who generally do not insure against heat-related losses, thereby ignoring the class of extremes where climate change has the largest impacts.

Second, there is high confidence in the projected rates of intensification for both extreme heatwaves and extreme rainfall events. These rates of change are well-simulated in climate models, and the physical processes which contribute to these changes are also well-understood. As shown in Figure 3.9, future projections of both mean temperatures and extreme high temperatures can be expressed as a simple linear response to anthropogenic increases in global-mean warming. Over land, mean temperatures are found to warm faster than the global average, which in turn relates to differences in the speed of projected warming over land versus oceans (Joshi et al., 2007[147]) and has been explained largely as a result of atmospheric dynamics (Joshi et al., 2007[147]; Byrne and O'Gorman, 2013[148]; Byrne and O'Gorman, 2018[149]). For the case of high-temperature extremes (bottom row of Figure 3.9), there is an additional amplification factor found for moisture-limited regions like the Mediterranean (Seneviratne et al., 2016[150]; Vogel et al., 2017[151]; Vogel, Zscheischler and Seneviratne, 2018[152]). For example, (Vautard et al., 2020[153]) found that "without human-induced climate change", heatwaves as exceptional as the European events of June and July 2019 would have had "temperatures about 1.5 to 3 degrees lower". Synthesizing the evidence places the rates of intensification of high temperature extremes at between 1 and 3 degrees per degree of global warming – though it is emphasised that this range intends to represent all populated land regions, and any individual region would likely have a narrower range of uncertainty.

Figure 3.9. Change in local temperatures per degree of global warming



Note*:* Projected changes in average temperatures (top row) and annual maximum daily maximum temperatures (bottom row) under future warming scenarios, for a range of selected regions (CNA = central North America; CEU = Central Europe; MED = Mediterranean; WAF = Western Africa). Results are presented as changes relative to corresponding increases in global mean temperature; the black line denotes a 1:1 relationship
Source: (Seneviratne and Hauser, 2020[154])

With respect to the physical processes driving the intensification of rainfall extremes, there is more moisture in a warmer atmosphere, which increases the intensity of all precipitation events if one assumes that atmospheric circulation does not otherwise change (Allen and Ingram, 2002[155]; Allan and Soden, 2008[156]). However, other physical factors not explored in detail here may reduce (Pendergrass, 2018[157]) or intensify events (Meredith et al., 2015[158]; Meredith et al., 2015[159]; Prein et al., 2015[160]; Prein et al., 2016[161]; Fowler et al., 2021[162]). A synthesis of the rates of intensification for extreme rainfall span the range of 5% - 15% per degree of global warming: differences of course exist depending on what region of the world and duration of events (Westra et al., 2014[163]; Prein et al., 2016[161]; Hodnebrog et al., 2019[164]) are considered or how extreme the events of interest are (Fischer and Knutti, 2015[142]; Kharin et al., 2018[165]; Pendergrass, 2018[157]).

Third, several attribution studies (Freychet et al., 2019[166]) have shown that large swathes of Asia (particularly India) and parts of the US exhibit a suppressed GHG signal of heatwave intensification, because of the cooling effects of aerosol emissions associated with local air pollution and/or large scale irrigation. Consequently, there exists high confidence that efforts to improve air pollution or modify irrigation practices in the future would affect these temporary dampening effects, thereby risking a potentially sudden worsening of relative heatwave severity over the regions in question. So seemingly paradoxically, one of the effects of reduced burning of fossil fuels might be to increase temperatures in some parts of the world, since the cooling effect of atmospheric aerosols would rapidly dissipate.

Fourth, many extreme events with multivariate drivers (like heat stress, agricultural drought or wildfires) often result in attribution statements which are more uncertain when compared with a univariate extreme event. This is in part due to the lack of high-resolution, high-quality observations for variables beyond rainfall and temperature. Climate models and event attribution tools can however still usefully selectively identify and decompose the *relative* importance of individual variables to otherwise complex signals of change (Uhe et al., 2017[167]; Philip et al., 2018[168]; Kew et al., 2021[169]). For example, multi-month or multi-year precipitation deficits rarely show changes in response to current levels of global warming (Otto et al., 2015[170]), except for some specific regions (Otto et al., 2018[171]). And while this absence of any change in the frequency of low-rainfall years was also found for California, (Diffenbaugh, Swain and Touma, 2015[172]) demonstrated that concurrent temperature increases meant the overall risks of drought were still in fact rising. In addition, since 2010, Chile has been affected by a 'mega-drought', name given to an extraordinary drought phenomenon affecting the countries' most populated areas, which is unprecedented in historical and/or instrumentally recorded logs or paleo-climate records covering the last 1000 years. Attribution studies have shown that approximately 25% of the precipitation deficit during the years 2010 to 2015 can be attributed to anthropogenic climate change, and that this factor will continue in the future, favoring the occurrence of these events and increasing the rate of aridification in central and southern areas of the country (CR2, 2015[173]).

Box 3.5. Known sources of uncertainties in event attribution studies

Uncertainties in quantifying the impacts of different classes of extreme weather

Better understanding of losses and damages from climate change requires better quantification of the impacts caused by extreme weather events. However, the monitoring and systematic reporting of climate impacts associated with different classes of extreme weather – let alone of the underlying exposures and vulnerabilities – is often sparse and inconsistent between poorer and wealthier countries (Guha-Sapir, Hargitt and Hoyois, 2004[174]; Visser, Petersen and Ligtvoet, 2014[175]; Noy, 2016[176]; Noy and duPont IV, 2018[177]; Tschumi and Zscheischler, 2019[178]). Chapter 2 (Section 2.2.1.) summarises the different dimensions of uncertainty that exist when quantifying the impacts of different classes of extreme weather, namely flooding, wildfires, heatwaves and droughts.

Different aspects of attribution uncertainty for different classes of extreme weather

The most important limiting constraint when quantifying the role of anthropogenic climate change on any extreme weather event relates to whether available climate models can meaningfully simulate the physical drivers of the event in question (Box 3.4). Attribution scientists consider other factors for those classes of event where evaluation identifies high confidence in climate models (e.g. large-scale extreme rainfall events or land-based heatwaves) (van Oldenborgh et al., 2021[135]).

One source of uncertainty concerns the choice of spatial and temporal scale considered when defining the extreme event in question (Angélil et al., 2014[179]). Attribution scientists typically choose the scale based on isolating the most significant impacts of the event e.g. where/when temperature anomalies were most extreme. Such a choice is necessary, but is made with the knowledge that an alternative selection can sometimes change the severity of both the observed 'event' itself, as well as the estimated influence of climate change on the event (Cattiaux and Ribes, 2018[180]). This is not because of any real-world difference in how much climate change has strengthened the intensity of that heatwave. Rather, it is because translating that intensification into a "change in recurrence frequency" considers how much a given signal has emerged from background variability and the noise associated with heat extremes increases at smaller spatio-temporal scales. Indeed, for heat-related extremes, systematically reanalysing the same heatwave event at increasingly finer spatial or temporal scales typically reduces the magnitude of any *frequency*-based attribution metrics (Angélil et al., 2014[179]). For example, a study shows climate change made the extreme heat in Europe in 2018 between 2 and 100 times more likely, depending on choices of spatial and temporal scales for analysing the event (Leach et al., 2020[181]).

For rain-related extremes, topographic features and other local effects mean that opposing signals of future precipitation change can also be found in nearby locations (Caloiero, 2014[182]). Similarly, opposing signals of climate change can also be found when considering changes in wintertime and summertime rainfall for the same location (Guillod et al., 2017[183]). As a consequence, there is significant potential for cancellation of otherwise-robust climate change signals when looking at precipitation-related extremes over increasingly large spatial or temporal scales. Thus, any attempt to quantify drying or wettening signals under climate change requires careful treatment of climatological rainfall characteristics over the region in question.

These considerations lead to three general rules for analysis. Choosing spatio-temporal scales that map closest to impacts means that extreme rainfall analyses consider short timeframes (days) and smaller spatial scales (cities to regions). Heatwave analyses consider a range of spatial scales (cities to continents) but often small temporal scales (days to weeks). Finally, drought analyses consider large spatial (regions to continents) and temporal scales (months to years).

Note: Chapter 2 considers uncertainties in more detail.

3.5.2. Expected emergence of unprecedented changes in extreme heat

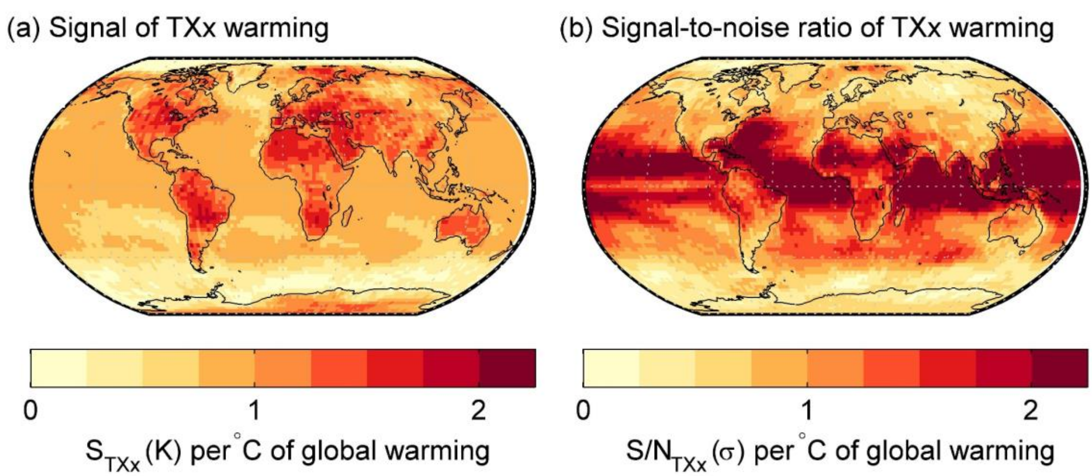
There are often questions of when certain regions of the world might become 'uninhabitable' due to change extreme heat or heat stress in the future. This section attempts to demonstrate the patterns and relative speed of change associated with distributional shifts in the hottest day per year for different parts of the world. It also tries to explain why there will never be a simple, binary disaggregation of future regions on the basis of where humans can or cannot continue to live.

Relative change in hottest day of the year as proxy for extreme high temperatures

Figure 3.10, panel (a), considers the signal of relative change in the hottest day of the year (TXx) as a proxy for extreme high temperatures. These changes are normalised to show the signal of change per degree of global-mean warming (under a high-emissions RCP8.5 scenario). TXx has been analysed extensively in the past (Sillmann et al., 2013[184]; King et al., 2015[185]; King et al., 2016[186]; Harrington et al., 2018[187]). It maps well to changes in extreme heatwaves over multi-day timescales, too (Perkins and Alexander, 2013[188]; Cowan et al., 2014[189]; Russo, Sillmann and Fischer, 2015[190]; Russo et al., 2016[191]; Angélil et al., 2017[192]).

Results show an unambiguous signal over land of warming signals in TXx. This outpaces corresponding changes in global mean temperature by a factor of up to 1.8 in some locations. As explained earlier, these patterns of change are very well understood. They relate primarily to two differences. First, they relate to the factors determining mean warming rates over land versus oceans (Joshi et al., 2007[147]). Second, they relate to an additional acceleration over moisture-limited continental areas where further intensification of the hottest days of the year are driven by soil moisture feedback mechanisms (Vogel et al., 2017[151]).

Figure 3.10. The "new normal": Future extreme heat and changes relative to past experiences



Note: (a) Multi-model medial spatial patterns of the change in TXx per °C of warming under future warming scenarios. (b) Same as panel (a) but showing the spatial patterns of signal-to-noise ratios (S/N ratios) of TXx. Future changes in TXx are normalised on the basis of year-to-year variations experienced in the historical record (S/N ratios). An S/N ratio of 1 means that projected increases in temperatures on the hottest day of the year will equal the standard deviation of year-to-year variations in TXx in the present climate.

A new "average" hottest day of the year based on historical year-to-year variations

Figure 3.10, panel b considers future changes in TXx normalised on the basis of year-to-year variations in the historical record. Specifically, the signal of warming in TXx is divided by the local standard deviation of

TXx. This is calculated using linearly detrended historical data from all years in the 20th century (hereafter "signal-to-noise" or S/N ratios). An S/N ratio of 1 means the future change (increase) in the average temperature of the hottest day of the year is the same as the standard deviation of the temperature of the hottest day of the year in the present climate. In other words, the new "average" hottest day would previously have been about a 1-in-6 year event. This enables a globally comparable assessment that measures whether future changes in heat extremes are *unusual* relative to the range of experiences common to individual locations (and ecosystems or societies therein) (Hawkins and Sutton, 2012[193]; Frame et al., 2017[194]; Hawkins et al., 2020[195]).

When viewed through this lens, Figure 3.10 panel (b) reveals that tropical oceans are, by far, witnessing the most rapid *relative* changes in high-temperature extremes. They are followed by North African and Middle East arid regions, and then other tropical land areas. These patterns also align with results elsewhere that show marine heatwaves are already becoming more intense and frequent. These reports show speeds of change are unrivalled when considering climate extremes elsewhere in the climate system (Oliver et al., 2017[143]; Frölicher, Fischer and Gruber, 2018[144]). These extremes are, however closely, followed by the worsening of tropical land-based heatwaves (Perkins-Kirkpatrick and Gibson, 2017[146]) and heat stress waves (Mora et al., 2017[196]).

To further highlight the diversity in relative changes in extreme heat between different regions of the world, Table 3.3 presents the median S/N ratio of changes in TXx for different warming levels. It presents for the globe, for LDCs and for the OECD as of June 2021. Globally, the average relative change in extreme heat is found to follow global mean temperature changes at a near 1:1 ratio. OECD member states experience slower than average relative changes in extreme heat. By contrast, the average changes experienced by LDCs are some 50% faster than the global average. This pattern of lower income countries experiencing faster relative changes in extreme heat has also been corroborated extensively in previous research (Mahlstein et al., 2011[197]; Harrington et al., 2016[198]; Frame et al., 2017[194]; Harrington et al., 2018[187]; King and Harrington, 2018[199]).

Table 3.3. Population exposure to future extreme heat outside the norms of past experiences

	Signal-to-noise ratio (σ) of TXx experienced by median person		
Global warming since 1861-80	**Worldwide**	**LDC members**	**OECD members**
+ 1.0°C	1.0 (0.3/1.7)	1.5 (0.3/2.2)	0.8 (0.3/1.5)
+ 1.5°C	1.5 (0.6/2.3)	2.2 (0.6/3.3)	1.3 (0.6/2.1)
+ 2.0°C	2.0 (1.0/3.1)	3.0 (1.1/4.4)	1.8 (1.0/2.8)
+ 2.5°C	2.6 (1.3/3.8)	3.8 (1.4/5.4)	2.3 (1.3/3.5)
+ 3.0°C	3.2 (1.5/4.6)	4.5 (1.6/6.5)	2.9 (1.6/4.1)
+ 3.5°C	3.7 (1.8/5.2)	5.2 (1.9/7.4)	3.3 (1.8/4.7)

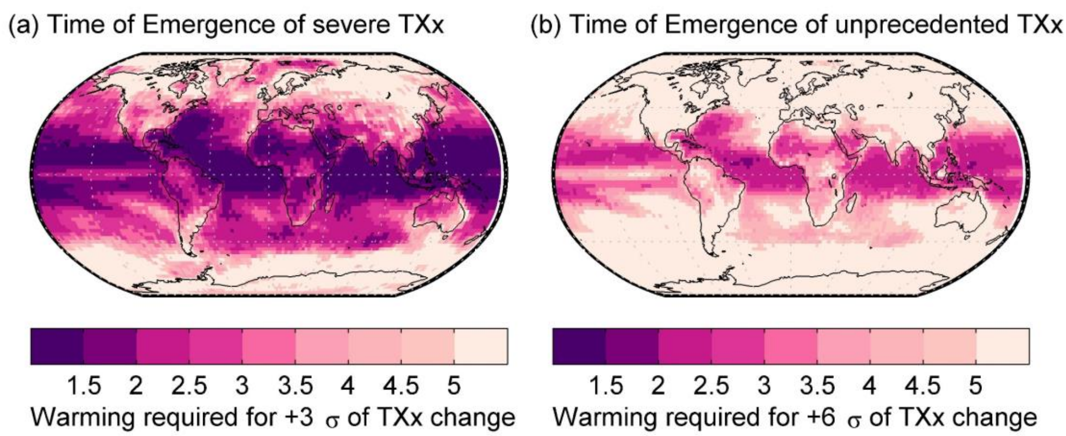
Note*:* Model projections of the signal to noise (S/N) ratios of TXx experienced by the median person under future warming thresholds (using RCP8.5), for three population groupings: the global population, the combined population of 46 Least Developed Countries, and the combined population of 38 OECD member countries. Gridded population data are fixed at 2015 levels and taken from (Center for International Earth Science Information Network - CIESIN, 2005[200]). The main numbers show the multi-model median TXx S/N ratio experienced by the median person of each population grouping. The bracketed values show climate model uncertainty (multi-model 10th and 90th percentiles) associated with S/N ratios for the median individual in response to the specified level of warming.

Every tonne of carbon released will make the future increasingly unrecognisable

Figure 3.11 shows the levels of global mean warming required to locally exceed future thresholds of extreme heat emergence. These thresholds are represented by levels of change +3σ and +6σ. The +3σ levels approximate when the hottest day of an average year in the new climate would be considered rare in the past. Meanwhile, +6σ represents levels when the hottest day of even the coolest year in the future would still exceed the hottest temperatures ever experienced in the past.

The worsening patterns of change that accompany warming everywhere in Figure 3.10 strengthens the conclusion that every additional tonne of carbon emissions released into the atmosphere will only make the future more and more unrecognisable. This is especially the case when comparing the experiences of extreme future heat with those of the past several decades. A comparison with a pre-industrial climate would be even more dramatic.

Figure 3.11. Warming required to exceed future thresholds of extreme heat beyond past experiences



Note: Panels (a) and (b) use the results presented in panel 4.1b to estimate the global mean temperature increase required to witness signal-to-noise ratios in excess of 3 and 6, respectively, at each grid cell. Panel (a), +3σ, approximates levels when the hottest day of an average year in the new climate would be considered rare in the past. Panel (b), +6σ, approximates levels when the hottest day of even the coolest year in the future would still exceed the hottest temperatures ever experienced in the past.

No singular definition or threshold is precise enough to identify when a location will no longer be suitable for "human habitability". Different countries, as well as communities therein, have developed significantly different levels of tolerance to unusual heat over time (whether via cultural, technological or physiological change). No one index of extreme heat (or heat stress) can capture this myriad of regional and sub-regional differences in susceptibility to future change (Matthews, 2018[201]; Vanos et al., 2020[202]). Any choice of climate metric, or threshold to define "catastrophic changes", will therefore emphasise some regions over others. Too often, it will also mischaracterise the differing levels of resilience within individual communities and countries, or indeed potential to adapt.

3.5.3. The importance of exposure and vulnerability when assessing the future impacts of extreme weather

Extreme event attribution has evolved to primarily assess probabilistic changes in the likelihood of witnessing extreme meteorological hazards. It thereby offers a quantitative framework to understand how the impacts of today's extreme weather events might be worsening due to anthropogenic climate change.

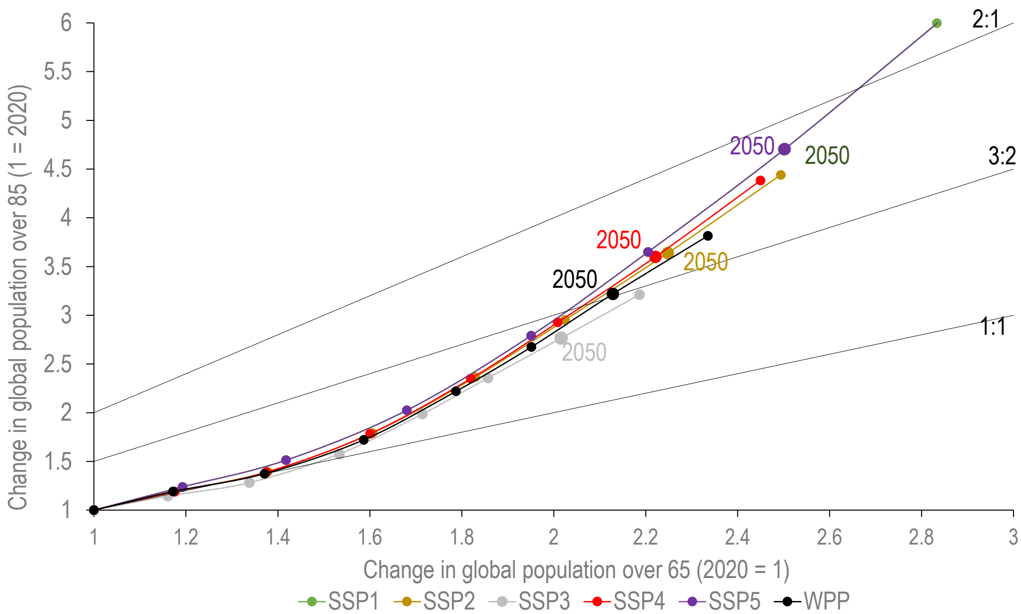
However, it is equally crucial to assess how non-hazard factors (i.e. exposure and vulnerability) modulate the severity of extreme weather impacts, as well as their potential for change over time. This is crucial for decision makers to understand how the risks and impacts from extreme weather might improve or worsen.

This section considers several non-hazard determinants of extreme weather impacts, as well as the range of possible changes expected over the 21st century.

The share of vulnerable populations is projected to grow

Figure 3.12 presents projected changes in two categories of vulnerable people – those aged over 65 and over 85 years. In so doing, it creates five alternative storylines of socio-economic outcomes over the 21st century (the Shared Socio-economic Pathways, or SSPs). Each circle represents a new decade, as global elderly populations grow from 2020 levels (set to equal 1).

Figure 3.12. Population ageing scenarios



Note: Projected changes (relative to 2020) in the global population aged over 65 years (horizontal axis) and 85 years (vertical axis) for each decade between 2020 and 2070 under the five Shared Socio-economic Pathways and the population scenarios developed for the UN World Population Prospects 2019. Each circle denotes a new decade; larger filled circles show the values for 2050. Note that the pathways for SSPs 1 and 5 overlap one another.

Two clear patterns emerge related to global population growth and the most vulnerable populations. First, the rates of global population growth in the age group most often assessed as "vulnerable" – those over 65 – are significant. They will increase by a factor of between 2 and 2.5 by 2050 depending on the scenario considered.

Second, and more concerning, the rates of growth when isolating only the most vulnerable (Whitty and Watt, 2020[203]) within this grouping (those over 85 years old) are even more rapid. By mid-century, 3- to 4-fold increases in population size are expected, which will shift to 5- to 20-fold increases by the end of the century (not shown in Figure 3.12). The rate of growth accelerates beyond corresponding changes in the over-65 group with every successive decade under all scenarios.

These projected rates of change are driven by an ageing global population and improving health-care outcomes. They clearly indicate the collective risks posed by extreme weather, and particularly extreme heatwaves (Whitty and Watt, 2020[203]), could increase significantly. This will be the case even if the climate-related hazards themselves remain unchanged. Chapters 1, 2 and 5 explore other socio-economic factors potentially at the origin of exposure and vulnerability of human and natural systems.

The severity of the hazard is an imperfect proxy for the severity of impacts

The impacts of an extreme weather event can be different depending on the vulnerability of exposed communities (Quigley et al., 2020[204]). Indeed, the rarity of the meteorological hazard in question can often fail as a proxy for how impactful the weather event might be. Consider two examples of recent extreme weather events that were the subject of event attribution analyses. The first case examines how persistent heavy rainfall caused flooding in the southern United Kingdom in the winter of 2013-14 (Schaller et al., 2016[205]); the second case looks at how extreme rainfall caused flooding over Southern China during the March-July rainy season of 2019 (Li et al., 2021[206]), both summarised in Figure 3.13.

Figure 3.13. Extreme weather hazards versus impacts

	Severity of Weather Hazard	Severity of Event Impacts
China Floods Spring 2019	1-in-10 years	-USD 3 billion in damage -19,000 houses collapsed -83,000 houses damaged -420,000 ha of crop damage -91 deaths
South UK Floods 2013/14	1-in-250 years	-USD 1.5-2.2 billion in damage -11,000 houses damaged -45,000 ha of farmland flooded

Note*:* Schematic representation of the two case study extreme events: the Southern China floods of spring 2019, and floods in the southern United Kingdom of the winter of 2013-14. The size of the coloured circles and boxes respectively represent the relative severity of the weather event itself, and the magnitude of the social, economic or health impacts associated with the event. The event severity is described as a return period, which denotes the probability of witnessing an event of equal or greater severity within any given year.

Floods in southern United Kingdom, 2013-14

The magnitude of the rainfall that fell over southern United Kingdom during the winter of 2013-14 was exceptional (Schaller et al., 2016[205]). According to the UK Met Office (2014[207]), 12 storms passed over the UK region between mid-December 2013 and mid-February 2014, marking the stormiest period in over 20 years. The UK Environment Agency estimated total costs and impacts of the winter 2013-14 floods at USD 1.5-2.2 billion, equivalent to GBP 1.0-1.5 billion in 2014 (Chatterton et al., 2016[208]). Of this, most costs were associated with the 11 000 damaged residential properties. Meanwhile, an estimated 45 000 ha of farmland were flooded during the event. The sequence of back-to-back storm systems was unusual: the rainfall anomalies were described as a 1-in-250 year event for those most heavily affected southern regions (UK Met Office, 2014[207]).

While the impacts resulting from the flooding were significant, they were nevertheless smaller than other UK floods in the previous decade. Indeed, although the autumn floods in 2000 were less severe from a meteorological standpoint (UK Met Office, 2014[207]), their total costs were higher than those of the 2013-14 event (Pall et al., 2011[209]). Meanwhile, the summer floods of 2007 resulted in almost three times the economic impacts as the 2013-14 event. Much of the reduced costs was attributed to improved flood defences and early warning systems in the intervening period (Chatterton et al., 2016[208]).

Floods in China, 2019

During March to July of 2019, Southern China also experienced the impacts of severe weather. A protracted, intense rainy season produced widespread flooding impacts over a highly populated region of the country (Li et al., 2021[206]). While the "first rainy season" typically spans from April to June in this area of China, the onset was some 28 days early in 2019 and also finished 22 days later than usual (Li et al., 2021[206]). This persistent, above-average rainfall culminated in severe flooding impacts during the second week of June. According to the China Ministry of Emergency Management, flooding and landslides directly affected 6 million people. They also led to 91 deaths, the damage or collapse of over 100 000 houses, and damage to some 419 000 ha of crops. In total, the direct costs of the event were estimated at USD 3 billion (Li et al., 2021[206]).

However, a multi-method assessment of the meteorological drivers of the event found it was actually comparably unremarkable, from a statistical perspective. Indeed, Li et al. (2021[206]) estimate the recurrence frequency in today's climate from a 1-in-6 to a 1-in-28 year event, with a central estimate of a 1-in-10 year event. This qualitatively corroborates with a similarly impactful flooding event that affected the same region in 2008.These examples highlight the inherent vulnerability of those exposed to the impacts of extreme weather. In particular, it reveals how relatively common weather hazards can still cause significant and detrimental impacts if they strike vulnerable, exposed communities.

Fortunately, the improved outcomes associated with recurrent floods in the United Kingdom also point to the significant potential for resilience-building measures in climate-vulnerable nations. That is, for many types of extreme weather and regions, the potential for targeted disaster risk reduction measures over the medium term can often counteract any climate change-induced worsening of the hazard over the same period [(Jongman et al., 2015[210]; Kreibich et al., 2017[211]) and explored in Chapter 5].

The opportunities to reduce vulnerability are largest in poorer countries

As highlighted above, the impacts of future extreme weather can often be reduced – even if climate change is making the hazards themselves worse. Targeted measures can improve climate resilience, often via wider improvements in living standards and economic prosperity (Schleussner et al., 2021[212]). These include poverty alleviation health care, social safety and adaptation measures, among others.

Supporting evidence can be found in the widespread reduction in deaths associated with climate extremes as economic prosperity grew over the 20th century (Ritchie and Roser, 2014[213]). The potential for resilience-building measures to alleviate the otherwise-worsening impacts of extreme weather is therefore significant. This is especially true for countries most vulnerable to extreme weather impacts today (Schleussner et al., 2021[212]). Barriers to implementing these measures exist, however, primarily related to governance and finance (Andrijevic et al., 2019[214]).

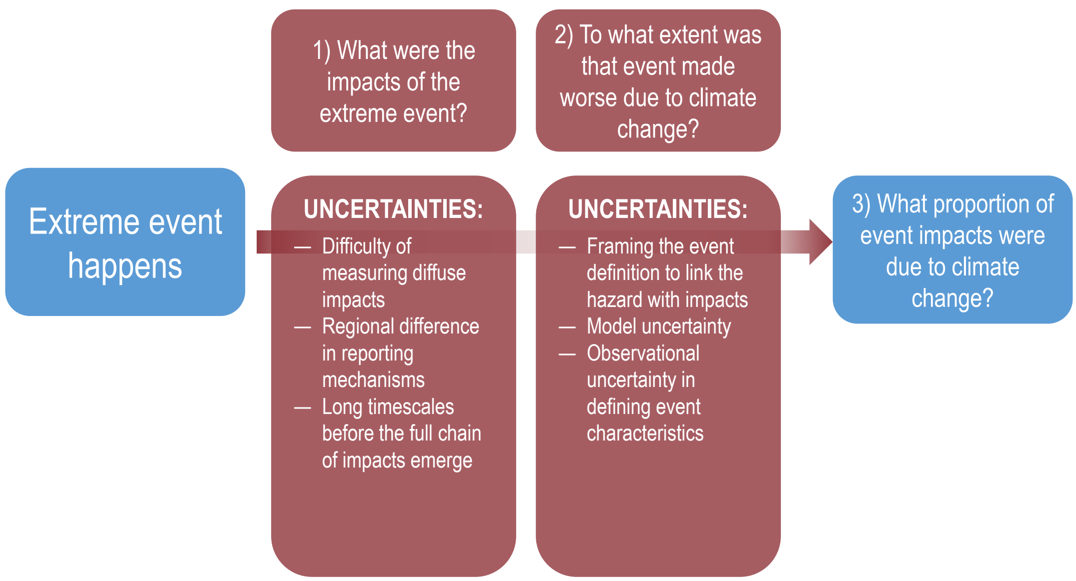
3.5.4. Developing an inventory of extreme weather impacts attributable to anthropogenic climate change

An inventory of the impacts of extreme weather caused by anthropogenic climate change is urgently needed. Such an effort would complement disaster databases, which compile extreme weather impacts without considering whether they were influenced by a warming climate. This disaggregation will help inform future adaptation priorities at the local decision scale (Otto et al., 2015[215]). They will also strengthen the evidence base informing wider policy discussions relating to losses and damages from climate change and climate finance more broadly.

Figure 3.14 proposes a preliminary framework for an inventory of the impacts of climate change from extreme weather in three parts. First, it identifies all possible impacts associated with the extreme weather event in question. Second, it determines the fraction of attributable risk associated with the extreme weather event known to have caused these impacts. Third, it multiplies the two to yield an estimate of the event-related impacts that would have not occurred if an equally rare event occurred in a "world without climate change" (Allen, 2003[216]; Frame et al., 2020[138]; Clarke, E. L. Otto and Jones, 2021[139]).

This framework, of course, abstracts from any consideration of the exposure and vulnerability to that particular hazard. It also does not consider whether earlier policies and decisions influencing these factors could have reduced impacts. Further development of such an inventory could track the evolution of exposure and vulnerability to specific types of hazard to inform efforts to reduce the overall risk of losses and damages.

Figure 3.14. An inventory framework for extreme weather impacts due to climate change



Note: Schematic representation of applying attribution science to develop an estimate of the impacts from extreme weather attributable to anthropogenic climate change. The list of uncertainties associated with each of steps (1) and (2) is discussed further in Sections 2.2 and 2.3, respectively.

As with other branches of climate science, any method to quantify how large-scale, time-averaged signals of climate change translate to the finer scales most relevant for decision making introduces uncertainty (Maraun et al., 2017[217]; Shepherd and Sobel, 2020[218]). This truism applies to the attribution step of the inventory framework conceptualised in Figure 3.14. Moreover, uncertainties are further compounded by other factors relating to the quantification of impacts associated with an extreme event. However, uncertainty alone does not represent a definitive barrier to useful, actionable information (Shepherd, 2019[12]), particularly if that uncertainty is well understood and its drivers separated (Marotzke et al., 2017[219]).

3.5.5. Barriers to understanding impacts and drivers of extreme weather in lower income countries

The benefits of probabilistic attribution are manifold, particularly in offering a method to causally link the impacts of recent extreme weather events with climate change. However, the same methods too often end up with an inconclusive result when considering weather extremes that impact lower income countries. Multiple factors combine to explain why the geographic coverage of attribution studies is heavily skewed towards higher income countries and are discussed elsewhere (Otto et al., 2020[133]; Otto et al., 2020[220]).

Specific impediments to raising the quality and quantity of event attribution studies over lower income countries are detailed below.

1. ***Poor observational records***: Attribution studies are more successful in regions where scientists can quantify the severity of the extreme weather event relative to historical records. The capacity to perform attribution analyses is therefore always going to be limited in regions where observational records either do not exist, are not publicly available, or have short record lengths. In many lower income countries, the limited observational coverage of past weather, both in space and time, fundamentally limits the ability to contextualise the severity of the event, or readily validate the quality of any climate models used.
2. ***Climate model deficiencies***: Many low income countries are located in tropical regions, where extreme weather events are heavily influenced by physical processes (like convection or ocean-atmosphere interactions). These processes are significantly more difficult to adequately simulate in climate models. As an alternative interpretation, climate model simulations require a much higher spatial resolution to achieve comparable levels of quality in the tropics (when compared with higher latitude regions). This is because processes affecting the formation of extreme weather are both more uncertain, and coarse-resolution models simulate them poorly. This adds a further barrier to successfully performing the same quality of attribution study in different parts of the world.
3. ***Modes of internal climate variability affecting extreme flooding and drought***: The signal of climate change for hydrological extremes (like drought and flooding) affecting low-latitude nations is modulated by important modes of natural climate variability (such as the Madden-Julian Oscillation, El Niño-Southern Oscillation and Indian Ocean Dipole). Even if a hypothetical climate change signal in extreme rainfall were uniform for all countries, it would take longer for that signal to be detectable in these tropical countries – of which many are disproportionally low income – by virtue of these large drivers of natural variability in the climate system. These modes of climate variability are also notoriously difficult to simulate in climate models. This places a further constraint on which models can be considered “fit-for-purpose” for an attribution analysis.
4. ***Selection biases***: No systematic method exists for deciding which extreme weather event warrants an attribution analysis. Most attribution studies are initiated on the basis of identifying impactful events that scientists know about. This leads to a preferential focus on those regions for which the impact reporting structures are most robust, information flows immediate and for which weather-related impacts generate international media attention. Moreover, attribution scientists in wealthy countries often derive funding from a national government or meteorological service, which often leads to an emphasis on extreme events within the country of the funder. These factors result in a systematic oversampling of attribution studies for events in wealthy countries, irrespective of whether the data and modelling tools are more suited to that region.
5. ***The detectability of extreme weather impacts***: The most easily-reported extreme weather impacts are damage to insured physical assets post-event – particularly from flooding, wildfires and tropical cyclones/hurricanes. Lower income countries also have lower rates of insurance coverage for the types of physical assets susceptible to extreme weather. This translates to a mismatch in the magnitude of impacts recorded in disaster databases. Similarly, many of the worst outcomes from extreme weather in lower income nations – like droughts – come in the form of diffuse impacts. Such impacts both emerge over time and require more sophisticated monitoring tools to quantify. Combined, these issues further exacerbate the selection biases and inequities in the regional coverage of attribution studies.
6. ***Differences in extreme event impact reporting mechanisms***: Finally, the institutions that report extreme weather impact data to natural disaster databases also differ between lower and higher income nations. Well-resourced governments tend to perform this role directly for higher income countries. By contrast, non-governmental organisations (NGOs) and other aid agencies typically fill this role in lower income nations. The work is by-product of monitoring systems to identify

locations with the greatest need for humanitarian aid. This, however, leads to disparities in the classes of climate event and types of information monitored and subsequently reported. European governments, for example, have developed robust mechanisms to quantify the impacts of extreme heatwaves soon after the event. However, similarly severe events occurring in sub-Saharan Africa often go undetected (Harrington and Otto, 2020[221]) because NGOs can only identify the humanitarian impacts of floods and droughts. As a consequence, most databases of heatwave impacts over the 20th and 21st centuries place an artificial emphasis on European events. This mistakenly implies that no heat-related impacts have occurred whatsoever in many low income nations.

A multitude of research, data and funding gaps need to be addressed to fully understand, quantify and monitor the worsening impacts of extreme weather from climate change. First, extremely large information gaps exist when it comes to quantifying what impacts were actually generated by extreme weather. Targeted support is needed to reduce geographic disparities in the coverage of on-the-ground monitoring programmes. This is equally true for the meteorological characteristics of extreme weather, and the subsequent social, health and economic impacts of these extreme events.

There is an equally urgent need for a systematic, bottom-up reporting system to record the meteorological characteristics of all extreme weather events. Such recordings should have enough detail for a subsequent attribution analysis. A step-change is needed in the way science is resourced, particularly in lower income countries. The barriers to completing an attribution study will always be in these countries. Therefore, higher income countries need to offer both scientific expertise and financial support to ensure robust applications of event attribution science (broadly understood) can be accessible for all countries.

3.6. Cascading impacts of crossing a climate tipping point: Collapse of the Atlantic Meridional Overturning Circulation

Passing tipping points in the climate system, leading to widespread, abrupt and/or irreversible damages, are among the largest risks from climate change (Lenton et al., 2008[4]; Lenton et al., 2019[64]). The IPCC defines a tipping point as an irreversible “level of change in system properties beyond which a system reorganises, often in a non-linear manner, and does not return to the initial state even if the drivers of the change are abated. For the climate system, the term refers to a critical threshold at which global or regional climate changes from one stable state to another stable state.” (IPCC, 2018[5]). Passing tipping points could cause severe social and economic impacts (Lenton and Ciscar, 2012[70]; Lontzek et al., 2015[222]; Cai, Lenton and Lontzek, 2016[68]).

There are multiple subsystems of the Earth’s climate system – termed “tipping elements” (Lenton et al., 2019[64]) – that could pass a tipping point this century under climate change. Examples include a collapse of the AMOC, irreversible shrinkage of the Greenland or West Antarctic ice sheets, disruption of major monsoon systems or dieback of the Amazon rainforest (Lenton et al., 2008[4]; Lenton et al., 2019[64]).

For over a decade, scientific assessment has agreed that several tipping points have significant (~10s of a percentage) probabilities even at low levels of warming. This rises to “more likely than not” (>50%) under unmitigated global warming (Kriegler et al., 2009[66]). The effectiveness of collective action to avoid crossing climate tipping points may still depend on reducing uncertainty about where the tipping points lie (Barrett and Dannenberg, 2014[223]). However, the latest scientific evidence is clear that some tipping points could be crossed within the 1.5-2°C Paris climate target range, with many more at risk under 3-4°C of warming [(Lenton et al., 2019[64]) and Table 3.1]. The diverse impacts of crossing different climate tipping points remain seriously understudied (Table 3.2).

Recent work has also emphasised the risk that crossing one tipping point can increase the likelihood of crossing another, potentially leading to a “cascade” of impacts (Cai, Lenton and Lontzek, 2016[68]; Lenton et al., 2019[64]). In the worst case scenario, such a cascade might lead to a new, less habitable, “hothouse” climate state (Steffen et al., 2018[224]). Interactions could happen through ocean and atmospheric circulation or through feedbacks that increase GHG levels and global temperature (Table 3.2).

Given this context, this chapter focuses on the cascading impacts of a potential collapse of the AMOC, and its cascading effects on other tipping elements. It has chosen the AMOC collapse because it is the most studied tipping element, it connects together the climate system and it could have huge impacts.

3.6.1. Why is the collapse of the AMOC of concern?

A collapse of the AMOC represents a fundamental reorganisation of ocean circulation. It would redistribute heat around the planet and lead to a corresponding coupled response from sea ice and the atmosphere (Box 3.6 explains the AMOC and how its collapse could occur). In the past, the AMOC collapse has resulted in a drastically colder Europe. It has shifted rainfall patterns that made parts of Europe and northern Africa and India drier, and areas in the southern hemisphere wetter. It also profoundly affected marine and terrestrial ecosystems (physical impacts are explored in Table 3.2).

In AMOC weakening scenarios (without total collapse) where deep convection shuts off in the Labrador Sea region, the impacts are still significant (Table 3.2). They can unfold faster than a full AMOC collapse (Drijfhout et al., 2015[225]; Sgubin et al., 2017[226]). These include dynamic effects on sea level, with increases down the eastern seaboard of the United States of around 20 cm in the regions around Boston, New York and Washington, DC (Yin, Schlesinger and Stouffer, 2009[227]). A rise in sea level along the northeast coast of North America was, in fact, observed between 2009-10 – time in which the AMOC had a marked turndown – with the sea level rising 128 mm in New York (Yin, Schlesinger and Stouffer, 2009[227]).

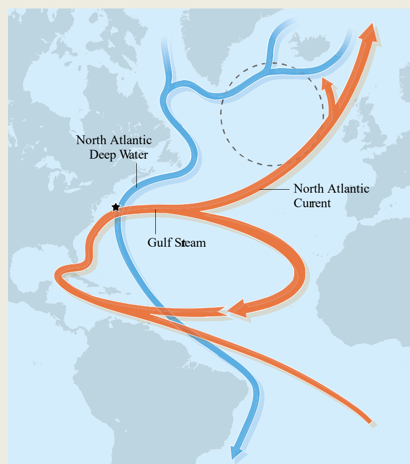
The climate effects may be likened to the Little Ice Age (LIA), a period of significantly colder weather patterns in the northern hemisphere between the 15 and 19 centuries (Moreno-Chamarro et al., 2016[228]). This was one of several centennial-scale climatic oscillations during the present interglacial period. As the most commonly accepted explanation for the LIA, volcanically triggered changes in the AMOC helped amplify internal climate variability (Schleussner and Feulner, 2013[229]). Specifically, changes in freshwater forcing may have reduced the formation of Labrador Sea Water and contributed towards the onset of LIA cooling (Moffa-Sánchez et al., 2014[230]). The AMOC collapse, or the abrupt weakening associated with subpolar gyre (SPG) collapse, could therefore have cascading effects far beyond the parts of the globe where it occurs (Wunderling et al., 2021[69]).

Global warming can slow down the overturning circulation and could trigger a tipping point collapse of the AMOC (Lenton et al., 2008[4]). There are two relevant effects – thermal and haline (salinity). Warming, which is greater in the high latitudes than the tropics, makes high-latitude surface waters less dense. This weakens circulation but is unlikely to collapse it. The bigger risk comes from increased freshwater input making the North Atlantic less salty (Hawkins et al., 2011[231]). Warming tends to increase atmospheric moisture content and high-latitude precipitation that falls directly on the North Atlantic. It also drains off the land into the Arctic basin and North Atlantic. Warming is also causing accelerating melt of the Greenland ice sheet, adding freshwater close to the regions of deep convection.

Box 3.6. What is the AMOC and why does it have a tipping point?

The Atlantic Meridional Overturning Circulation (AMOC) is the Atlantic branch of the thermohaline circulation (THC), which transports heat and salt around the global ocean. The THC, sometimes referred to as the ocean's "great conveyor belt", carries some 30 times more water than all the world's freshwater rivers combined. The AMOC is a system of currents in the Atlantic Ocean that transports heat from the southern hemisphere and the tropics to the northern mid-high latitudes, bringing warm surface water up to Europe (red arrows in Figure 3.15). In the North Atlantic, one arm of the Gulf Stream breaks towards Iceland, forming part of the AMOC that transports heat far northward. As that warm water heads north, it loses heat to the atmosphere, cooling it down. It also evaporates freshwater to the atmosphere, leaving it saltier. Both effects make the surface water denser.

Figure 3.15. The Atlantic Meridional Overturning Circulation



Source: (Praetorius, 2018[232])

On either side of Greenland, the surface waters get cold enough, salty enough, and therefore dense enough to sink to great depth in the ocean through a process known as deep convection. This North Atlantic Deep Water (NADW) formation propels a southward return flow of cold water at depth (blue arrow in Figure 3.15). These cold deep waters eventually return to the surface in the Southern Ocean, completing the loop of the overturning circulation.

The AMOC is self-sustaining due to a process known as the salt-advection (positive) feedback (Cheng et al., 2018[233]). In essence, the circulation itself maintains the salty dense North Atlantic surface waters that can sink to the depths and drive the circulation. The circulation can be shut down, such that the AMOC moves to another stable state (Stommel, 1961[234]). If the AMOC draws in salt at its southern boundary (around 34S in latitude), it is in a regime of "bi-stability" where both "on" and "off" states are stable. Current observational evidence suggests the AMOC is bi-stable at present. Conversely, many climate models are biased too stable in that they do not show net salt input and hence are in a "mono-stable" regime.

The tipping point between "on" and "off" states can be triggered if sufficient freshwater enters the NADW formation there. Once the AMOC has collapsed and is in the "off" state, there is a different tipping point at which the AMOC can be switched back "on". These two tipping points bound the region of "bi-stability" where both states are stable under the same global climate boundary conditions.

Current concern about an AMOC tipping point stems in part from understanding tens of thousands of years of the prehistoric climate record (Barker and Knorr, 2016[235]). In the past, the AMOC has switched on and off repeatedly, triggering rapid changes in temperatures and precipitation patterns around the North Atlantic and beyond (Barker and Knorr, 2016[235]). During the last ice age, there were more than 20 "Dansgaard-Oeschger events" (named after their discoverers) in which the AMOC abruptly strengthened. Some thousand or more years later, it abruptly collapsed, with associated abrupt changes in sea-ice cover and atmospheric circulation patterns (Buizert and Schmittner, 2015[236]). Proxy evidence suggests the subpolar gyre and the AMOC are not completely stable in the current interglacial period, even absent anthropogenic climate change. Section 3.6.2 explores whether and how global warming could affect their stability.

The Greenland ice sheet is melting at the upper end of projections, or about six times faster than in the 1990s. According to one study, the subpolar North Atlantic recently became less salty than at any time in the past 120 years (Holliday et al., 2020[237]). Recent studies have inferred the AMOC has weakened by 15% since the 1950s (Rahmstorf et al., 2015[238]). This manifests itself as a "cold spot" in the ocean to the South of Greenland – the only place on the planet not consistently warming (Caesar et al., 2018[239]). This AMOC slowdown is unprecedented in the past 1 000 years (Rahmstorf et al., 2015[238]; Caesar et al., 2021[240]). Freshwater budgets suggest the largest contribution is coming from increased precipitation in the high northern latitudes. However, meltwater from Greenland is also making a significant and growing contribution (Bamber et al., 2018[241]).

Additional evidence supports the inference of an AMOC slowdown, including an increase in salinity of the South Atlantic in recent decades. This suggests that more of the salt that once travelled north with the AMOC is remaining in the tropics (Zhu and Liu, 2020[242]). Further research has argued that the Gulf Stream along Florida's coast has weakened. It also suggests this weakening has been particularly strong over the past two decades (Piecuch, 2020[243]). Significant early warning signals in multiple independent AMOC indices based on observational data have been found (Boers, 2021[244]).

Although recent research shows the AMOC is at its weakest in a millennium, the latest IPCC AR6 gives medium confidence there will not be an abrupt AMOC collapse before 2100 (IPCC, 2021[14]). The AMOC is "very likely" to further weaken this century. However, collapse within the 21st century is deemed very unlikely, but physically plausible (Douville et al., 2021[245]). This is partly limited by the clause that collapse must complete during this century. There is a different interpretation to model results used by IPCC. Collapse of the AMOC occurs in one model at 1.4°C warming relative to pre-industrial global temperatures, in two additional runs of the same model at 1.6-1.9°C, and in two runs of a different model at 2.2-2.5°C (Drijfhout et al., 2015[225]; Sgubin et al., 2017[226]). Furthermore, IPCC models have been found to be biased too stable with respect to observational constraints. Correcting for this bias leads to the AMOC collapse under a doubling of CO_2 in one model (Liu et al., 2017[246]).

The present report considers the possibility of an AMOC collapse at 2-3°C global warming above pre-industrial temperature to be a significant risk worthy of assessment. Such a collapse is consistent with earlier expert elicitation (Kriegler et al., 2009[66]). Furthermore, the impacts of expected AMOC weakening are a scaled down version of those from total collapse. Hence, an impact assessment is useful for both eventualities. Even if a complete AMOC collapse does not occur, a collapse of deep convection in the North Atlantic SPG, and associated abrupt weakening of the AMOC, would still have major impacts (Sgubin et al., 2017[226]; Swingedouw et al., 2021[247]). In this scenario, deep convection shuts off in the Labrador Sea region and is left only in the Greenland–Iceland–Norwegian Seas.

This analysis assesses the above scenario to be "as likely as not" (33-66% probability) at 1.5-2°C global warming above pre-industrial temperatures. The assessment is based on this probability occurring in three climate models at 1.1-1.4°C, in five additional runs across four models at 1.6-1.9°C and with a further instance at 2.0°C (Drijfhout et al., 2015[225]; Sgubin et al., 2017[226]). In this section, state-of-the-art climate model experiments (refer to Annex 3.A for detailed methodology) are used to examine the impacts of an

AMOC collapse and how it interacts globally with other tipping elements in the climate system to either increase or decrease their likelihood.

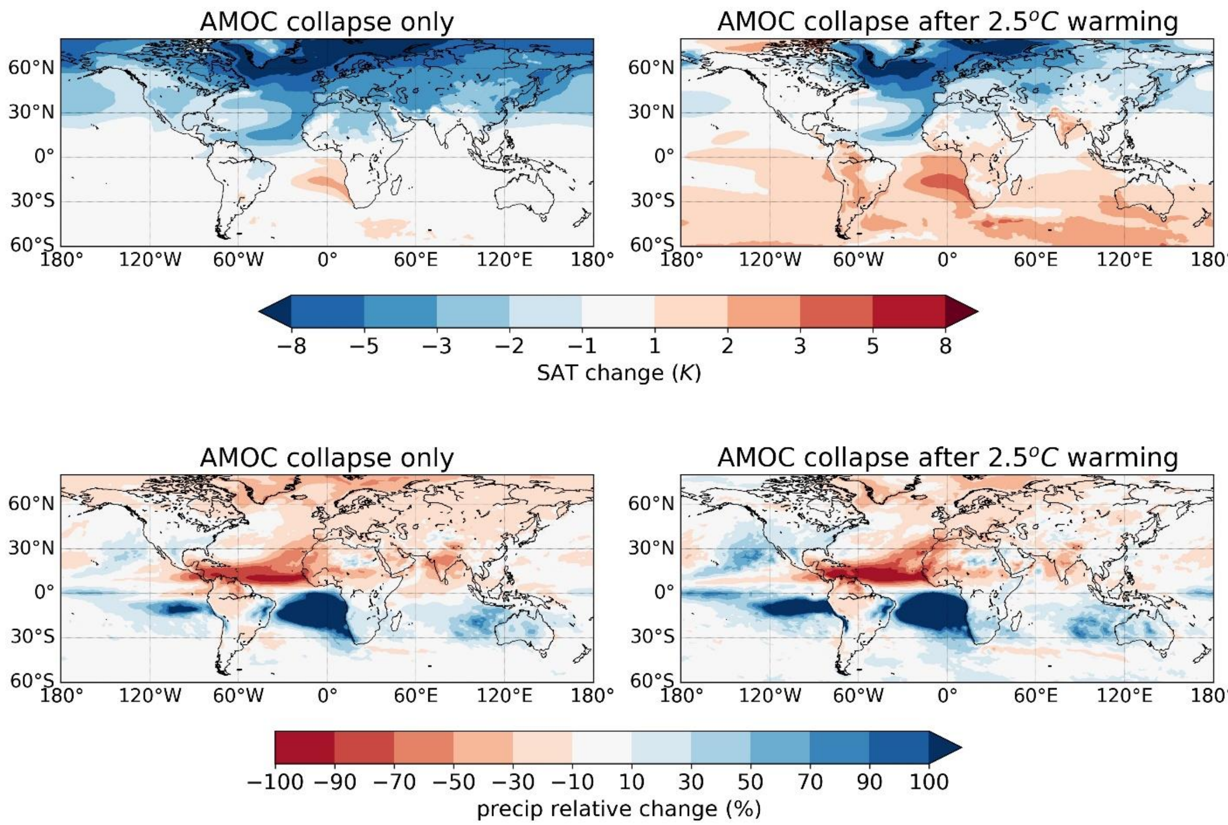
3.6.2. Climatic impacts of an AMOC collapse and cascading effects on other tipping elements

Surface air temperature and precipitation

A collapse of the AMOC on its own (without underlying warming) would lead to large-scale climatic impacts globally (Jackson et al., 2015[248]; Mecking et al., 2016[249]). The left column of Figure 3.16 provides temperature and precipitation responses. The top left panel illustrates that an AMOC collapse (without underlying warming) would lead to widespread cooling across the northern hemisphere, with the more extreme consequences farther north. Specifically, Europe would observe a drop of 3°C to 8°C in annual mean surface air temperature. For its part, North America would experience a less severe decline of 1°C to 3°C. In contrast, there is little temperature change in the southern hemisphere – only a small increase in temperature in the Atlantic Ocean off the southwestern coast of Africa.[7]

Large equatorial anomalies in precipitation correspond to a southward shift of the Intertropical Convergence Zone (ITCZ) under a collapse of the AMOC (Figure 3.16, bottom left panel). Most of the northern hemisphere experiences a drying with the exception of North America, which becomes slightly wetter on average. India would lose more than half of its current rainfall if the AMOC were to collapse. This suggests a significant disruption to the Indian summer monsoon, affecting the livelihood of millions of people as well as the regional economy (Gadgil and Gadgil, 2006[250]). The bottom left panel of Figure 3.16 also indicates a significant drying in the Amazon basin.

Figure 3.16. Surface air temperature and precipitation response to an AMOC collapse alone and an AMOC collapse after 2.5ºC warming above pre-industrial



Note: Surface air temperature (SAT, top row) and precipitation (bottom row) response to AMOC-collapse scenarios. Left column, the climatic impacts of just an AMOC collapse without the additional global warming most likely to accompany a collapse in any realistic future scenario is isolated. The isolated impacts of an AMOC collapse are analysed by taking the difference of 30-year means of the control run and the AMOC-off run, once the simulation is approximately stationary, performed by the HadGEM3-GC2 model. Right column, the analysis is expanded to include the impacts of an AMOC collapse against a more realistic future climate state, accounting for the additional effects of global warming using the future scenario SSP1-2.6 in the model HadGEM3-GC31-MM. The forcing scenario SSP1-2.6 refers to Shared Socio-economic Pathway SSP1 and Regional Concentration Pathway RCP2.6 - a low-emissions pathway with high sustainability. Under the SSP1-2.6 scenario, HadGEM3-GC31-MM reaches a mean global warming of 2.5°C above pre-industrial levels by the end of the century (2071-2100). This warming pattern is overlaid to the impacts of an AMOC collapse to establish the overall impact if the AMOC were to collapse after 2.5°C global warming relative to the present-day climate (2006-35).

The left column of Figure 3.16 highlighted the direct impacts from an AMOC collapse alone. Conversely, the right column shows the impacts in a more realistic scenario of an AMOC collapse after 2.5ºC warming since pre-industrial conditions relative to the present-day climate (see Annex 3.A). Overlaying this warming trend (top right panel) shows contrasting temperature responses between the northern and southern hemispheres. The northern hemisphere still displays a widespread cooling (particularly over the North Atlantic) although mitigated partly due to the underlying warming.

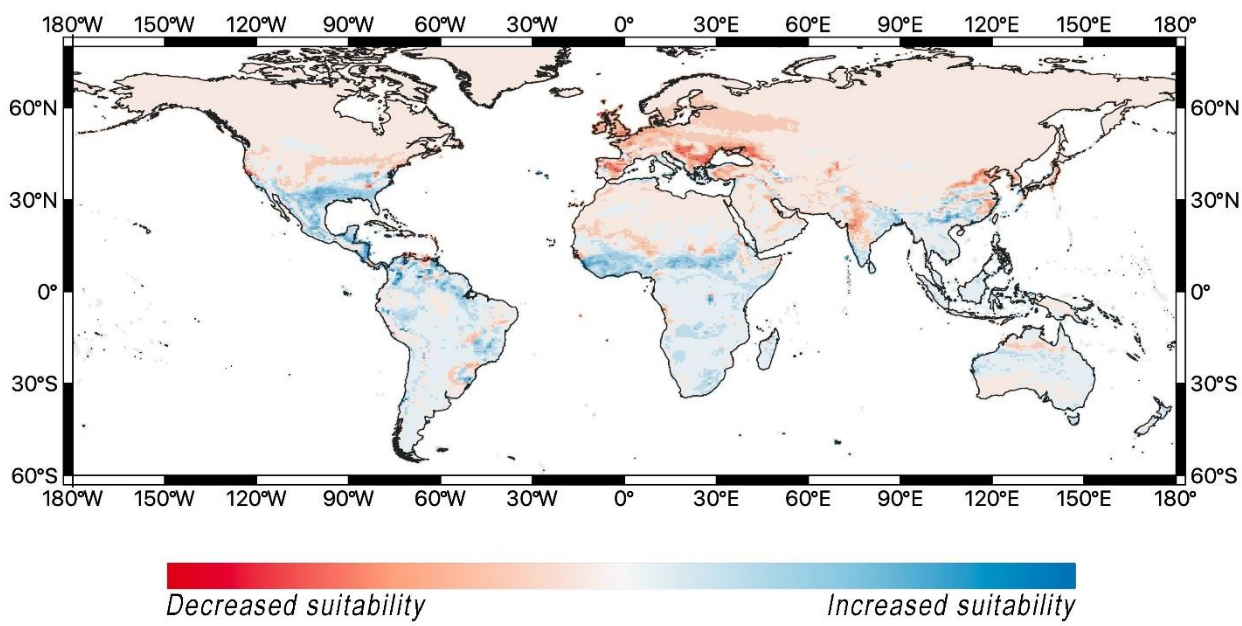
Conversely, the southern hemisphere continues to experience widespread warming due to the underlying warming trend, largely unaffected by an AMOC collapse. Interestingly, the precipitation patterns and size of anomalies are mainly unchanged from just considering an AMOC collapse alone. The main differences are less drying over Asia, but more drying in the tropics of the Atlantic Ocean for an AMOC collapse after 2.5ºC warming.

Climate niche

The results of Xu et al. (2020[251]) provide an illustrative indication of impacts of an AMOC collapse on climate "suitability" for humans. The study showed that humans, like all species, have an "apparent climate niche". In this niche, population density peaks (both now and at different times in the past). The climate niche is characterised by a major mode centred on ∼11 °C to 15 °C mean annual temperature (MAT) and ~1 000 mm mean annual precipitation (MAP), with a secondary mode at ~25 °C (Xu et al., 2020[251]). Many other social factors influence human population density. Further, there is remarkable consistency in the distribution of population density with respect to climate over millennia (Xu et al., 2020[251]). This may in part reflect historical contingency – people simply live where others have lived before. Nevertheless, food production clearly depends on climate. Moreover, the density of crop production and animal rearing with respect to climate is strikingly similar to the density of people (Xu et al., 2020[251]).

As discussed above, a collapse or weakening, of the AMOC will lead to changes in temperature and precipitation, geographically shifting the apparent climate niche for humans. Previously, Xu et al. (2020[251]) examined the effect of global warming moving the apparent climate niche. The analysis here considers the effects of an AMOC collapse in isolation, and on top of global warming. The pre-industrial population density distribution is used as a baseline for constructing the human climate niche. The population density distribution with respect to MAT and precipitation is assumed to sum to unity, providing a normalised measure.

Figure 3.17. The modelled change in the human climate niche following the simulated collapse of the AMOC

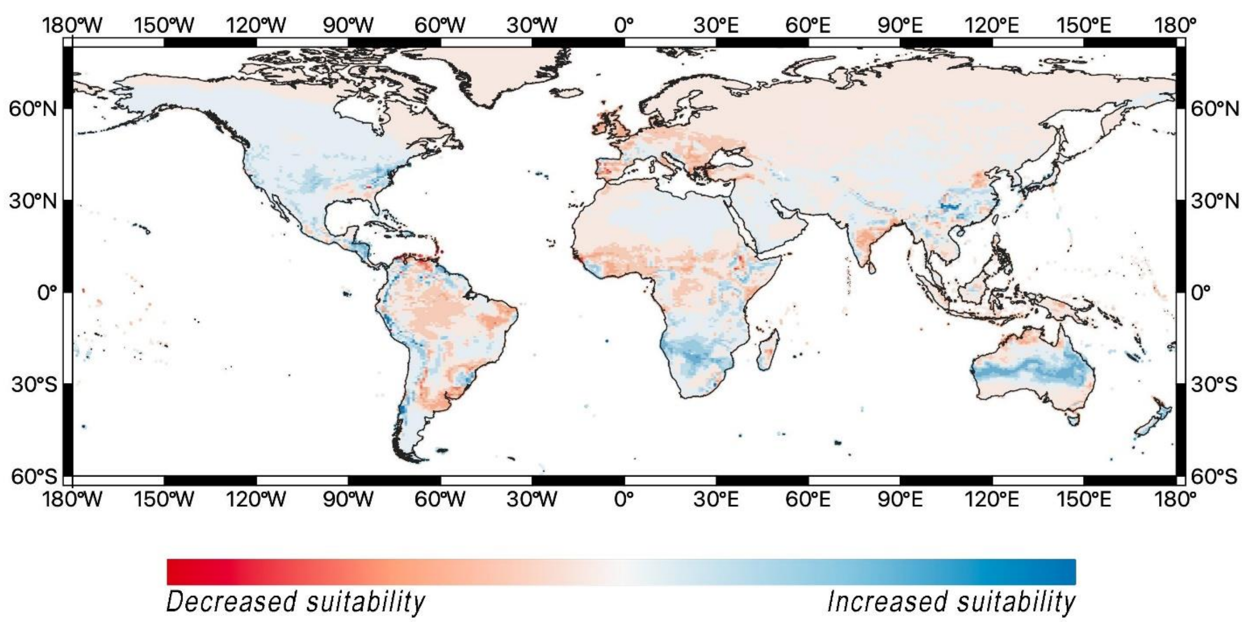


Note*:* The isolated impacts of the AMOC collapse without any additional warming. This is a theoretical simulation as additional warming would be necessary to trigger the collapse of the AMOC. The change in the human climate niche is presented as the difference between the calculated climate niche for the AMOC-on control run and the climate niche after the simulated collapse of the AMOC. The control scenario is representative of a pre-industrial world. The climate niches are calculated using 30-year means of the control run and the AMOC-off run, once the simulation is approximately stationary, performed by the HadGEM3-GC2 model.

Changes in climate "suitability" are then calculated as the proportions of summed niche gain or loss. The global "suitability" for human populations in AMOC-on and AMOC-off scenarios (Figure 3.17) are then mapped. The projected geographical shift of "suitable" conditions is substantial. Conditions deteriorate in some regions but improve in others (Figure 3.17). Regions south of the equator would mostly become more “suitable”. Sub-Saharan Africa, as well as Central and South America, would see the largest gain in “suitability”. On the other hand, a collapse of the AMOC would result in a reduction in “suitability” in the Global North: across Europe, the United States and northern Africa.

The SSP1-2.6 low-carbon emissions pathway reaches a mean global warming of 2.5°C above pre-industrial levels by the end of the century. If these impacts are added to those of the AMOC collapse, the results show some marked differences to the effect of the AMOC collapse in isolation. Europe, the region most influenced by the warming effect and the precipitation brought by the Gulf Stream, would have the largest decrease in climate “suitability”. While North America would mostly become more “suitable”, large chunks of South America, particularly Brazil, would become less suitable. The decrease in suitability in Brazil is largely due to two factors: a change in precipitation patterns and the effect of global warming, which is further amplified by the AMOC collapse in the Global South. Much of Africa would have only a mild increase or decrease in “suitability”. However, including warming markedly changes the picture for central Africa. There, SSP1-2.6 warming would lead to a decrease in suitability. This effect is amplified by the southern hemisphere warming due to a collapse of the AMOC (Figure 3.18).

Figure 3.18. The modelled change in the human climate niche following the simulated collapse of the AMOC after 2.5ºC warming above pre-industrial temperatures according to SSP1-2.6



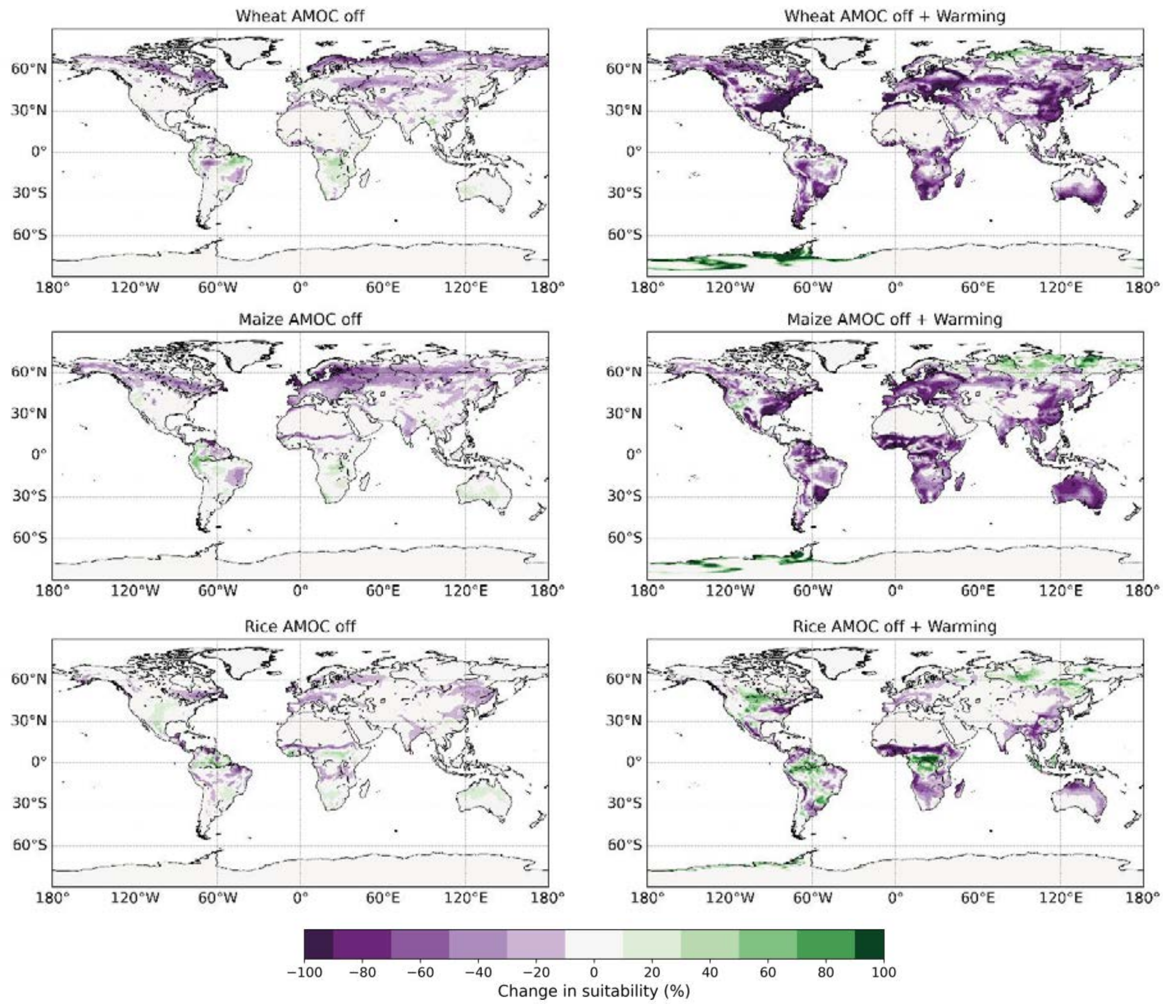
Note: The impacts on the suitability of climate for human populations for a more realistic scenario involving the AMOC collapse triggered by 2.5°C warming above pre-industrial according to scenario SSP1-2.6. The change in the human climate niche is presented as the difference between the calculated climate niche for the AMOC-on control run and the climate niche after the simulated collapse of the AMOC. The control scenario is representative of a pre-industrial world. The climate niches are calculated using 30-year means of the control run and the AMOC-off run, once the simulation is approximately stationary, performed by the HadGEM3-GC2 model. The effects of the AMOC collapse are overlaid over the additional effects of global warming according to the SSP1-2.6 scenario run in the HadGEM3-GC31-MM model. The forcing scenario SSP1-2.6 refers to Shared Socio-economic Pathway SSP1 and Regional Concentration Pathway RCP2.6 – a low-emissions pathway with high sustainability. Under the SSP1-2.6 scenario, HadGEM3-GC31-MM reaches a mean global warming of 2.5°C above pre-industrial levels by the end of the century (2071-2100). This warming pattern is overlaid to the impacts of an AMOC collapse to establish the overall impact if the AMOC were to collapse after 2.5°C global warming relative to the present-day climate (2006-35).

The simplicity of this approach is appealing but has inherent limitations. While the success of human societies is linked in complex ways to climate (Carleton and Hsiang, 2016[252]), climate alone cannot predict where and which societies will thrive. Furthermore, populations in a location are historically adapted to climate. Changes thus pose their own challenges, even if the climate is nominally becoming more “suitable” in a particular location. Therefore, the geographical shift in the human climate niche shown here should not be taken as a prediction of human migration or loss of the ability for humans to thrive in a particular region. Rather, it illustrates the potential large-scale impacts of the collapse of the AMOC both in isolation and in the context of a global warming scenario.

Effect on agriculture

In this sub-section, a more detailed “niche” based approach assesses effects on climate suitability for the major staple crops of wheat, maize and rice. The major staple crops of wheat, maize and rice provide over 50% of global calories (FAOSTAT, 2021[253]). The growth suitability of these crops is assessed with ECOCROP data on the optimal temperature, precipitation and growing season length. A location is deemed suitable for crop growth for a given year if it has temperature and precipitation within the ECOCROP bounds for the growing season length of the crop. The proportion of the 150 years with climate suitable for crop growth for the growing season length is examined. The same is then performed for the AMOC-off run, and the AMOC-off run with the added warming. The analysis shows that an AMOC collapse reduces suitability for wheat, although there are areas of increase (see Figure 3.19 and Figure 3.20). Maize suitably declines across Europe and Russia and the higher latitudes of North America, but increases in parts of South America, southern Africa and Australia. Changes in rice suitability follow a similar pattern but over a smaller area.

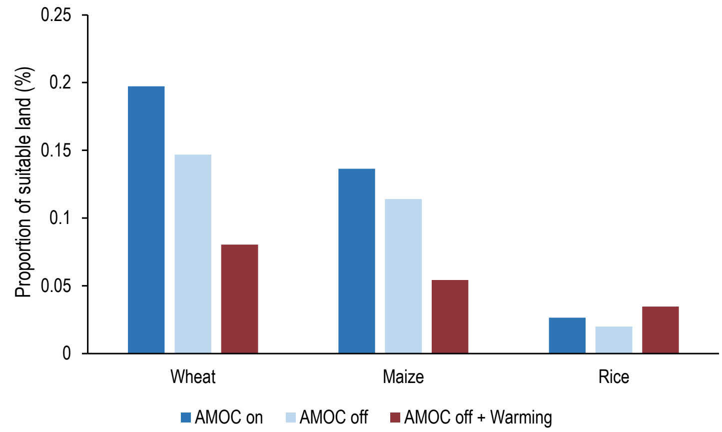
Figure 3.19. Differences in crop growing suitability between AMOC-on and AMOC-off, and AMOC-off plus warming



Note: Differences shown here are the AMOC-on suitability (percentage) minus either the AMOC-off or AMOC-off plus warming suitability.

To summarise these changes, the percentage of land that would have a suitability greater than 90% in each of the three cases is calculated (see Figure 3.19 and Figure 3.20). With AMOC-off but no warming, ~5% of the land loses suitability for wheat. This corresponds to a loss of nearly a quarter of the current suitable area. Meanwhile, ~2% of the land becomes unsuitable for maize (a loss of 16% of the currently suitable area). Rice experiences a smaller change. When climate change is also considered, approximately half of the remaining suitable land is lost for wheat and maize. For rice, there is a modest increase in suitable area, exceeding that in the baseline state. However, gains in suitable area for rice cultivation are dwarfed by losses in suitable area from wheat and maize. This analysis does not overlay the subset of areas where each crop is actually grown. However, an AMOC collapse would clearly pose a critical challenge to food security. Such a collapse combined with climate change would have a catastrophic impact.

Figure 3.20. Bar chart showing the percentage of total land grid boxes suitable for crop growth in each simulation



Note: Here, a location is considered suitable for crop growth if more than 90% of the 150 years analysed are suitable, as detailed in the main text. AMOC off refers to AMOC-off without warming included.

Climate analogues

The change induced by a collapse or slowing down of the AMOC can also be quantified. A number can be identified by comparing the projected climate of some major cities to the current climate to find climate analogues (Table 3.4). The statistical technique of "climate analogues" quantifies the similarity of a location's climate relative to the climate of another place and/or time. Similarity is calculated using the mean temperature and total precipitation for averaged monthly values. Using climate analogue analysis, the 14 selected cities generally shift towards colder climates. There is a much larger impact on cities in the northern hemisphere than in the southern hemisphere. European cities are more impacted than North American cities with a high degree of cooling.

With the inclusion of the SSP1-2.6 warming, some cities shift towards warmer analogues. Conversely, in the AMOC collapse-only scenario, all cities examined shifted towards colder climates. However, many of the cities show a similar climate shift both with and without warming. This is largely due to the influence of changes in precipitation on which the AMOC exerts the dominant influence.

Table 3.4. Climate analogues for the isolated effects of a simulated AMOC collapse for 14 major cities

AMOC-on control			Analogue – AMOC collapse		
City	*T*(°C)	*P*(mm yr-1)	Nearest city	*T*(°C)	*P*(mm yr-1)
Amsterdam	10.3	798.0	Aleutian Islands, Alaska, US	6.0	725.9
Bangkok	29.0	889.4	Addis Ababa, Ethiopia	28.2	890.7
Berlin	9.3	651.2	Stockholm, Sweden	5.6	534.9
Cape Town	18.0	551.7	Cape Town, South Africa	18.9	813.8
Istanbul	14.7	963.0	Ghent, Brussels	11.5	773.1
London	10.4	717.1	Aleutian Islands, Alaska, US	6.1	607.4
Miami	24.5	1135.7	Jacksonville, Florida, US	23.5	1 191.8
Nairobi	20.1	1228.6	Nairobi, Kenya	20.0	1 339.6
New York	12.1	1562.3	Providence, Rhode Island, US	10.3	1 617.4
Paris	10.8	748.5	Copenhagen, Denmark	7.2	626.1
Rio de Janeiro	23.3	1258.2	Rio de Janeiro, Brazil	22.8	1 341.3
San Francisco	16.2	1291.1	San Francisco, California, US	14.9	1 401.5

Note: Climate analogues are calculated employing a statistical model that quantifies the similarity of climates based on average monthly temperatures and precipitation rates. Analogues are calculated by comparing the climate of the target city in the AMOC-collapse run with the climate of cities in the AMOC-on control run to determine an AMOC-on analogue for each target city in the collapsed AMOC scenario. This generates a set of co-ordinates for the closest climate analogue. Analogue cities are picked as the closest large city to the set of analogue co-ordinates. Temperatures are presented as the average annual temperatures for each target city for the AMOC-on control run and for the analogues in the AMOC-collapse run. Precipitation is presented as the average annual cumulative precipitation for each target city for the AMOC-on control run and for the analogues in the AMOC-collapse run.

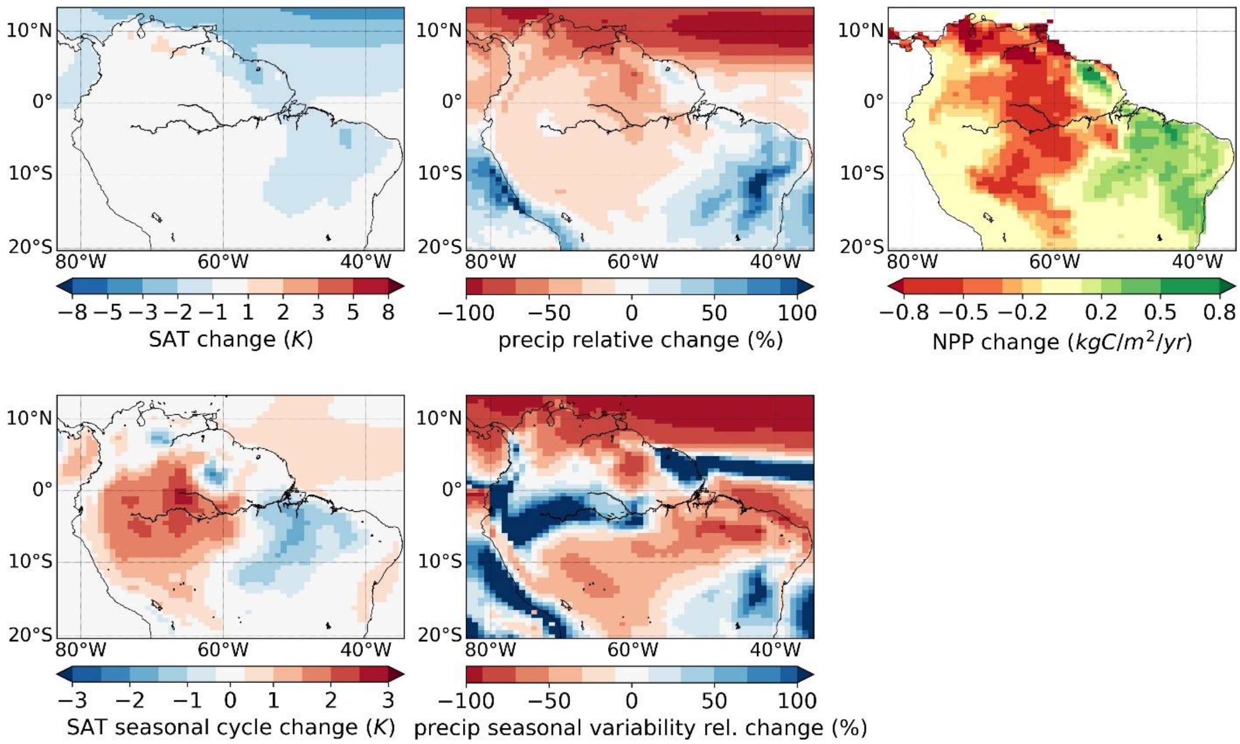
Potential cascading effects – triggering other tipping points

As the AMOC is the "great connector" in the climate system, its collapse could trigger tipping cascades (Wunderling et al., 2021[69]). This sub-section examines the impact of an AMOC collapse on other recognised tipping elements, namely the Amazon rainforest, boreal forests, and the monsoon systems of India and West Africa [for the effect on ENSO see Williamson et al. (2017[254])].

Amazon rainforest

The AMOC collapse would have a cascading effect on the Amazon rainforest, which has been suggested as another climate tipping point (Lenton et al., 2008[4]). Dieback of the rainforest would have global implications due to the loss of carbon storage, as well as other considerations. These include loss of biodiversity and a change in precipitation patterns (Cox et al., 2004[255]). As seen previously, changes in climate can be found within the Amazon basin. In particular, a shift in the ITCZ caused a southward shift in precipitation. The following sub-section looks in more detail on the potential effect of this shift on the rainforest.

Figure 3.21. Impacts of an AMOC collapse on the Amazon rainforest

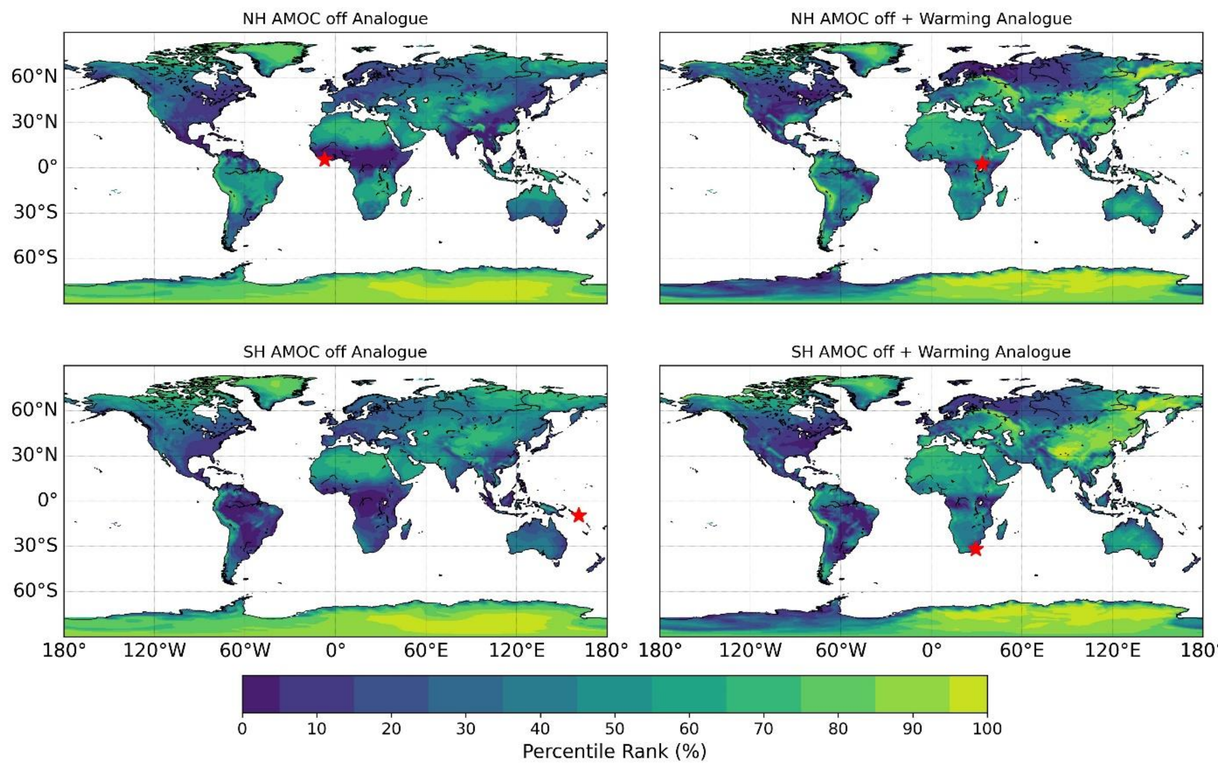


Note*:* Climatic impacts on the Amazon rainforest following an AMOC collapse without the additional global warming most likely to accompany a collapse in any realistic future scenario is isolated. The isolated impacts of an AMOC collapse are analysed by taking the difference of 30-year means of the control run and the AMOC-off run, once the simulation is approximately stationary, performed by the HadGEM3-GC2 model. Climatic impacts include surface air temperature (SAT, left column) anomaly (top) and seasonal cycle amplitude anomaly (bottom); precipitation (middle column) anomaly (top) and seasonal variability change (bottom); 8°C anomaly (NPP, right).

Figure 3.21 indicates the impact of an AMOC collapse alone on the Amazon rainforest without any underlying warming trend applied. Despite little change to the annual mean surface air temperature over the Amazon basin, the seasonal cycle increases by up to 2°C after a collapse of the AMOC. Additionally, precipitation reduces by up to 50% as does the seasonal variability in the precipitation. These changes indicate an extension to the dry season combined with more extreme temperatures, which would ultimately cause large-scale dieback. Although there is no dynamic vegetation within the model run,[8] the net primary productivity (NPP) would suggest that dieback tipping is likely. Specifically, NPP decreases by more than 0.5kgC/m^2/yr over much of the Amazon. It even approaches a drop of 1kgC/m^2/yr in northern regions of the Amazon. On the other hand, the NPP increases east of the Amazon, largely due to more precipitation and a small drop in annual mean temperature in the region.

The climate analogue of the AMOC is analysed to help determine what sort of vegetation will be found in the Amazon with an AMOC collapse. To that end, the analysis examines the land grid boxes in the AMOC-on run that most closely match the precipitation and temperature mean annual cycles from the Amazon basin. Because of the change in seasonality across the equator, the analysis is run separately for the northern and southern hemispheres.

Figure 3.22. Climate analogue analysis for temperature and precipitation, for the northern hemisphere and southern hemisphere Amazon basin



Note*:* Climate analogue analysis for temperature and precipitation, for the northern hemisphere (NH; top row) and southern hemisphere (SH; bottom row) Amazon basin; NH: northern hemisphere; SH: southern hemisphere. Red stars show the closest climate to the AMOC-on Amazon NH/SH climate.

Figure 3.22 shows the climate analogue analysis for both the northern hemisphere (top) and southern hemisphere (bottom) for an AMOC collapse in isolation (left) and combined with climate change (right). Darker colours refer to grid boxes that have a closer AMOC-on climate to Amazon AMOC-off climate, with the red star showing the closest climate in each instance. With an AMOC collapse in isolation there is not much change in temperature in the Amazon, but precipitation patterns are very different.

When combining the above effects, this analysis finds the Sahel is the closest climate analogue for the northern hemisphere, and the Solomon Islands for the southern hemisphere. When future climate change is combined with an AMOC collapse, the overall pattern of climate analogue ranking remains broadly similar. However, the closest analogue moves to East Africa for the northern hemisphere Amazon and to South Africa for the southern hemisphere Amazon. This analysis supports the inferences made above that the biome would be transformed away from a rainforest state.

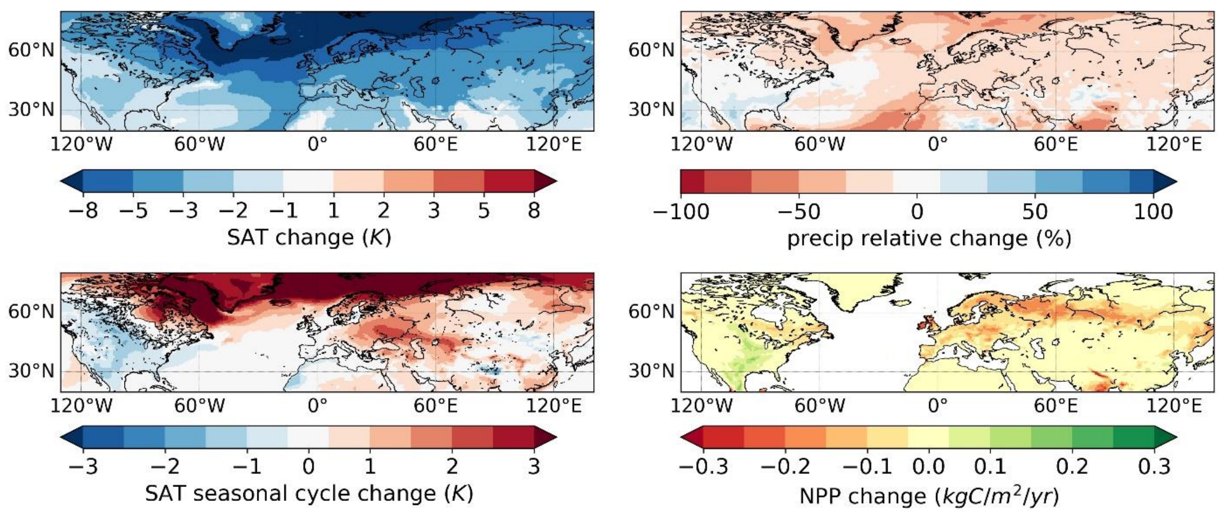
Boreal forests

The boreal forests in North America and north Europe/Asia remove carbon from the atmosphere and help limit global warming. Under an AMOC-collapse scenario without underlying warming (Figure 3.23), the boreal forests over Europe and Asia respond differently to those in North America. As previously discussed, there is a widespread cooling over the northern hemisphere, though Europe and Asia will experience stronger cooling compared to North America. The amplitude of the seasonal cycle increases in Europe and Asia, pointing towards greater cooling to winter temperatures than to summer temperatures.

Conversely, the amplitude of the seasonal cycle decreases in North America, resulting in bigger impacts to summer temperatures.

Opposite responses between the two regions are also observed in the precipitation. There would be widespread drying across Europe and Asia, but in North America precipitation would increase. This leads to a negative impact on the NPP of boreal forests in Europe and Asia and therefore a possible tipping event. In eastern Canada, NPP also declines, but productivity increases further south in the United States. This would suggest a stabilising effect to the boreal forests with the possibility of a southward advance.

Figure 3.23. Potential impacts of an AMOC collapse on boreal forests



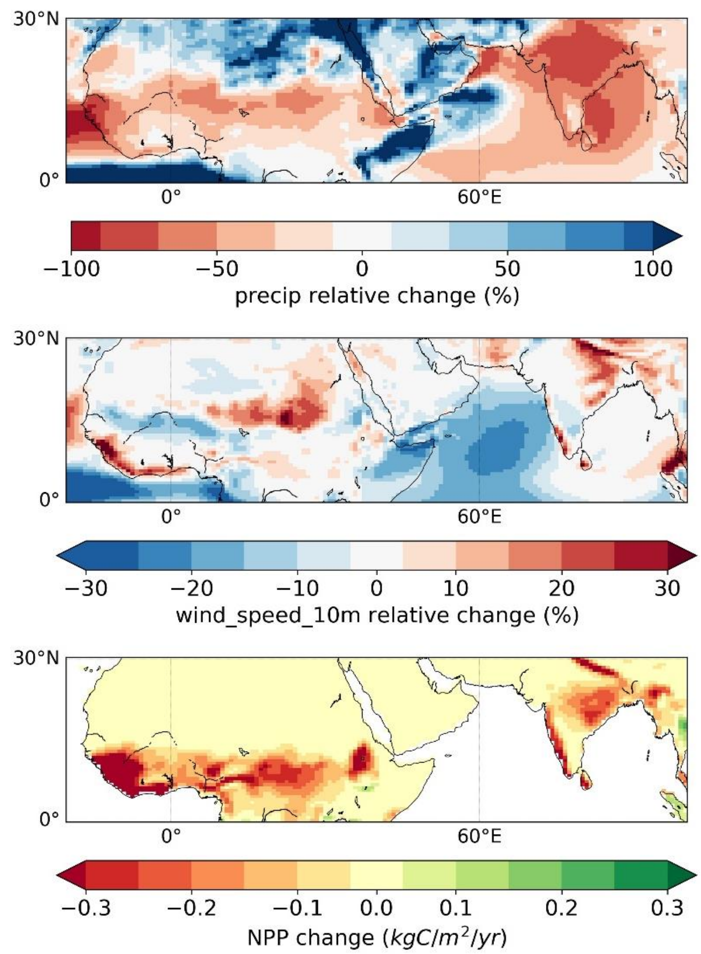
Note*:* Climatic impacts on boreal forests following an AMOC collapse without the additional global warming most likely to accompany a collapse in any realistic future scenario is isolated. The isolated impacts of an AMOC collapse are analysed by taking the difference of 30-year means of the control run and the AMOC-off run, once the simulation is approximately stationary, performed by the HadGEM3-GC2 model. Climatic impacts include surface air temperature (left column) anomaly (top) and seasonal cycle amplitude anomaly (bottom); precipitation relative change (top right); net primary productivity anomaly (NPP, bottom right)

Monsoon systems

As the main driver of the Indian summer monsoon, the land warms faster than the ocean during the summer, creating a temperature gradient that generates winds. These winds, emanating from the Indian Ocean, contain moisture that falls as precipitation once over land. Precipitation releases latent heat that increases the temperature over land and therefore amplifies the monsoon winds (Levermann et al., 2009[256]). The African monsoon is strengthened when northern hemisphere summer insolation is high (Rossignol-Strick, 1985[257]). A collapse of the AMOC would result in reduced northern hemisphere temperatures and therefore a weakening of the African monsoon.

Figure 3.24 suggests a collapse of the AMOC alone would disrupt both the Indian summer monsoon and the African monsoon. The summer (JJA) wind speeds over the Indian Ocean and western Atlantic will be significantly reduced. Weaker winds coming off the oceans will consequently carry less moisture and therefore summer precipitation over the land is vastly reduced – in north India, summer precipitation decreases by more than 70%. Weaker winds and less rainfall also negatively affect productivity. Reduced productivity, in turn, impacts the ability of farmers to grow crop. Therefore, a disruption to the monsoon season would have negative implications for millions of livelihoods.

Figure 3.24. Summer (JJA) impacts of an AMOC collapse on the West African and Indian monsoons



Note*:* Summer (JJA, June-July-August) climatic impacts on the West African and Indian monsoons following an AMOC collapse without the additional global warming most likely to accompany a collapse in any realistic future scenario is isolated. The isolated impacts of an AMOC collapse are analysed by taking the difference of 30-year means of the control run and the AMOC-off run, once the simulation is approximately stationary, performed by the HadGEM3-GC2 model. Climatic impacts include precipitation relative change (top); wind speed at 10 m relative change (middle); net primary productivity anomaly (NPP, bottom).

3.6.3. Summary findings

Socio-economic implications and impacts

Serious weakening or the shut-off of the AMOC and the resulting climatic shift would have profound implications. This is especially the case for the landmasses and the people occupying those landmasses around the North Atlantic. The climate changes induced by an AMOC collapse (and global warming) would affect ecosystems, as well as human health, livelihoods, food security, water supply and economic growth in many ways. These changes are summarised below.

Economic shocks

A collapse of the AMOC may lead to a substantial reduction in global economic output and exacerbate global economic inequalities. As detailed above, a possible shutdown of the AMOC would have global impacts on climate "suitability". Burke, Hsiang and Miguel (2015[258]) show how overall economic productivity depends nonlinearly on temperature. It gives a peak in productivity at an annual average temperature of 13.6ºC. This is comparable to the peak of population density identified by Xu et al. (2020[251]).

However, the impact of an AMOC collapse cannot be adequately characterised by a derived relationship of current temperature to current productivity. This relationship only considers economic activities directly exposed to the weather (Keen et al., 2021[259]). Several studies have taken such an approach [e.g. (Tol, 2009[260]; Link and Tol, 2010[261]; Anthoff, Estrada and Tol, 2016[262])]. They consider only the overall change in temperature from global warming and an AMOC collapse combined. However, one would follow the other, each with its own impacts. Many impacts are associated with changes in other aspects of climate than temperature, notably the water cycle.

Some studies have even argued that an AMOC collapse would have a net economic benefit. For the reasons detailed above, this seems untenable. Other research has speculated on the past influence of the AMOC on the concentration of geopolitical power and wealth in the North Atlantic region (Railsback, 2017[263]). However, such "climate determinism" is widely contested.

An exploration of the potential economic impacts of the collapse of the AMOC (or the tipping of any other climate tipping point) centres not on theoretical effects on human productivity due to climate, but on the physical drivers. In passing tipping elements, the spatial patterns and modes of temporal variability of the climate could change drastically (Lenton and Ciscar, 2012[70]; Rodgers et al., 2021[264]). If such drastic changes were to happen, drawing on inferences from the current spatial-temporal pattern (which societies have had centuries to adapt to) would be useless (Keen et al., 2021[259]).

Effect on agriculture

The collapse of the AMOC would have a huge impact on agriculture globally. Much of the northern hemisphere would become less suitable for growth of many staple crops. However, Europe would be particularly affected. The AMOC makes Europe both warmer and wetter than it would be otherwise. If the AMOC weakened or collapsed in the coming decade as a consequence of further warming, Europe's seasonality would strongly increase. This, in turn, would lead to harsher winters, and hotter and drier summers.

This shift in Europe's climate is projected to reduce agricultural productivity and render most land unsuitable for arable farming. Consequently, the climate would be less suitable for the growth of maize and wheat (with the exception of wheat growth in the United Kingdom). This may lead to an increase in food prices. Conversely, the southern hemisphere would have an increase in suitability for rice growth. This would be especially the case in South East Asia, where rice is one of the main staple crops produced in the region. However, this growth is not analysed within the context of a potential failure of the Asian monsoon, which could have detrimental effects on agriculture throughout Asia.

Amazon rainforest

Changes in sea-surface temperature and rainfall patterns in the tropical Atlantic will impact the stability of the Amazon. Previous research found the global warming and an AMOC collapse processes are likely to have competing impacts on the rainfall in the Amazon (Ciemer et al., 2021[265]). The study further concludes that the tipping of the AMOC from the strong to the weak mode may have a stabilising effect on the Amazon rainforest. Changes in precipitation in the data used in the present analysis reveals a general decrease across the basin.

In terms of the effect from an AMOC collapse alone, Ciemer et al. (2021[265]) find significant decreases in rainfall. These decreases are not countered by changes in climate. However, without dynamic vegetation used in the model, local hydrological effects cannot be ruled out. Climate analogues that consider both temperature and precipitation find the future climatology of the Amazon region to match current savannah or grasslands type regions in Africa. This suggests loss of the rainforest. A conversion of 40% of the Amazon rainforest to savannah would result in a loss of approximately 90 gigatonnes (Gt) of CO_2 stored in the vegetation. Conversely, full conversion could lead to losses up to 255 Gt CO_2 (Steffen et al., 2018[224]).

Boreal forests

Similar to the Amazon rainforest, boreal forests are a key component in regulating Earth's climate by sequestering carbon. Boreal forest dieback will cause the transition to steppe grasslands, which store less carbon than boreal forests (Koven, 2013[266]). Consequently, dieback of the boreal forests could release over 100 Gt CO_2 to the atmosphere (Steffen et al., 2018[224]) and therefore amplify global warming further.

This analysis finds that an AMOC collapse alone would likely cause dieback to the boreal forests in northern Europe and Asia. On the other hand, an enhanced boreal forest in North America (about one-third of current global boreal forests) will increase carbon storage (Steffen et al., 2018[224]). However, there is no dynamic vegetation in the model. Using net primary productivity as an indicator instead makes it difficult to determine the overall impact to boreal forests under an AMOC-collapse scenario.

Monsoon systems

The Indian summer monsoon, which occurs from May to September, is instrumental to the Indian economy and agriculture (Bhat, 2006[267]). The monsoon has been identified as a potential future tipping element due to climate change (Lenton et al., 2008[4]). Using a simple box model for the Indian monsoon Zickfeld et al. (2005[268]) suggests that an increase to the planetary albedo, such as sulphur emissions and/or land-use changes, could disrupt the monsoon. There have been indications in the second half of the 20th century that the monsoon may be in decline with decreased summer rainfall. This has led to more frequent droughts (Ramanathan et al., 2005[269]) and reduced rice harvests (Auffhammer, Ramanathan and Vincent, 2006[270]). One major drought in 2002 (Bhat, 2006[267]), is estimated to have cost the Indian government USD 340 million in drought relief programmes. It has also caused an increased number of suicides among farmers (Liepert and Giannini, 2015[271]). Weakening of the Indian summer monsoon following a collapse of the AMOC would most likely have detrimental impacts on Indian farmers' rice harvests.

This analysis finds that, under global warming projections, West Africa will experience the largest decreases in rainfall on the planet. A collapse of the AMOC will exacerbate this effect, disrupting the African monsoon and leading to further reduction in precipitation. This, in turn, will potentially lead to widespread drought over much of the region. The lack of adaptive capacity to climate change across the region will compound the problem. As an area with high rates of poverty, individuals do not have the means to prepare for or adapt to ongoing climate change. Meanwhile, governance fails to act to mitigate the negative impacts of climate change.

Further socio-economic effects

In addition to the socio-economic impacts explored above, other knock-on effects will result from an AMOC collapse:

- A decrease in ocean NPP for the AMOC-collapse scenario seems related to a reduction in north-eastward nutrient transport through the Faroe-Shetland region associated with a retarded North Atlantic Current.
- SLR will occur at rates up to 20-25 mm/yr (Levermann et al., 2005[272]).
- Additional SLR will occur around European and North American coasts of up to 50 cm (Vellinga and Wood, 2007[273]; Levermann et al., 2009[256]).

- European land protection and population relocation would require an additional EUR 1.4 billion per year, based on calculations from Vousdoukas et al. (2020[274]).
- Energy demand and consumption will change due to changing temperature patterns. In a scenario that combines global warming and an AMOC collapse, some parts of Europe may remain warmer than pre-industrial conditions. However, the cooling effect of AMOC in winters would win out over global warming, cooling some regions to below pre-industrial temperatures.

The potential tipping point explored here is just one of the many parts of the Earth system that could produce this effect. Recent research shows the AMOC is at its weakest in a century. However, according to the latest IPCC AR6, there is medium confidence that the projected decline in the AMOC will not involve an abrupt collapse before 2100 (IPCC, 2021[14]). Still, this timeline cannot be ruled out.

A slowing down of the AMOC is already detected and likely to continue. The results presented here are specific to the model and scenario chosen; a more comprehensive assessment would require an ensemble of models. Despite these limitations, results agree with previous research. They show the potential for far-reaching impacts of crossing the tipping threshold of one of the planet's most important systems.

Climate change is reshaping the global socio-economic structure, and will continue to do so. This is likely to impact on progress towards the Sustainable Development Goals, disrupt global trade and amplify social conflict, inequalities and human security. Rapid and deep reductions in GHG emissions are needed to prevent crossing critical thresholds of the climate system.

An international effort for measuring and monitoring key tipping elements, such as the AMOC, is key. This will provide countries with time to develop strategies (including through adaptation and preventive measures) to deal with the consequences of these abrupt changes of climate systems.

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Annex 3.A. Cascading impacts of crossing a climate tipping point: Collapse of the Atlantic Ocean Overturning Circulation – methodology

The model used for the study of the Atlantic Ocean Overturning Circulation (AMOC) is HadGEM3, the latest version of the UK Met Office's state-of-the-art climate model. The model and its performance have previously been described in detail elsewhere (Williams et al., 2015[275]) but briefly, it is the Global Coupled 2.0 model (GC2) configuration of the HadGEM3 model (Hewitt et al., 2011[276]) consisting of coupled atmosphere, ocean, sea-ice and land-surface models.

Details of the experimental design and of the runs analysed here have also been given previously (Jackson et al., 2015[248]; Mecking et al., 2016[249]; Williamson et al., 2017[254]). Two runs of the model are compared to isolate the effects of an AMOC collapse: a steady state control run (the AMOC is in its usual on state in this run) and an AMOC-off steady state run. The AMOC is collapsed using the methodology of Vellinga and Wood (2002[277]). This involves perturbing the salinity in the upper layers of the North Atlantic to inhibit deep convection and hence quickly shut down the AMOC (the absence of the sinking branch of the AMOC, referred to here as the AMOC-off state).

This method of collapsing the AMOC is unrealistic. The most likely cause of an AMOC shutdown in global warming projections, in fact, is progressively increasing freshwater addition from Arctic runoff and melt of the Greenland ice sheet. However, the method is useful for investigating the impacts of a shutdown.

The salinity perturbations are applied to the upper 536 m of the Atlantic and Arctic Ocean north of 20°N each December for only the first ten years. Each salinity perturbation is equivalent to continuously adding freshwater at a rate of 1Sv (1Sv=10^6 m^3/s) for ten years (total of 10 SvYr). To give an idea of the size of this annual perturbation, a freshwater flux from the Greenland ice sheet of 1Sv would melt it completely in nine years. The AMOC-off run is integrated for a total of 450 years from the start of the salinity perturbations. No external forcing is applied to the model apart from diurnal and annual cycles of the radiative fluxes and atmospheric CO_2 concentrations are fixed to 1978 levels.

As the perturbations are applied, the AMOC collapses from the steady ~15 Sv (maximum stream function at 26.5°N) in the control run and remains very weak for the full model simulation period of 450 years. As a result, meridional Atlantic Ocean heat transport at 30°N is halved from ~1 to ~0.5 PW and surface air temperature (SAT) is reduced by ~4°C in the North Atlantic (Jackson et al., 2015[248]). The AMOC-off simulation is approximately stationary 60 years after the salinity perturbations end. However, the maximum in the AMOC stream function at 26.5°N does have a very slow increasing trend reaching ~5 Sv at the end of the 450 years. Further North, however, the AMOC shows no signs of recovering (Mecking et al., 2016[249]).

First, the climatic impacts of just the AMOC-collapse without the additional global warming most likely to accompany a collapse in any realistic future scenario is isolated. The isolated impacts of an AMOC collapse are analysed by taking the difference of 30-year means of the control run and the AMOC-off run once the simulation is approximately stationary. Following a similar approach to that used by Vellinga and Wood (2007[273]), the analysis is expanded to include the impacts of an AMOC collapse against a more realistic future climate state. In so doing, it accounts for the additional effects of global warming using the future scenario SSP126 in the model HadGEM3-GC31-MM (Williams et al., 2015[275]). The model uses the Global Coupled model 3.1 (GC31) configuration of the HadGEM3 model and has the same atmospheric and ocean resolutions as used in the AMOC hosing experiments. The forcing scenario SSP126 refers to

Shared Socio-economic Pathway SSP1 and Regional Concentration Pathway RCP2.6 - a low-emissions pathway with high sustainability (Riahi et al., 2017[278]).

Under the SSP126 scenario, HadGEM3-GC31-MM reaches a mean global warming of 2.5°C above pre-industrial levels by the end of the century (2071-2100). This warming pattern is overlaid to the impacts of an AMOC collapse to establish the overall impact if the AMOC were to collapse after 2.5°C global warming relative to the present-day climate. As discussed in the previous section, this scenario is considered a plausible scenario with a significant, albeit "unlikely" (0-33%) probability in IPCC language.

Notes

[1] Droughts are an exception and may last from a few months to a few years (Spinoni et al., 2013[280]). Despite the potentially long duration of droughts, this chapter classifies them as extreme weather events (as opposed to slow-onset events).

[2] The economic loss data comprise "all financial losses directly attributable to a major event", including damage to buildings, infrastructure, motor vehicles and other physical assets, as well as "business interruption as a direct consequence of the property damage") (Swiss Re Institute, 2021[281]). The data include any event that resulted in insured losses of more than USD 52.7 million, economic losses of more than USD 105.4 million, 20 or more deaths, 50 or more injuries or 2 000 or more people made homeless. Weather-related extreme events refer to events primarily classified by Swiss Re as: (i) cold, frost; (ii) drought, bush fires heatwaves; (iii) flood; (iv) hail; or (v) storm.

[3] As governments and the insurance sector have improved post-disaster data capture over time, reporting of economic losses has likely also become more comprehensive. As a result, some portion of the growth in economic losses from catastrophes over time is likely due to improved data capture.

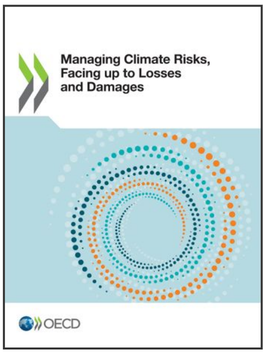
[4] The warming from 1850-1900 until 2011-20 has been assessed as 1.09ºC, with a likely range of 0.95 to 1.20ºC (IPCC, 2021[14]).

[5] There is no universal definition of SIDS; the list of territories belonging to this category differs across the literature.

[6] Considering globally aggregated numbers, for a 10-year return period, heat waves increase in likelihood by 9.4 times, whilst heavy precipitation and drought increase by 2.7 and 4.1 times (IPCC, 2021[14]). It has been shown, however, that for some individual events, such as the prolonged Siberian heat of 2020, the increase in likelihood is orders of magnitude higher than in a climate without human influence (Ciavarella et al., 2021[283]).

[7] The magnitude of temperature changes is model-dependent, but there is general agreement across models that there would be widespread cooling across the northern hemisphere (Vellinga and Wood, 2002[277]; Jacob et al., 2005[279]; Vellinga and Wood, 2007[273]; Swingedouw et al., 2009[282]; Drijfhout, 2015[65]).

[8] A caveat: there is no dynamic vegetation in the model, i.e. there is no interaction between vegetation and the atmosphere. Because of this, one cannot see if the vegetation is altered by the change in the precipitation. One can, however, assume the forest is stable under the conditions seen in the AMOC-on run, and then compare conditions when the AMOC collapses.



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