2

Climate tipping points and their cascading effects

This chapter provides a summary review of the state-of-the-art science on climate tipping points. It provides an overview of the global and regional impacts of a number of selected tipping elements, including on their socio-economic impacts. The chapter is structured as follows. First, it provides a general overview of what climate tipping points are and the general characteristics of key tipping elements. Second, it examines interlinkages amongst tipping elements and between tipping points and socioeconomic and ecological systems. This includes both the possibility that crossing one tipping point triggers further tipping elements throughout the earth system, and the impacts of crossing tipping points cascading through socioeconomic and ecological systems. Third, it reviews the potential impacts associated with selected policy-relevant tipping points with the goal of better characterising their physical and economic risks. This is important to inform near-term action dealing with these risks, which is the focus of Chapter 3.

In Brief

The latest scientific evidence on the risk of crossing climate tipping points, on the potential for cascading impacts and economic costs

Climate system tipping elements are components of the Earth system susceptible to a tipping point, that is, a critical threshold beyond which the system reorganises, often abruptly and/or irreversibly. Improved scientific understanding has shown that triggering climate system tipping points already this century cannot be ruled out, far sooner and at lower levels of warming than previously assumed. The goal of this chapter is to review the state of knowledge of climate system tipping points.

Tipping elements have been identified in three types of climate sub-systems: the cryosphere (or ice bodies), the circulations of the oceans and the atmosphere (circulation patterns) and the biosphere. Key examples include the collapse of the West Antarctic and Greenland Ice Sheets and the melting of the Arctic Permafrost (cryosphere), the slowdown or collapse of the Atlantic Meridional Overturning Circulation (circulation patterns) and the dieback of the Amazon Forest and the destruction of coral reefs (biosphere). Of concern, there are signs already today some of the key sub-systems may have already crossed or are being pushed to cross critical thresholds.

If triggered, climate system tipping points may lead the regional or global climate to change from one stable state to another, the latter with characteristics that are potentially much less suitable for sustaining human and natural systems. At the **regional level**, individual tipping points are associated with different types of potentially severe regional or local impacts, such as extreme temperatures, higher frequency of droughts, forest fires and unprecedented weather. At the **global scale**, tipping points could potentially lead to cascading global impacts with additional carbon emissions and higher sea-level rise rates. In addition, the tipping of one element has the potential to trigger the tipping of other elements, leading to a tipping cascade. The impacts associated with crossing a tipping point can also cascade through **socio-economic and ecological systems** over timeframes that are short enough to defy the ability and capacity of human societies to adapt. In the world today, impacts propagate through sectors and international borders via as global trade, financial flows and supply networks, affecting sustainability and security and hindering the achievement of e.g. Sustainable Development Goals.

It is only in recent years that economic studies have started to incorporate the costs of tipping points into analyses of the economic costs of climate change. While findings vary widely, these studies reveal that omitting the risk of cascading tipping points leads to the economic cost of climate change being severely underestimated, by a factor of up to 8. Such underestimation essentially means a complete redefinition of cost-effective benchmarks with drastic implications for what optimal policy pathways actually entail, and strongly emphasises that stringent climate policies and immediate action are the only options for societies to address the risk of tipping points.

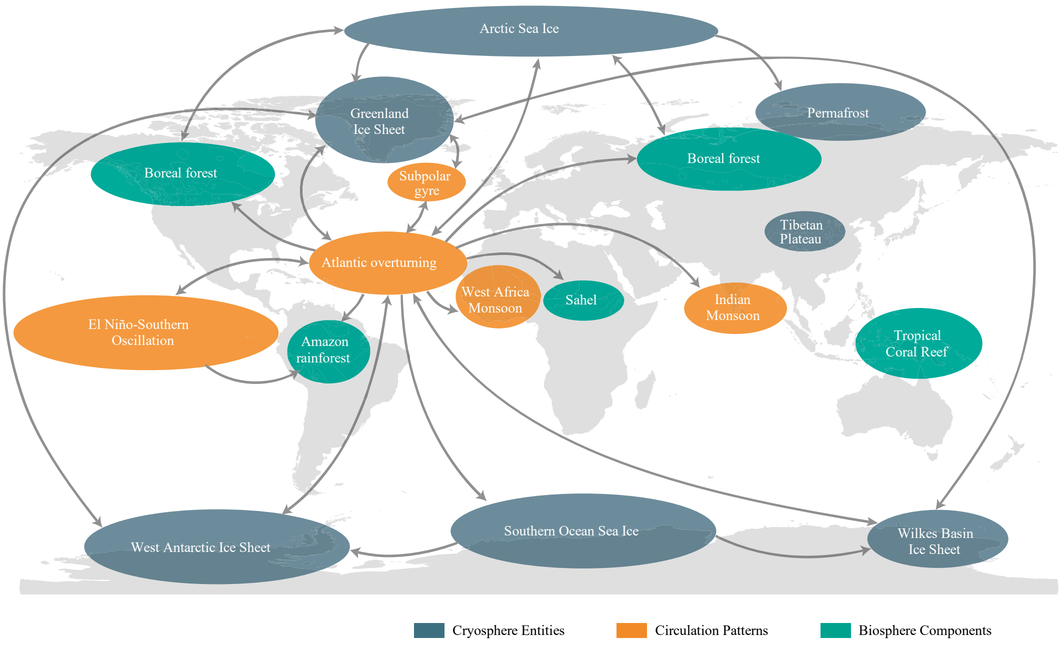
Recent findings suggest that many climate tipping points can be crossed, with a considerably higher probability and at much lower levels of warming than previously assumed and are an imminent threat today, challenging the previously well-accepted consideration that climate system tipping points are indeed low-likelihood outcomes. Given the magnitude and severity of the impacts associated with the crossing of climate system tipping points, it is crucial that climate strategies today adequately address the risks of crossing tipping point.

2.1. General overview of climate tipping elements and their policy relevance

According to the IPCC, a tipping point is a critical threshold beyond which a system can reorganise in an abrupt or irreversible manner (IPCC, 2021[1]). An abrupt climate change is defined as a “large-scale change in the climate system that takes place over a few decades or less, persists (or is anticipated to persist) for at least a few decades and causes substantial impacts in human and/or natural systems” (Ibid). In addition, “a perturbed state of a dynamical system is defined as irreversible on a given time scale if the recovery from this state due to natural processes takes substantially longer than the time scale of interest” (Ibid). Climate “tipping elements” refer to at least sub-continental scale parts (or subsystems) of the climate system that can pass a climate tipping point, or elements “that can be switched—under certain circumstances—into a qualitatively different state by small perturbations” (Lenton et al., 2008[2]).

Tipping elements have been identified in three types of climate sub-systems including the cryosphere (or ice bodies), the circulations of the oceans and the atmosphere (circulation patterns) and the biosphere. There are multiple tipping elements under each of these groups. Examples include: under the cryosphere, the collapse of the West Antarctic Ice Sheet or the melting of the Arctic Permafrost; under circulation patterns, the slowdown or collapse of the AMOC and under the biosphere, the dieback of the Amazon Forest and the death of coral reefs. Figure 2.1 summarises policy-relevant tipping elements, defined here as those that may pass a tipping point this century due to anthropogenic climate forcing. As a result of atmospheric and ocean circulation, the different tipping element candidates are not isolated systems, but they interact at a global scale (as denoted by the arrows in Figure 2.1). This means that the tipping of one element has the potential to trigger tipping cascades (Lenton et al., 2019[3]; Wunderling et al., 2021[4]), discussed in detail in 2.2.

Figure 2.1. 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*:* (OECD, 2021[5]); (Kriegler et al., 2009[6]; Cai, Lenton and Lontzek, 2016[7]; Wunderling et al., 2021[4])

Evidence that climate tipping points may be approaching has led scientists to declare a climate and ecological emergency (Lenton et al., 2019[3]; Ripple, 2020[8]). For example, irreversible loss of part of the

West Antarctic Ice Sheet may have begun (Good et al., 2018[9]), while the Greenland ice sheet may also have a tipping point wherein irreversible loss begins at 1.5°C of warming (Lenton et al., 2019[3]). Ocean ecosystems are already experiencing large-scale changes and ocean heatwaves and acidification are causing mass bleaching of warm-water coral reefs; above 2°C 99% of coral reefs are projected to be lost (Lenton et al., 2019[3]). Also of concern is recent evidence that deforestation – itself a key contributor to climate change – combined with a warming climate, raises the probability that the Amazon will cross a tipping point, shifting from a humid to a dry state, already during the 21st century (Lenton et al., 2019[3]; Arias et al., 2021[10]).

The probability of crossing individual climate tipping points changes with different levels of projected warming. Table 2.1 summarises the most current knowledge on global warming (above pre-industrial) thresholds and uncertainty ranges for crossing different policy-relevant climate tipping points, based on paleoclimate, observational, and model-based studies (McKay et al., 2022[11]). Table 2.1 also summarises current understanding of tipping elements in terms of their potential to cause abrupt change and their irreversibility, based on information from AR6 (Lee, 2021[12]).

Table 2.1. Temperature thresholds and uncertainty ranges of tipping points

Impact scale	Type	Tipping point	Temperature threshold (°C)		Potential for Abrupt Change?	Irreversibility if forcing reversed
			Central estimate	Range		
Global	Cryosphere	Greenland Ice Sheet collapse	1.5°C	0.8 - 3°C	No (high confidence)	Irreversible for millennia (high confidence)
Global	Cryosphere	West Antarctic Ice Sheet collapse	1.5°C	1 - 3°C	Yes (high confidence)	Irreversible for decades to millennia (high confidence)
Global	Ocean-atmospheric circulation	Labrador-Irminger Seas / SPG Convection collapse	1.8°C	1.1 - 3.8°C		
Global	Cryosphere	East Antarctic Subglacial Basins collapse	3°C	2 - 6°C		
Global	Biosphere	Amazon rainforest dieback	3.5°C	2 - 6°C	Yes (low confidence)	Irreversible for multidecades (medium confidence)
Global	Cryosphere	Boreal Permafrost collapse	4°C	3 - 6°C	Yes (high confidence)	Irreversible for centuries (high confidence)
Global	Ocean-atmospheric circulation	AMOC collapse	4°C	1.4 - 8°C	Yes (medium confidence)	Reversible within centuries (high confidence)
Global	Cryosphere	Arctic Winter Sea Ice collapse	6.3°C	4.5 - 8.7°C	Yes (high confidence)	Reversible within years to decades (high confidence)
Global	Cryosphere	East Antarctic Ice Sheet collapse	7.5°C	5 - 10°C		
Regional	Biosphere	Low-latitude coral reefs die-off	1.5°C	1 - 2°C		
Regional	Cryosphere	Boreal Permafrost abrupt thaw	1.5°C	1 - 2.3°C		
Regional	Cryosphere	Barents Sea Ice abrupt loss	1.6°C	1.5 - 1.7°C		
Regional	Cryosphere	Mountain Glaciers loss	2°C	1.5 - 3°C		
Regional	Biosphere	Sahel greening	2.8°C	2 - 3.5°C		
Regional	Biosphere	Boreal Forest southern dieback	4°C	1.4 - 5°C	Yes (low confidence)	Irreversible for multidecades (medium confidence)
Regional	Biosphere	Boreal Forest northern expansion	4°C	1.5 - 7.2°C		

Note: Literature-based temperature threshold estimates, including a central estimate and an uncertainty range for crossing of key tipping elements of the climate system. Central estimate column colour codes: red, dark orange and light orange denote respectively central global warming threshold are within the Paris Agreement range of 1.5-2°C, within temperature range in line with current policies (2-4°C) and 4°C and above. Range column colour codes: red, dark orange and light orange denote respectively that current warming already within uncertainty range, levels in line with the Paris Agreement range within uncertainty rage and range above Paris Agreement range. Compared to previous characterization of tipping elements in the literature, the following tipping elements had not yet been featured: Labrador-Irminger Seas /SPG Convection (collapse), East Antarctic Subglacial Basins (collapse), Barents Sea Ice (abrupt loss). Information on potential to cause abrupt change and irreversibility, including timescales, and timescales from IPCC AR6 ((Lee, 2021[12]), Table 4.10). IPCC confidence levels of potential to cause abrupt change reflect the author team's judgement about the validity of the findings by an evaluation of evidence and agreement (Lee, 2021[12]).
Source: Adapted from (McKay et al., 2022[11]) and (Lee, 2021[12])

In summary, Table 2.1 shows that current global warming of ~1.1°C is already within the lower end of the uncertainty range of five climate system tipping points, including the collapse of the Greenland and West Antarctic ice sheets, die-off of low-latitude coral reefs, and widespread abrupt permafrost thaw (McKay et al., 2022[11]). This means that the crossing of these tipping points is already "possible" (*Ibid*). Within the Paris Agreement range of 1.5 to <2°C warming, these climate tipping points and another two (Barents Sea

Ice abrupt loss and Labrador-Irminger Seas / SPG Convection collapse) become “likely” (*Ibid*). Some tipping points showing a considerably higher best estimate temperature threshold for critical transition are however associated with larger uncertainty ranges making them also “possible” within Paris Agreement range. This is the case for a potential collapse of the AMOC: while best estimate threshold for tipping is around 4°C of warming, the large associated uncertainty range does not allow ruling out collapse already at much lower levels of warming starting at 1.4°C.

These findings suggest that many climate tipping points can be crossed, with a considerably higher probability and at much lower levels of warming than previously assumed and are an imminent threat today. Importantly, while not yet scientific consensus, these findings inevitably challenge the previously well-accepted consideration that climate system tipping points are indeed low-likelihood outcomes. The threshold at which tipping points are crossed and the likelihood of crossing them is, for a number of reasons, difficult to predict. For example, the parameters that induce a shift from one state to another often experience only incremental changes before the state of the system makes a sudden and persistent transition. Considering the potential drastic consequences for climate policy today, it is important that research in the area of climate tipping points continues to shed light on whether it is pertinent to continue considering these as low-likelihood.

The IPCC also estimates the speed and irreversibility of various tipping points. Examples of tipping elements that could lead to potentially abrupt and irreversible (in timescales that are relevant to humans) impacts include, with at least a medium degree of confidence: release of GHGs trapped in permafrost, the West Antarctic ice sheet and shelves and the AMOC. Confidence in the possibility of abrupt changes in tropical and boreal forests tipping points is lower. The induced changes in these tipping elements would be, however, irreversible for multiple decades. Crossing tipping points for arctic summer sea ice and the Greenland ice sheet would not lead to abrupt changes (high confidence) but if triggered, the melting of the Greenland ice sheet would be irreversible for millennia.

Combined, the three aspects of tipping elements analysed in Table 2.1, namely the temperature thresholds at which they will potentially be crossed, their potential both for causing abrupt change and their irreversibility, are extremely policy-relevant. First, information on temperature thresholds for crossing tipping points indicates levels of mitigation needed to safeguard against the potentially catastrophic impacts of crossing tipping points. Second, whether changes happen abruptly or not can inform courses of action in adapting to changes if tipping points are crossed as abrupt changes are more difficult to adapt to after the change has already occurred. Third, the irreversible nature of certain tipping elements emphasises the need for stringent, early mitigation in order to avoid their crossing. Chapter 3 of this report explores how this information can be used to inform climate strategies that directly integrate the risk of climate system tipping points.

2.2. Potential cascading impacts of climate system tipping points

With increasing global temperatures, there is a growing risk that tipping elements of the climate system will cross critical thresholds, leading to impacts cascading through interlinked climate–ecological–social systems. This section examines how the impacts of crossing critical thresholds in the climate system can cascade through socioeconomic and ecological systems. It also examines ways by which these impacts can cascade within the climate system, that is, how the tipping of one element can trigger the tipping of other elements of the climate system.

2.2.1. The crossing of climate system tipping points can cascade through socio economic and ecological systems

The crossing of critical thresholds in the climate system will lead to different types of potentially severe regional or local hazards, such as extreme temperatures, higher frequency of droughts, forest fires and unprecedented weather. Because earth and human systems are intrinsically linked, abrupt changes in the physical climate can also result in cascading impacts through socioeconomic and ecological systems. Cascading impacts can be defined as "a sequence of events where abrupt changes in one component lead to abrupt changes in other components. These changes could also interact with each other and propagate from larger to smaller spatial scales or vice versa" (Brovkin et al., 2021[13]).

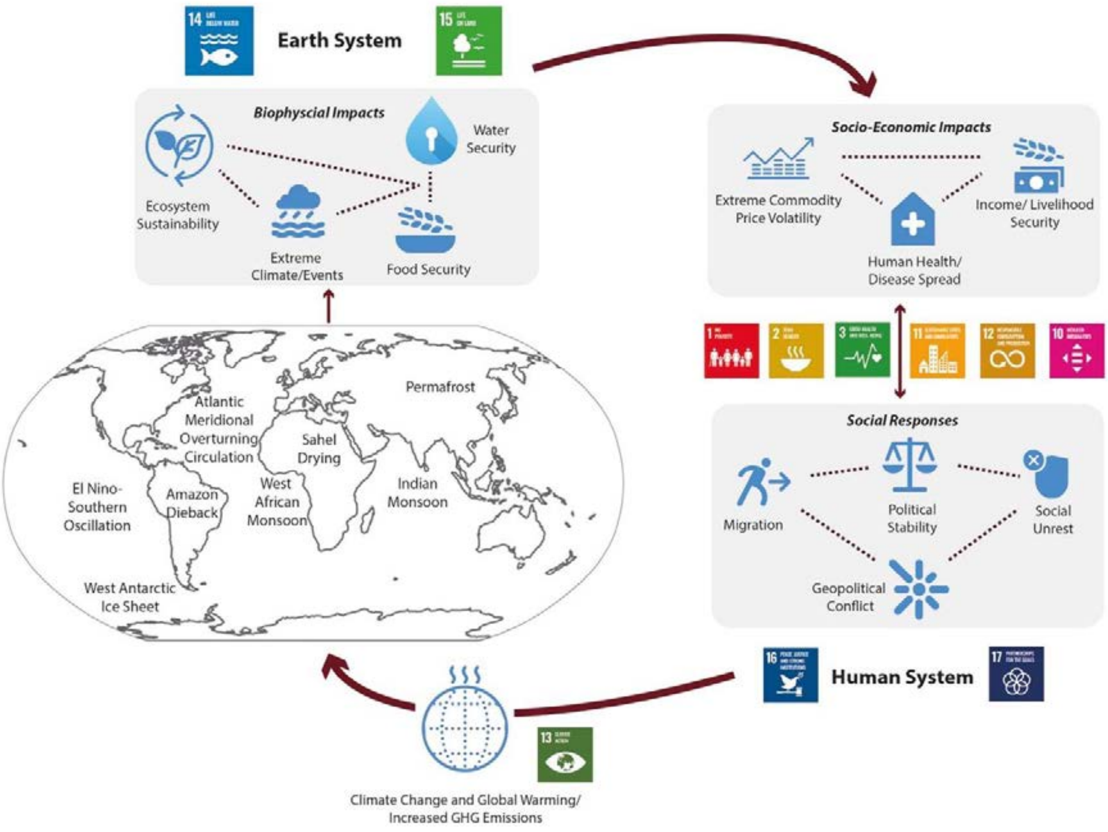
In the world today, shocks propagate quickly through sectors and international borders via international processes, such as global trade, financial flows and supply networks (Acemoglu et al., 2012[14]). These systemic risks remain poorly understood, making it a challenge to include them in risk assessment strategies (Koks, 2018[15]; Challinor et al., 2018[16]). Work relating to cascades covers a broad range of topics and thematic areas, including human-ecosystems dynamics, ecology, natural and climate-related hazards research and systems theory. Progress on understanding cascading impacts from climate change has been evolving mainly along three axes: socio-ecological resilience, disaster risk reduction (UNDRR, 2015[17]) and systems dynamics (Lawrence, Blackett and Cradock-Henry, 2020[18]).

Compared with previous assessment reports, the IPCC's AR6 incorporates the inherently complex nature of climate risk, hazard, vulnerability, exposure and resulting impacts, including feedbacks and non-linear behaviour, as well as the potential for surprise. The report states that "adverse impacts from climate hazards and resulting risks are cascading across sectors and regions (high confidence), propagating impacts along coasts and urban centres (medium confidence) and in mountain regions (high confidence)". Some examples of cascading impacts and risks include (Ara Begum, 2022[19]):

- Hazards and cascading risks can trigger tipping points in sensitive ecosystems and social-ecological systems impacted by ice melt, permafrost thaw and changing hydrology in polar regions;
- In many regions, wildfires have impacted species and ecosystems, people and their built assets, economic activity, and health;
- In cities and settlements, consequences of climate-related impacts on key infrastructure affect economic activity and lead to losses and damages across food and water systems, with impacts that extend beyond the area directly exposed to the climate hazard;
- In the Amazon region, and in some mountain regions, cascading impacts from climatic-stressors (e.g. heat) in combination with non-climatic stressors (e.g., land use change) will lead to irreversible and severe losses of ecosystem services and biodiversity at 2°C of global warming and beyond;
- Sea level rise will bring cascading and compounding impacts resulting in losses of coastal ecosystems and ecosystem services, groundwater salinisation, flooding and damages to coastal infrastructure that cascade into risks to livelihoods, settlements, health, well-being, food and water security, and cultural values in the near to long-term.

As reviewed in section 2.3, the crossing of climate system tipping points will lead to the intensification of a range of climate hazards. Franzke et al (2022[20]) explore the potential cascading effects of large and potentially catastrophic impacts associated with tipping points and how these can affect sustainability and security. Figure 2.2 depicts some of the potential interactions and cascading effects of climate system tipping points on human systems. Once tipped, major large scale tipping point elements have biophysical impacts on ecosystems, water and food systems. Through those, they cascade through the human system inducing socio-economic impacts. Some social responses to these impacts may also potentially tip social subsystems into a different state, such as by inducing political instability or migration. The responses of the human system can have positive or negative feedbacks by increasing or mitigating global warming and, thus, potentially affecting further tipping elements. Further implications of tipping points are highlighted through their potential impacts on Sustainable Development Goals (SDGs) (Franzke et al., 2022[20]).

Figure 2.2. Schematic of possible interactions and cascading effects between Earth and human systems



Source: (Franzke et al., 2022[20])

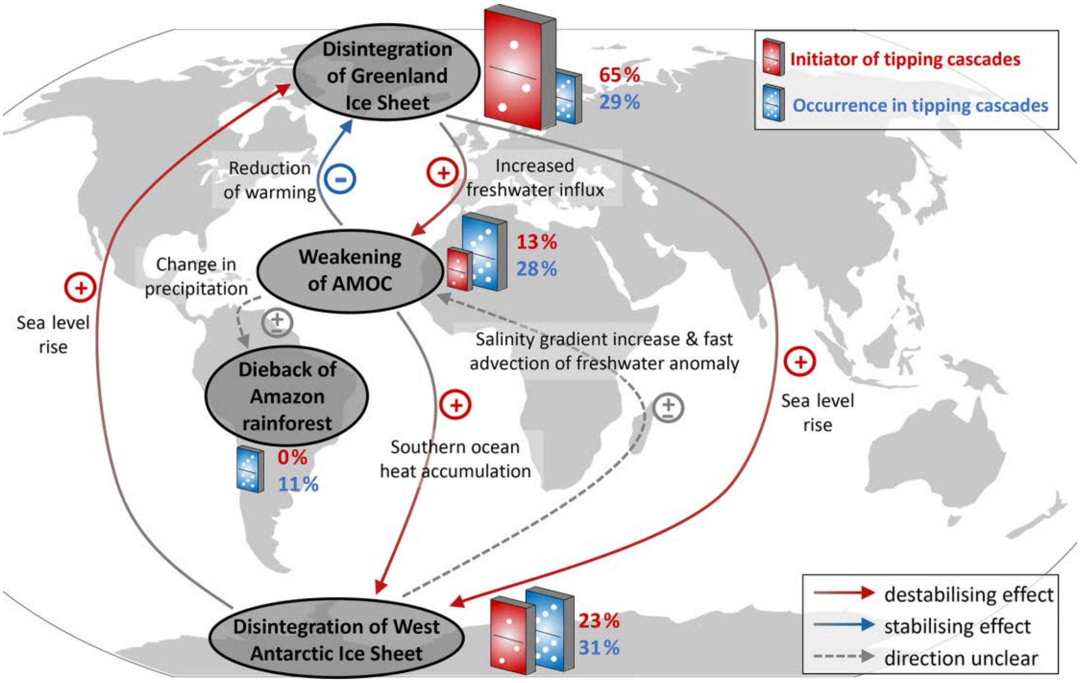
The potential for cascading impacts highlights the need for a better understanding of risk transmission mechanisms across sectors and international boundaries (Challinor, Adger and Benton, 2017[21]). Li et al (2021[22]) find that the “systemic risk induced by climate change is a holistic risk generated by the interconnection, interaction, and dynamic evolution of different types of single risk […] [and] the extent of risk propagation and its duration depend on the characteristics of the various discrete risks that are connected to make up the systemic risk”. A number of case studies and examples on how to better integrate risk transmission knowledge into risk assessment strategies have been proposed (Challinor, Adger and Benton, 2017[21]; LI et al., 2021[22]), and are considered in Chapter 3 of this report discussing approaches that can improve policy responses targeting climate tipping points.

2.2.2. The crossing of one climate system tipping point can generate positive feedbacks that increase the likelihood of crossing other climate system tipping points

As a result of atmospheric and ocean circulation, the different tipping element candidates are not isolated systems, but they interact at a global scale (as denoted by the arrows in Figure 2.1). This means that the tipping of one element has the potential to trigger tipping cascades (Lenton et al., 2019[3]; Wunderling et al., 2021[4]). This section provides a short overview of some of the mechanisms by which different tipping elements may interact with each other leading to an increased risk of climate domino effects under increasing global temperatures.

In a large expert elicitation, Kriegler et al. (2009[6]) assessed probability intervals for the occurrence of some of the most policy-relevant potential climate system tipping points, including the AMOC, the Greenland and West Antarctic ice sheets, the Amazon rainforest and El Niño Southern Oscillation. The paper concludes that the probability of triggering a tipping point can be increased or reduced by the crossing of other tipping points in the Earth system (Ibid). More recent research analysing the effects of known physical interactions among the West Antarctic and Greenland ice sheets, the AMOC and the Amazon rainforest finds that these tend to destabilise the network of tipping elements (Wunderling et al., 2021[4]). In addition, this work further identifies the West Antarctic and the Greenland ice sheets as "initiators of tipping cascades" and the AMOC as the "mediator transmitting cascades" concluding that the polar ice sheets are of particular importance for the stability of the climate system as a whole (*Ibid*). This is particularly concerning as the most recent science suggests that the ice sheets may already be at their tipping or will tip earlier than previously expected (McKay et al., 2022[11]).

Figure 2.3. Interactions between climate tipping elements and their roles in tipping cascades



Note: Interactions between the Greenland Ice Sheet, the West Antarctic Ice Sheet, the Atlantic Meridional Overturning Circulation (AMOC) and the Amazon rainforest and their roles in tipping cascades. Destabilising links between the tipping elements are depicted as red arrows whereas stabilising interactions are depicted as blue arrows. Where the direction is unclear, the link is marked in grey. Where tipping cascades arise, the relative size of the dominoes illustrates how many ensemble members the respective climate component initiates tipping cascades in (red domino) or how many tipping cascades the respective climate component occurs in (blue domino).
Source: (Wunderling et al., 2021[4])

There are many potential interactions between the AMOC, West Antarctic and Greenland ice sheets (Figure 2.3). In summary, the melting of the Greenland ice sheet would lead to an influx of fresh water into the North Atlantic could weaken and destabilise the AMOC. On the other hand, the weakening of the AMOC would lead to the cooling of the North and could have a stabilising effect on the Greenland ice sheet. Further, the shutdown of the AMOC could lead to a warmer South, therefore potentially destabilising the West Antarctic ice sheet, with as of yet unclear further effects on the AMOC. In addition, due to sea level changes, the interaction between the Greenland and the West Antarctic ice sheets is regarded as mutually destabilising (Wunderling et al., 2021[4]).

The effect of an AMOC collapse on the Amazon Basin remains unclear (Wunderling et al., 2021[4]) with studies projecting both a stabilising effect (Ciemer et al., 2021[23]) and conversely a drying of the Amazon basin (OECD, 2021[5]). Collapse of the AMOC would likely also impact boreal forests, inducing widespread drying across Europe and Asia, but increases in precipitation in North America. This would cause dieback to the boreal forests in northern Europe and Asia and, in contrast, an enhanced boreal forest in North America (currently making up about one-third of global boreal forests) resulting in increases in carbon storage (Steffen et al., 2018[24]; OECD, 2021[5]).

Monsoon systems are likely to also be affected by a potential collapse or slowdown of the AMOC. Analysis by the OECD (2021[5]) finds that West Africa will experience the largest decreases in rainfall on the planet under global warming scenarios. The shutdown of the AMOC will exacerbate this effect, disrupting the African monsoon and leading to further reduction in precipitation that can in turn, cause widespread drought over much of the region. A collapse of the AMOC would also lead to the weakening of the Indian summer monsoon which could lead to more frequent droughts with potentially detrimental impacts on Indian farmers' rice harvests.

The cascading effect of a potential shut-down of the AMOC on the Amazon rainforest, Monsoon systems and on the West Antarctica and Greenland ice sheets (and from melting of the latter two on the AMOC itself) are some examples of how the crossing of one tipping point can trigger other tipping elements in the climate system. Given the devastating socio-economic and ecological impacts crossing single tipping points described in the previous sub-section, the potential for these cascading effects only reinforces the need to include tipping points in climate risk management strategies.

2.3. Overview of latest science on selected individual key tipping elements and their impacts

This section provides a systematised overview of individual tipping elements, with a focus on their potential impacts on social, economic and natural systems and geographies. It aims at classifying the potential impacts of each of the tipping points analysed into broad categories (e.g. loss of biodiversity, food security, social and cultural impacts, sea-level rise, etc.) and distilling scientific information that can directly feed into strategies dealing with tipping points that is relevant for practitioners discussed in Chapter 3 of this report. The subsection focuses on the following policy-relevant climate tipping points: a collapse of the AMOC, the dieback of the Amazon and the Boreal Forests and cryosphere tipping points including Greenland ice sheet meltdown, West Antarctic ice sheet collapse, Arctic summer sea-ice loss, year-round loss of Arctic sea ice, and abrupt permafrost collapse. Table 2.2 summarises the potential physical climate impacts associated with the crossing of these policy-relevant tipping points, including potential timescales at which these impacts might unfold if tipping points are crossed.

Table 2.2. Potential impacts of crossing selected tipping points

Tipping point	Timescale (years)	Weather	Sea-level rise	Biodiversity/ Ecosystems	Climate and carbon feedbacks	Maximum impact on global temperature	Socio-economic	Interaction with other tipping points
Greenland ice sheet meltdown	10 000	Local warming, local shifts in rainfall	+ 1 m by 2100	Indirect negative impacts (through sea-level rise)	Flooding of permafrost, ↑CO_2, CH_4	0.13°C	Indirect negative impacts (through sea-level rise)	Trigger AMOC collapse Flooding of permafrost
West Antarctic ice sheet collapse	2 000	Local warming, local shifts in rainfall	+1 m by 2100	Indirect negative impacts (through sea-level rise)	Flooding of permafrost, ↑CO_2, CH_4	0.05°C	Indirect negative impacts (through sea-level rise)	Destabilising/stabilising impact on AMOC
Year-round collapse of Arctic sea ice	20	Arctic warming amplification through loss of surface albedo effect	No significant effect	Loss of sea-ice dependent ecosystems	Increased permafrost thawing, ↑CO_2, CH_4	0.60°C	Arctic coastal hazards; Arctic communities' food security and autonomy	Contribute to northern permafrost and ice sheet decline; increase ocean acidification
Atlantic overturning (AMOC) collapse	50	↓ in temperatures in the Northern Hemisphere, drier Europe, storm surges in North America, disruption to precipitation patterns in the tropics	Increased along North American coast	Potential reduced precipitation on the Amazon	↑CO_2 from ocean and land, biome changes	-0.50°C	Critical threat to global food security	Increase WAIS disintegration, stabilising effect on Greenland ice sheet
Permafrost abrupt collapse	50	Local warming		Tundra and boreal biome shifts	PCF: CO_2 and CH_4 release; Up to >800 Gt CO_2	0.2-0.4°C	Damages to infrastructure Release of infectious diseases	Increases risk of other tipping points with increased warming
Boreal forest dieback	100	Decrease winter local temperatures and increase in global temperatures, potential decrease in regional precipitation	-	Forest biodiversity loss	Increased CO_2, potential increased permafrost thawing	-0.18°C	Major disruption of ecosystem services for local communities	
Amazon rainforest dieback	100	Local and regional warming, lower local precipitation	-	Forest biodiversity loss	Increased CO_2	0.2°C	Major disruption of ecosystem services, migration, food security and health	Potential contribution to the weakening of the AMOC

Source: Authors and (OECD, 2021[5]; McKay et al., 2022[11])

2.3.1. Collapse of the Atlantic Meridional Overturning Circulation (AMOC)

The AMOC slowdown and potential collapse

The Atlantic Meridional Overturning Circulation (AMOC) is the Atlantic branch of the thermohaline circulation (THC), sometimes referred to as the ocean's "great conveyor belt". It drives part of the ocean circulation through fluxes of heat and freshwater carrying large-scale flows of warm salty water from the southern hemisphere and the tropics to the Northern hemisphere. As this warmer surface water circulates along the European coast, it loses both heat and freshwater to the atmosphere and thereby becomes denser. Around Greenland, the water forming the current has become salty and cold enough to sink into much lower depths of the ocean, forming the North Atlantic Deep Water (NADW). This cold water is returned southward and comes back to the surface in the Southern part of the Atlantic (OECD, 2021[5]).

The AMOC has been relatively stable in the past 8,000 years (Fox-Kemper et al., 2021[25]), but changes in the Atlantic circulation associated with climate changes in paleo-records suggest that instabilities and irreversible changes could be triggered and the existence of a tipping point cannot be excluded. A collapse of the AMOC would represent a complete reorganisation of ocean circulation, with dramatic impacts on the climate system. It would lead to a redistribution of heat around the planet and shifting rainfall patterns affecting sea ice, global sea levels, agricultural systems, and marine and terrestrial ecosystems. Paleo-records show that, in the past, changes in the strength of the AMOC have played a prominent role in transitions between warm and cool climatic phases. In addition, changes in surface temperatures and precipitation patterns induced by an AMOC collapse or weakening, which are described below, have the potential to affect other tipping elements of the climate system, specifically the stability of the Amazon and boreal forests as well as the global monsoon system, as discussed in Section 0.

In the past, the AMOC has repeatedly switched abruptly between different states, leading to rapid changes in temperatures and precipitation patterns in the North Atlantic and beyond (Barker and Knorr, 2016[26]), as well as in sea-ice coverage. The latest IPCC assessment concludes that a continued decline of the AMOC is very likely during this century and, with medium confidence, that a collapse of the AMOC is not anticipated before 2100 (Fox-Kemper et al., 2021[25]). However, a sparse and short observational record as well as observational uncertainties have led to an underestimation of AMOC variability (Eyring et al., 2021[27]). In addition, models neglect meltwater influxes from the Greenland ice sheet, even though a tipping point could be triggered if unexpectedly high releases of melted freshwater entered the NADW formation (Reintges et al., 2016[28]; Arias et al., 2021[10]). Looking at longer timescales, a model inter-comparison study including Greenland melt processes showed an important impact of Greenland freshwater influxes on the AMOC leading to a 44% likelihood of AMOC collapse by 2300 for high-end warming scenarios[1] (Bakker et al., 2016[29]). The neglected effect of Greenland Ice Sheet mass loss, as well as a limitation of the time horizon to the 21st century, help to explain the IPCC's relatively low assessment of the likelihood of an AMOC collapse (OECD, 2021[5]).

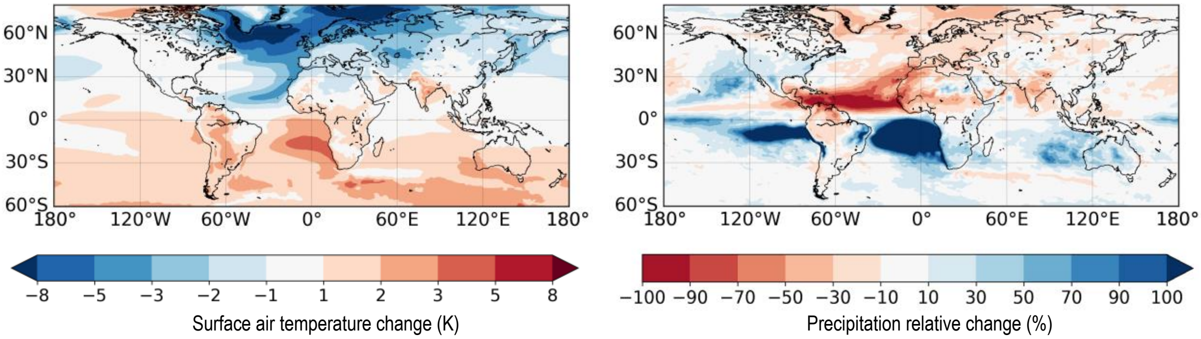
A recent analysis, synthesising paleoclimate, observational and model-based studies, gives a best estimate for a collapse of the AMOC at a threshold of 4°C (with a range of 1.4°C to 8°C). Observations suggest that the AMOC has weakened in 2004-2017 compared to 1850-1900. Reconstructions indicate the circulation is currently at its weakest point in over 1,000 years (Thornalley et al., 2018[30]; Caesar et al., 2021[31]) and current early-warning signals are consistent with the AMOC losing stability and being close to a critical transition (Boers, 2021[32]). Even if a collapse does not occur, further weakening of the AMOC would still have major impacts, essentially a scaled-down version of those resulting from a complete collapse (OECD, 2021[5]).

Potential impacts of an AMOC collapse

Climatic impacts

An abrupt AMOC collapse would cause profound and abrupt shifts in regional weather patterns and water cycles. Consequences would include a southward shift in the tropical rain belt, a weakening of African and Asian monsoons, and a strengthening of monsoons in the Southern Hemisphere (Arias et al., 2021[10]). The climatic consequences would partly be offset by an increase in the heat carried by the atmosphere compensating the decrease in heat carried by the AMOC (Fox-Kemper et al., 2021[25]). Models show that, without the effects of underlying global warming, temperatures and precipitation patterns in Greenland and around the Atlantic would be affected, with a projected widespread cooling across the northern hemisphere. Europe and North America would experience a drop of 3°C - 8°C and 1°C - 3°C respectively. In the southern hemisphere, there is little predicted temperature change, but strong disruptions to precipitation patterns in the tropics corresponding to a southward shift of the Intertropical Convergence Zone (ICTZ). The northern hemisphere would overall become drier, except for North America where stronger storms are projected (Jackson et al., 2015[33]). A weakened Asian monsoon would mean that rainfall in India would be halved. Models also agree that a strong thermosteric sea-level rise along North America would occur, even under a weakening of the AMOC (Little et al., 2019[34]; Lyu, Zhang and Church, 2020[35]). Taking into account the effects of global warming in addition to those of an AMOC collapse alone, the northern hemisphere would still undergo a cooling, albeit mitigated, while climatic changes in the southern hemisphere would mainly be driven by the underlying warming, with AMOC collapse having only minimal impact. Figure 2.4 summarises these changes in temperature and precipitation under a scenario with an AMOC collapse after 2.5ºC of warming, which is consistent with several model projections of the temperature threshold for AMOC collapse.

Figure 2.4. Temperature and precipitation responses to an AMOC collapse under 2.5ºC of warming above pre-industrial levels



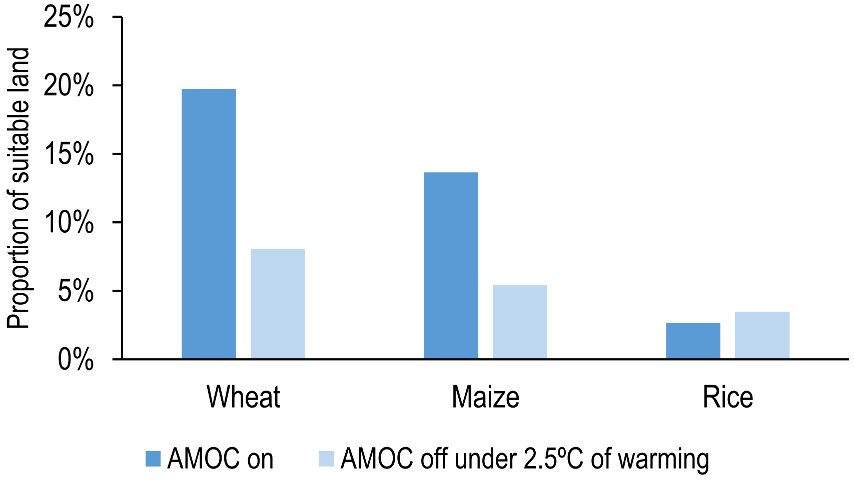
Note: Surface air temperature (left panel) and precipitation (right panel) response to AMOC-collapse scenarios. The analysis shows the impacts of an AMOC collapse under global warming using the future scenario SSP1-2.6 in the model HadGEM3-GC31-MM. The forcing scenario SSP1-2.6 refers to Shared Socio-economic 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).
Source: (OECD, 2021[5])

Agriculture and food security

Because of the induced shift in climatic conditions, an AMOC shutdown would have profound impacts on agriculture globally. Overall, a collapse of the AMOC would pose a critical threat to global food security (OECD, 2021[5]). An AMOC collapse under warming reduces the growth suitability of three major staple crops – wheat, maize and rice, which provide over 50% of global calories. For wheat these affects are global, whereas for maize and rice they affect primarily Europe, Russia and the northern part of North America (OECD, 2021[5]). Most of the northern hemisphere would become less suitable for growing these staple crops, but Europe would be especially affected. This is because Europe is currently rendered wetter and warmer by the AMOC. An AMOC collapse would thus increase seasonality, reducing agricultural productivity, with colder winters and drier summers. In Great Britain for instance, one study of the effects of an abupt AMOC shutdown in combination with global warming on land use and agriculture predicts widespread loss of arable land by 2080 because of climate drying. Technological change in the form of irrigation would mitigate the loss of agricultural output, but at prohibitive costs (Ritchie et al., 2020[36]).

Figure 2.5 shows the percentage of global land suitabile for growing wheat, maize and rice in a world without global warming and where the AMOC has not collapsed (AMOC on) and a world where the AMOC has collapsed under 2.5ºC of warming (AMOC off under 2.5ºC of warming). In the latter scenario, more than half of the suitable land for growing wheat and maize is lost, compared to a world without climate change. There is a modest increase in suitable area for growing rice, exceeding that in the baseline state. However, gains in the suitable area for rice cultivation are dwarfed by losses in the suitable area from wheat and maize. As such, an AMOC collapse would clearly pose a critical challenge to food security, and combined with other climate impacts would have a catastrophic impact (OECD, 2021[5]).

Figure 2.5 Percentage of global land suitable for crop growth



Note: The percentage of land represents lands that would have a suitability greater than 90% in each of the three cases. This analysis does not overlay the subset of areas where each crop is actually grown.
Source: Modified from (OECD, 2021[5])

Beyond impacts on agriculture, a serious weakening or collapse of the AMOC would have profound implications for ecosystems, human health, livelihoods, food security, water supply and economic growth, especially in the regions around the North Atlantic. Some socio-economic effects include additional sea-level rise along the North American coast of up to 50cm, population relocation, or shifts in energy demand and consumption because of changing temperatures in Europe (OECD, 2021[5]).

2.3.2. Amazon and Boreal forests dieback

Possible abrupt changes have also been identified in the biosphere, relating in particular to ecosystems and biogeochemistry. Such abrupt changes can happen in ecosystems such as the Amazon rainforest and the Boreal forest. Different mechanisms could lead to these abrupt changes, with a large range of potential local and global impacts, as reviewed in the sections below.

The Amazon rainforest dieback

The close association between the land surface and water cycles makes the Amazon potentially susceptible to abrupt change (Douville et al., 2021[37]). A number of studies indicate that climate change (Cox et al., 2000[38]) and deforestation (Boers et al., 2017[39]), especially when combined, can lead to changes that can push the Amazon past a critical threshold, beyond which a wide-scale ecosystem collapse becomes inevitable and where tropical forest would gradually turn into a drier savannah state.

Climate change has the potential to change air temperature and precipitation patterns in the region, and has led to an increase in temperature in the Amazon basin of 1-1.5ºC, which has been associated with a lengthening of the dry season in the region over the past two decades (Nobre et al., 2016[40]). In addition, deforestation can affect vegetation through changes in the regional climate, reducing evapotranspiration, which is critical for the maintenance of moisture levels in the forest (Boers et al., 2017[39]; Staal et al., 2018[41]). Together, drought and deforestation can disrupt the equilibrium state of the humid forest (Nobre et al., 2016[40]). Indeed, there is scientific evidence of pronounced loss of Amazon resilience[2] since the early 2000s, with three-quarters of the forest having lost resilience, indicating the Amazon may be approaching a tipping point (Boulton, Lenton and Boers, 2022[42]). This loss of resilience is more prounounced in regions with lower rainfall and in regions most affected by deforestation due to human activity (Boulton, Lenton and Boers, 2022[42]).

While there is uncertainty regarding temperature thresholds at which the forest would cross a tipping point, it is projected that continued Amazon deforestation, combined with a warming climate, raises the probability that the ecosystem will shift into a dry state already during the 21st century (Arias et al., 2021[10]). Indeed, recent evidence even points to a potential tipping point being crossed in the next 20-30 years under a business as usual scenario, far sooner than previously thought (Duffy et al., 2021[43]). If pressures are not successfully addressed, it is projected that at 2.5ºC of warming, forest cover would decrease by 60% due to the combined effect of climte change, deforestation and degradation and forest fires (Pörtner et al., 2022[44]). The temperature threshold at which the Amazon forest dieback would occur, independent of deforestation, has recently been estimated at 3.5°C (with a range of 2 to 6°C) based on existing scientific evidence, but this threshold is lilely lower when factoring in deforestation (McKay et al., 2022[11]). Given the vast scale of past deforestation, even if all deforestation is halted, reforestation will be neseccary in order to ensure the stability of the Amazon in the future, particularly when faced with warming conditions (Lovejoy and Nobre, 2018[45]; Lovejoy and Nobre, 2019[46]).

The impacts associated with the dieback of the forest could be severe and of global scale. First, the conversion of Amazon forest, which comprises half of the world’s current rainforest, into a drier svannah state would have profound implications for biodiversity, much of it endemic to the region, leading also to loss of ecosystem function. Furthermore, it would have dire consequences for local communities, in particular indigenous populations, due to dimished levels of biodiversity and food sources, higher exposure to respiratory problems, air pollution and diseases (Pörtner et al., 2022[44]). In addition, the loss of forest would act as an amplifying positive feedback on climate change with as much as 200GtC carbon currently stored in the forest being released into the atmosphere, leading to extra warming globally and locally (Steffen et al., 2018[24]; Canadell et al., 2021[47]).

Dieback of the boreal forests

Boreal forests are an integral component of regional and global climate systems and affect biosphere-atmosphere interactions as well as large-scale circulation patterns. Like the Amazon, boreal forests also exhibit a potential to dieback beyond a given tipping point. Under climate change, increased peak summer heat and water stress causing increased mortality, vulnerability to fire, as well as decreased reproduction rates could lead to large-scale dieback of the boreal forests, with transitions to open woodlands or grasslands (Lenton et al., 2008[2]).

Boreal forests are expected to experience the largest increase in temperatures of all forest biomes during the 21st century; in combination with development and extraction of natural resources, species resilience may decline leading to major biome-level changes (Gauthier et al., 2015[48]). Of concern, 80% of boreal forests are located in environments underlain by permafrost (Helbig, Pappas and Sonnentag, 2016[49]). Increases in temperatures and increased incidence of forest fires will expose permafrost land, with important consequences for local and global climate change (see also section 2.3.3).

The latest IPCC report assesses with high confidence that warmer and drier conditions have increased tree mortality and forest disturbances in many temperate and boreal biomes, negatively impacting provisioning services (Pörtner et al., 2022[44]). The impacts associated with a potential dieback of the boreal forest are severe locally and globally. For example, many communities and economies rely on the forests and could be negatively impacted by their loss. At larger scales, the long-term provisioning of global climate regulation through the exchange of energy and water is at risk.

Recent evidence shows that even modest climate change may lead to major transitions in boreal forests (Reich et al., 2022[50]). Indeed, 1.6 ºC of warming and associated climate change (i.e. change in precipitation patterns) can have drastic effects on the dominant tree species in North American boreal forests, including reduced growth and increased juvenile mortality of all species, which threatens the forest's ability to regenerate as well as its resilience (Reich et al., 2022[50]). Models project that shifts in the boreal forest begin at 1.5°C of warming and become widespread above 3.5°C (McKay et al., 2022[11]). A recent estimate gives a temperature threshold of 4°C (with a range of 1.4 to 5°C) for the dieback of southern boreal forests (*ibid*). This emphasises the need to limit global warming to low levels if these ecosystems are to continue provisioning critical ecosystem services regionnally and globally.

2.3.3. Permafrost abrupt collapse

Permafrost refers to the perennially frozen soil and rock, both in the near surface (within 3 to 4 meters) and in deeper layers of the ground, underlying a so-called active layer exposed to seasonal freeze and thaw. Permafrost is located in cold high-latitude and high-altitude areas across the Arctic, accounting for approximately half of the global permafrost surface (Miner et al., 2022[51]), as well as parts of the Antarctic and mountainous regions in Southwest Asia, Europe and South America. In total, permafrost makes up an estimated 25% of the Northern Hemisphere and 17% of exposed land area on Earth (Gruber, 2012[52]). In the Arctic region in particular, large amounts of organic carbon are stored within permafrost areas. Organic matter has accumulated over thousands of years and has stayed locked in permanently frozen grounds but would rapidly decay and decompose into carbon dioxide and methane if exposed to thawing. The total amount of carbon locked in the northern permafrost region is estimated at around 1,700 Gt, almost twice as much as the carbon currently stored in the atmosphere (Miner et al., 2022[51]).

The release of carbon dioxide and methane from permafrost thaw into the atmosphere due to global warming and its impacts leads to an amplification of surface warming, acting as a positive carbon-climate feedback, in a process known as the permafrost carbon feedback (PCF). Loss of carbon following permafrost thaw is irreversible over centennial timescales. The PCF has been hypothesised to have substantial implications for GHG emissions and the potential for abrupt permafrost thaw is considered to be a major tipping element of the Earth system (Lenton et al., 2019[3]). A total collapse of permafrost would release up to 888 Gt of carbon dioxide and 5.3 Gt[3] of methane over this century (Canadell et al., 2021[47]). By comparison, the remaining carbon budgets for maintaining warming below 1.5°C and 2°C [4] are respectively 400 and 1150 Gt CO_2 (Canadell et al., 2021[47]). Anthropogenic warming is already threatening to release some of this carbon into the atmosphere, making the permafrost, and the Arctic permafrost in particular, the single largest climate-sensitive carbon pool on Earth (Hugelius et al., 2014[53]; Parmesan et al., 2022[54]).

Overall, there is low confidence across models in the timing and magnitude of the PCF process, as well as in the significance of methane release relative to carbon dioxide. The additional emissions that would be caused by permafrost thaw are, however, undoubtedly strong enough that they would considerably reduce remaining carbon budgets as estimated in AR6. The IPCC AR6 projects with medium confidence that the global permafrost volume in the top 3m will decrease by up to 50% at sustained warming levels of 1.5°C to 2°C, 75% at sustained warming levels of 2 to 3 °C, and 90% at sustained warming levels of 3°C to 5°C, relative to 1995-2014 (Fox-Kemper et al., 2021[25]) .Yet, the potential for abrupt largescale thaw across the Arctic is still incompletely represented in Earth System Models, as major abrupt thaw processes such as fire-permafrost-carbon interactions or the potential for abrupt release through thermokarst, explained below, are not currently taken into account (Canadell et al., 2021[47]). This suggests that existing projections of permafrost thaw at different temperature thresholds are conservative.

Permafrost thaw can happen both gradually and abruptly. Over the past three to four decades, increases in ground temperatures in the upper 30m have been observed across all permafrost regions, with global permafrost temperature increase assessed at + 0.19°C between 2007 and 2016 (Biskaborn et al., 2019[55]). This has led to *gradual* permafrost thawing, reducing both permafrost thickness and areal extent. Current models project with high confidence that further warming will lead to further gradual reductions in the near-surface permafrost volumes; each additional 1°C of warming is anticipated to cause a 25% decrease in the volume of near-surface perennially frozen ground globally (Arias et al., 2021[10]).

Abrupt permafrost thaw can occur due to e.g. heatwaves, wildfires burning away surface soil layers insulating permanently frozen layers, thermokarst - whereby melting ice in the ground reshapes landscapes - and hydrological processes such as lake expansion and draining. Such abrupt thaw processes can expose several meters of permafrost carbon on very short timescales – days to years (Miner et al., 2022[51]). It is estimated that under a high-warming scenario, such abrupt processes can contribute to half of the net GHG release from permafrost in this century (Turetsky et al., 2020[56]). In addition to abrupt permafrost thaw, there is evidence that a synchronous large-scale permafrost collapse could occur because of abrupt permafrost drying and self-sustained internal heat production inside carbon-rich permafrost grounds – this is known as the "compost-bomb" instability (Hollesen et al., 2015[57]; McKay et al., 2022[11]). It is estimated that the temperature threshold for an abrupt thaw regionally lies between 1 and 2.3°C (best estimate at 1.5°C), while the large-scale collapse of permafrost is estimated to likely occur at higher warming levels of 3 to 6°C (McKay et al., 2022[11]).

The Arctic is both the biggest permafrost region and the fastest warming region on Earth. High Arctic regions have seen global warming levels more than double those of the global average. Surface warming is projected to continue to be more intense than the global average warming over this century (Arias et al., 2021[10]). This is to lead to virtually certain widespread permafrost warming and thawing across all climate scenarios (Arias et al., 2021[10]; Canadell et al., 2021[47]). The drivers of abrupt permafrost thaw are also all currently occurring in the Arctic region. Fire intensity and frequency have been increasing and are projected to further increase 130-350% by 2050 in some regions such as Alaska (Yue et al., 2015[58]). Heatwaves in Siberia in 2016, 2018 and 2020, with up to 6°C positive temperature anomalies, already induced extensive melting of permafrost (Overland and Wang, 2020[59]).

Alongside the global PCF and its contribution to global GHG emissions and warming, a collapse of permafrost would also pose risks to local ecosystems and to local human livelihoods, health and infrastructure. Permafrost thaw interacts with other climatic and human factors and leads to geomorphological alterations, hydrological regime shifts and biome shifts, with regional implications for the frequency and magnitude of floods and landslides, coastal erosion, and hydrological dynamics. Permafrost thaw is causing pronounced vegetation and ecosystem changes in boreal forests and tundra biomes that lie above permafrost areas. An overall greening of the tundra, and regional browning of boreal forests are projected, with potential associated changes in the range and abundance of ecologically important species, including in freshwater ecosystems. This is projected to negatively impact local communities' livelihoods and cultural identity (Caretta et al., 2022[60]).

Permafrost thaw poses risks to human health through the release of previously locked-in infectious diseases. Anthrax, for instance, is a zoonose disease that has been historically rare in the Arctic region but has seen recent outbreaks and extensive mortality events among humans and reindeers. These outbreaks have been linked to permafrost melt under higher than usual recent summer temperatures that left previously frozen animal carcasses exposed (Hueffer et al., 2020[61]; Ezhova et al., 2021[62]). Additionally, permafrost thaw is releasing contaminants, including mercury, in waters and food chains, negatively impacting water quality in Arctic rivers and lakes. Alongside its impacts on ecosystems and human health, the thaw of permafrost and resulting ground instability can cause severe damage to the infrastructure built above permafrost soil, creating challenges for economic development and human activities in concerned regions. In the longer-term, mitigation to hold global warming well below 2°C would significantly reduce the impacts of permafrost thaw on infrastructure in permafrost areas (Shaw, 2022[63]).

2.3.4. Greenland ice sheet meltdown and West Antarctic ice sheet collapse

Ice sheets are defined as large bodies of land-based ice of continental scale (> 50,000 km^2). They form over thousands of years through the accumulation of compacted snow. In our current era, the only ice sheets on Earth are the Greenland and Antarctic Ice Sheets, the latter being divided into the West Antarctic Ice Sheet, the East Antarctic Ice Sheet and the Antarctic Peninsula Ice Sheet (IPCC, 2021[1]). The Antarctic Ice Sheet covers 98% of the Antarctic continent, extends over 14M km^2 and is on average 2 km deep. The Greenland Ice Sheet covers 80% of Greenland, an area of around 1.7M km^2, with an average thickness of 1.5 km. In total, the volume of water held within the ice sheets would represent respectively 58m and 7.4m in mean global seal level rise if completely released into the world's oceans (Shepherd et al., 2019[64]; Fretwell et al., 2013[65]).

Past and current behaviour under warming

Improved data and models of ice sheet behaviour have revealed unexpectedly high melt rates. There is high scientific agreement on the mass loss of the Greenland Ice Sheet in the last three decades, caused in part by anthropogenic activities. Overall, between 1992 and 2020, the Greenland Ice Sheet is estimated to have lost around 4900 Gt of ice. Total ice loss for the Antarctic ice sheet over the same period is estimated at around 2700 Gt (Arias et al., 2021[10]). Overall, mass loss for the Greenland ice sheet doubled over the period from 2007-2016 when compared to 1997-2006, and tripled for the Antarctic ice sheet (Arias et al., 2021[10]).

Two main processes govern the mass loss of both the Greenland and Antarctic ice sheets: the melting and runoff of surface snow and ice, and a dynamic process of ice discharge through ice-ocean interaction, whereby marine-terminated outlet glaciers are released from ice sheets. These two processes are governed mainly by atmospheric and ocean warming (Shepherd et al., 2019[64]). Both processes have contributed equally to the mass loss of the Greenland ice sheet since 1992, but the recent accelerated rates of mass loss after 2000 are attributed mainly to an increase in surface melting and runoff under high warming levels in the region (Sasgen et al., 2020[66]; Arias et al., 2021[10]). In the Antarctic, two counteracting processes have influenced the rate of mass loss: increased snowfall and snow accumulation on the surface of the ice sheet have led to mass gains; on the other hand these have been outpaced by increased ice shelf basal melting – a process where the extensions of the ice sheet over the sea melt at their bases because of the heat of the water (Arias et al., 2021[10]).

Ice sheet tipping points

The IPCC AR6 assesses it as virtually certain that the Greenland ice sheet will continue to lose ice over this century under all emissions scenarios (Arias et al., 2021[10]). While there is a high level of agreement in the scientific community on the existence of a tipping point after which mass loss in the Greenland ice sheet becomes irreversible, the nature of this tipping point and the associated thresholds are still being evaluated and debated (Fox-Kemper et al., 2021[25]). Different models have given critical temperature thresholds for a collapse of the Greenland ice sheet of 1.5°C to 2.7°C (McKay et al., 2022[11]). The most recent assessment based on all current available evidence gives 1.5°C as a central estimate (*ibid*).

The West and East Antarctic ice sheets are also considered to be tipping elements of the climate system, with estimated thresholds at much lower levels of warming. Several studies highlight increasing evidence of an instability threshold for the West Antarctic ice sheet already at warmings levels of 1-3°C, with a most probably estimate at 1.5°C (McKay et al., 2022[11]). The extent of ice loss, however, remains debated. In most studies, limiting warming to below 2°C would result in only part of the West Antarctic ice sheet being lost, with associated sea level rise estimates at 0-1.2m. Several studies find, however, that the West Antarctic ice sheet would in fact completely disintegrate at this level of warming. In any case, even after the critical threshold is passed, disintegration would take multiple millennia (Fox-Kemper et al., 2021[25]). A collapse of the East Antarctic ice sheet is projected to occur at much higher warming levels, with an estimated tipping threshold of ~7.5°C (McKay et al., 2022[11]).

On much longer time scales, because the processes governing ice sheets are slow to respond to warming levels, a complete disintegration of the ice sheets is possible even if GHG emissions are entirely stopped. Even with a stabilisation of the climate at 2°C to 3°C of warming above 1850-1900 levels, ice sheets could be lost irreversibly and almost completely. At sustained warming levels of 3°C to 5°C, a near-complete loss of the Greenland and West Antarctic ice sheets is projected to be almost certain. This would mean that even after GHGs emissions are put to an end, global sea levels will continue to rise for centuries to millennia (Fox-Kemper et al., 2021[25]).

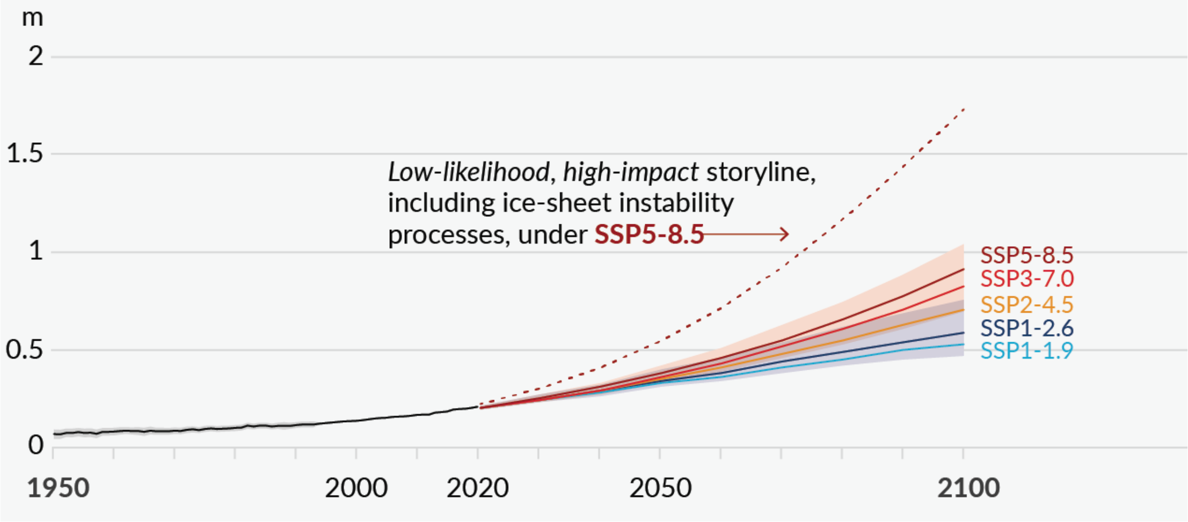
Impacts of ice sheets collapse

Sea-level rise

The cryosphere as a whole – frozen components of the Earth system, comprising snow cover, glaciers, ice sheets, ice shelves, sea ice, lake and river ice, permafrost – is estimated to have contributed to 45% of global sea level rise since the early 1990s (Mottram et al., 2019[67]). The Greenland and Antarctic ice sheets alone are major contributors to sea level rise. With accelerated rates of mass loss in the 21st century, the Greenland ice sheet has become, since the mid-1990s, the largest single contributor to sea-level rise (King et al., 2020[68]), accounting for 0.76 mm of the annual 3.5 mm, or around 20%, of global mean sea-level rise since 2005 (Sasgen et al., 2020[66]). In total, between 1992 and 2020, Greenland ice mass loss has already led to an estimated 13.5 mm of global mean sea level rise, while Antarctic ice loss contributed 7.4mm over the same time period (Fox-Kemper et al., 2021[25]).

Due to deep uncertainty characterising the possibility of abrupt ice-sheet disintegration, these are not taken into account in the IPCC's projection ranges of sea level rise before 2100. In light of these uncertainties, storylines[5] can be used to help understand the consequences of low-likelihood outcomes, such as that of ice sheet tipping points. Such an approach reveals that, although low-likelihood, an early disintegration of marine ice shelves, marine ice sheet instability and marine ice cliff instability can lead to an abrupt shift in the Antarctic ice sheet, while faster surface runoff and dynamical ice loss in Greenland can result in more rapid ice mass loss already this century. Combined, these elements will lead to more than one additional meter of sea-level rise over this century (Fox-Kemper et al., 2021[25]). Figure 2.6 shows how such a storyline compares to more conservative projections of sea-level rise which do not consider this low-likelihood, high-impact scenario, revealing the full range of risk the world currently faces.

Figure 2.6. Global mean sea level change relative to 1900



Source: (IPCC, 2021[69])

AMOC

As seen in section 2.2.2, the Greenland ice sheet and AMOC tipping elements are intimately linked. Greenland ice sheet mass loss is already affecting the AMOC and has the potential to bring it to a tipping point. By releasing freshwater in the northern part of the current, it is disrupting the deep convection process whereby warm water transported the north at the surface of the ocean loses freshwater by evaporation, thus becoming saltier and denser and eventually being propelled southward as a cold-water flow at depth. In combination with increased precipitation in the high northern latitudes, the Greenland ice sheet meltdown is increasingly contributing to the observed weakening of the AMOC (OECD, 2021[5]). Even though the IPCC AR6 gives medium confidence that there will not be an abrupt collapse of the AMOC before 2100 in spite of its current decline, such a collapse could occur under a scenario of unexpected abrupt rates of melting of the Greenland ice sheet (Arias et al., 2021[10]) (refer also to sections 2.2.2 on cascading effects and 2.3.1 on AMOC).

2.3.5. Arctic sea-ice loss

Contrary to ice sheets which originate on land, sea ice forms on the sea surface from the freezing of seawater, both in discontinuous moving pieces or in motionless land-fast ice. While part of the sea ice melts during the summer, some of it is perennial and survives one or several summers (IPCC, 2021[1]). It has been long debated whether Arctic summer and winter sea-ice present a tipping point or whether changes in sea-ice extent vary linearly with warming, presenting therefore no potential for abrupt or irreversible change. Contrary to slow processes such as ice sheet mass loss, sea ice coverage is quick to respond to warming levels and the Arctic summer sea ice has been shown, and is projected to continue to respond approximately linearly and with little temporal delay to global warming levels, with reversible losses on annual to decadal timescales (Fox-Kemper et al., 2021[25]). No critical threshold has been found above which the loss of summer sea ice becomes irreversible and the rate of loss increases (Lee, 2021[12]). The loss of winter sea-ice is also reversible, the rate of decline is however anticipated to increase with higher warming levels leading to the potential for abrupt change, as the ice retreats from shore lines (Bathiany et al., 2016[70]; Lee, 2021[12]). Considering the clear and consistent recent downward trend in Arctic summer and winter sea-ice extent, the potential for abrupt loss of winter sea-ice and the high impacts associated with the loss of Arctic sea-ice, approaches in managing the risk of sea-ice loss approximate approaches dealing with tipping points and are therefore relevant to this report.

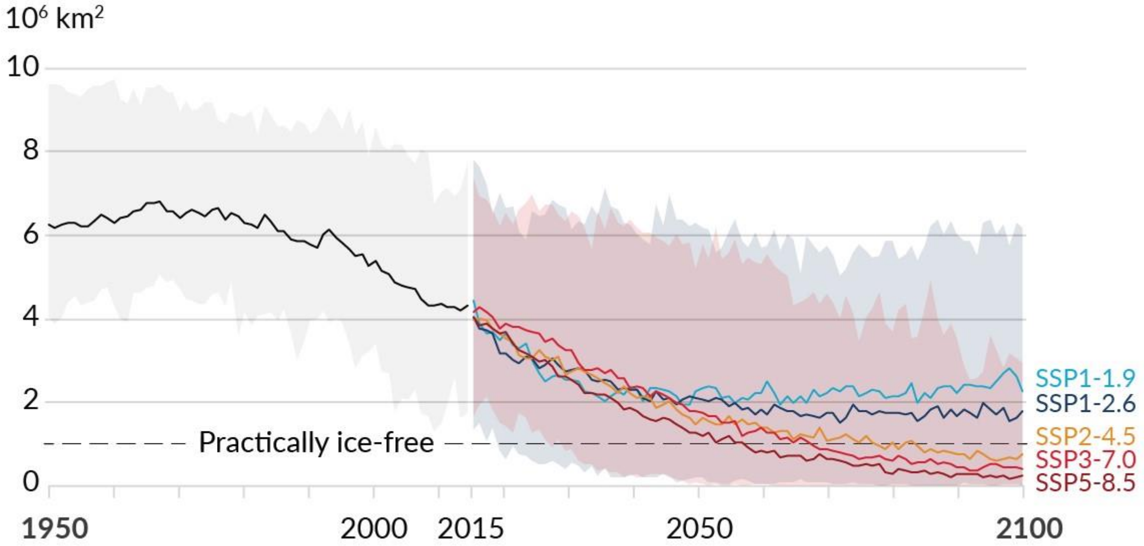
The currently observed decrease of Arctic sea ice is a key indicator of climate change. Satellite observations have established a 40% decrease in the Arctic sea ice area in September – the month of lowest annual extent - and a 10% decrease in March – the month of highest extent – between average levels in 2010-2019 compared to 1979-1988. This represents a decrease in the decadal mean Arctic sea ice from 6.2 to 3.8 million km^2 in September and from 14.5 to 13.4 million km2 in March. In the period 2011-2020, the annual mean Arctic sea ice reached its lowest extent since at least 1850, as shown by a recent reconstruction historic sea-ice cover (Walsh et al., 2017[71]; Gulev et al., 2021[72]). Summer sea-ice loss since 1979 is proven to be unprecedented in at least the last 1,000 years. Overall, the extent of Arctic sea ice has decreased for all months of the year since the late 1970s. Its thickness has also consistently been decreasing in both seasons over that same period. Arctic sea ice is therefore becoming both younger and thinner, as perennial sea ice – 33% of the Arctic sea ice cover in 1985, but only 1.2% in 2019 - is being replaced by thin seasonal ice (Perovich et al., 2020[73]; Gulev et al., 2021[72]). In contrast to Arctic sea ice, Antarctic sea ice, for both the summer and winter seasons, has shown no significant trend of decline since the end of the 1970s.[6]

Projected changes

Additional warming is projected to amplify the loss of Arctic sea ice in the near term. Under all 5 SSP climate scenarios assessed by the IPCC WGI, the Arctic is projected to be practically sea-ice free (less than 1 million km2 of sea ice) in the summer at least once by the mid-century (IPCC, 2021[69]). This is projected to happen around 2040 (Sigmond, Fyfe and Swart, 2018[74]), with more frequent occurrences at higher warming levels. By 2100, a summer sea ice-free state will become the new norm under higher emissions scenarios (SSP2-4.5, SSP3-7.0 and SSP5-8.5) (Lee, 2021[12]). Overall, the September sea-ice free state is anticipated to occur in some years at sustained warming levels of 1.5°C to 2°C, in most years at warmings levels of 2 to 3°C and throughout several months in most years at 3 to 5°C (Figure 2.7). The likelihood of a practically ice free Arctic ocean in the summer is already much higher at 2°C than 1.5°C of warming (Lee, 2021[12]). This assessment is substantiated by new approaches to reduce uncertainties in estimates of sea ice decline at 1.5°C-3°C of warming (Sigmond, Fyfe and Swart, 2018[74]).

Arctic winter sea ice is also projected to decrease under all assessed scenarios, but in much lower proportions. At warming levels of 1.5°c to 5°C, the Arctic will remain covered by winter sea-ice over the course of this century, but with a lowered sea-ice extent. Above these warming levels however, an abrupt collapse of the Arctic winter sea ice has been observed in several models due to local positive feedbacks, the process being self-amplifying as the loss of sea ice reduces the reflectance of solar radiations and increases temperatures locally. This makes the Arctic winter sea ice collapse a credible tipping point candidate. The likely threshold at which this tipping point would be crossed has recently been estimated at 6.3°C (McKay et al., 2022[11]).

Figure 2.7. September Arctic sea ice area projections to 2100



Note: September Arctic sea ice area in 10^6 km2 based on CMIP6 model simulations. Very likely ranges are shown for SSP1-2.6 and SSP3-7.0. The Arctic is projected to be practically ice-free near mid-century under mid and high GHG emissions scenarios.
Source: (IPCC, 2021[69])

Beyond 2100, the Arctic summer sea ice extent is anticipated to still be linearly correlated with global mean temperatures, implying a continued decline unless anthropogenic emissions are stabilised (Fox-Kemper et al., 2021[25]). In scenarios where temperatures begin to decrease, the Arctic summer sea ice recovers with a short lag of a few years to decades.

Impacts of Arctic sea ice loss

Oceanic and climatic conditions

Sea ice area changes impact exchanges of energy fluxes between the atmosphere and the ocean, and therefore influence atmospheric, oceanic and climatic conditions. The surface-albedo feedback results from the reflectance of solar radiations on the Earth's surface. The largest contributions in surface-albedo changes over the last decades have by far been due to changes in sea ice coverage, alongside changes in global snow cover (Forster et al., 2021[75]). Sea ice loss therefore amplifies warming. One study assessed that the decline in sea-ice feedbacks will contribute to reducing the so-called transient climate response (TCR) of the Earth, which is the amount of warming following a doubling of CO_2-eq concentration[7], under high cumulative emissions (Leduc, Matthews and de Elía, 2016[76]). Surface-albedo feedbacks due to the loss of sea ice have already played an important role in the amplification of warming in the Arctic, where surface temperatures have increased by more than double the global average in the last decades. A shift to a completely ice-free Artic ocean would highly reduce seasonal temperature variability and shorten the cold season (Lee, 2021[12]).

Arctic sea ice loss also contributes to ocean acidification. There is robust evidence that freshwater inputs from melted sea-ice enhances air-sea CO_2 exchanges and consequently, ocean acidification (Canadell et al., 2021[47]). Observed ocean surface acidification is currently largest in polar and subpolar regions (Canadell et al., 2021[47]).

Impacts on other tipping elements of the cryosphere

By affecting surface-albedo feedbacks and leading to warming amplification in the Arctic, sea-ice loss is contributing to losses in other components of the cryosphere. Amplified Arctic warming is accelerating permafrost thaw rates and Arctic ice sheet surface melt. Sea ice loss also has the potential to contribute to Antarctic ice sheet mass loss. Indeed, there is some evidence that sea ice coverage and thickness act as a control on ice sheets by affecting iceberg calving rates and ice-shelf flow in Antarctica (Fox-Kemper et al., 2021[25]). One study found evidence that regional loss of sea-ice had contributed to the disintegration of some ice shelves in the Antarctic Peninsula between 1995 and 2009 (Massom et al., 2018[77]). The loss of sea ice that is close to ice shelves additionally leads to higher solar heating in surface waters and increased sub-shelf melting (Fox-Kemper et al., 2021[25]). Through these two processes, sea ice decline could favour mass loss of nearby ice shelves, although there is only scarce evidence to substantiate the existence and extent of the underlying processes.

Polar ecosystems

Sea ice is also critical for polar and marine life, as unique ecosystems have developed to adapt to the impact of sea ice on light penetration, its regulation of water physics, chemistry and biology, as well as the strong seasonality of ice coverage. In particular, these ecosystems are marked by phytoplankton blooms when solar radiation seasonally returns with the melting of ice, which form the basis for polar food webs (Cooley et al., 2022[78]). Their disappearance has cascading effects up to top predators. As sea ice is lost, animals are at risk of local extinction – including polar bears and some seals and sea lions in the Arctic (Parmesan et al., 2022[54]).

The near-term risks for biodiversity loss have been assessed as very high in Arctic sea ice ecosystems by the IPCC WGII (IPCC, 2022[79]), including at 1.5°C to 2°C warming levels (O’Neill, 2022[80]). Polar ecosystems are already highly affected by climate change, with observed changed species distributions and abundances. The range of polar fish and ice-associated species has contracted to the benefit of temperate species. The loss of breeding and foraging habitat threatens the survival of sea-ice dependent seals, polar bears, whales and seabirds (Cooley et al., 2022[78]). Under an intermediate emission scenario (RCP4.5), a reduction in adult survival across most bear populations is projected by 2060, threatening the species with extinction (Molnár et al., 2020[81]). One of the main planned adaptation options for ecosystem conservation has been to expand protected areas to increase the resilience of ecosystems to climate change. However the complete loss of Arctic summer sea ice which is projected to occur at least once by the mid-century would be a case of a hard limit to ecosystems adaptation, where expanded protected areas would no longer be effective to protect unique Arctic ecosystems (O’Neill, 2022[80]).

Local livelihoods, food security and settlements

The Arctic hosts some of the largest fisheries on Earth in terms of catches (Cooley et al., 2022[78]). The access to wild foods is a primary concern in the region under a warming climate and polar ecosystem shifts, with loss of sea ice posing risks in terms of food security for coastal and inland communities. Some communities are dependent on sea ice quality and season length for hunting and transportation (Pearce et al., 2015[82]). The loss of summer sea-ice puts their autonomy at risk, as well as the conservation of traditional knowledge based on sea ice uses (Cooley et al., 2022[78]). In addition, the decline in the sea ice area along the Arctic coastline reduces natural coastal protection and enhances energetic wind-wave conditions, putting Arctic coastal settlements at risk through increased coastal hazards, namely open water storm surges, coastal erosion and flooding (Arias et al., 2021[10]).

Opportunities and risks from increased shipping traffic and resource extraction

The extent and seasonality of Arctic sea ice determines the viability of shipping routes as well as oil and gas exploration and exploitation. As the Arctic will more often become ice-free during the summer, new shipping lanes will become available and the season for offshore resource extraction will expand (Xie et al., 2015[83]). Concerns about associated geopolitical tensions and potential climate conflicts over access to shorter and more economic shipping routes (such as the Northwest Passages) and offshore hydrocarbons have been raised (Bezner Kerr, 2022[84]).

2.4. Modelling the economic cost of climate tipping points

As stressed by climate scientists [e.g. (Lenton et al., 2019[3])] and previous sections of this report, several tipping points could be crossed under current policy trajectories. In fact, it is increasingly understood that some tipping points may be crossed at lower thresholds, and thus far sooner, than previously thought, with potentially devastating consequences already this century. Climate tipping points are therefore not simply a problem of the future. Rather, the risk of crossing climate system tipping points has clear implications for short- and medium-term policy making. This adds to the urgency of considering climate tipping points in global economic costs estimations and economic analyses of climate change.

However, current modelling of the economic costs of climate change generally do not consider the possibility of large-scale singular events such as tipping elements (Rose, 2022[85]). Due to this gap in current economic modelling on climate change, and exacerbated by difficulties in connecting the physical science modelling with economic models, most existing estimates of the costs of reaching tipping points are in fact conservative. Estimates of climate impact damages serve as a key input to calculations of the social cost of carbon (SCC) – i.e. the marginal cost of the impacts caused by the emission of an additional tonne of carbon dioxide, a key climate policy input which allows a comparison of the costs and benefits of mitigation efforts. Estimates of the SCC are generally acquired through Integrated Assessment Modelling (IAM), combining socio-economic, emission and climate modules. However, IAMs have received criticism for underestimating damages from climate change, including by overlooking the risk of crossing climate tipping points (Riahi, 2022[86]).

Economic analyses that incorporate the risk of one or several tipping points show that the risk of tipping points significantly increases the present cost of GHG emissions. However, the representation of tipping points and their impacts differs across studies, as do assumptions about the discount rate and methodological choices on the treatment of uncertainty. These differences lead to large variations in the estimated SCCs – from only a 5% increase when only taking into account the Greenland ice sheet tipping point (Nordhaus, 2019[87]) to a potential doubling (Dietz et al., 2021[88]) and up to an eightfold increase when accounting for several interacting tipping points (Cai, Lenton and Lontzek, 2016[7]). Overall, analyses that incorporate several tipping points and capture part of their interactions show the largest increases in the SCC, indicating that, when accounting for tipping points, the global benefits of limiting warming below 2°C outweigh the mitigations costs over this century (Cai and Lontzek, 2019[89]; Cai et al., 2015[90]; Dietz et al., 2021[88]). Table 2.3 provides an overview of the studies that incorporate one or several tipping elements into an economic analysis, of their methodologies and of their key results in terms of SCC. Going beyond aggregate cost estimates, the suitability of climate to human life ("human climate niche") will also change be drastically with the crossing of tipping points, with potentially large effects on socio-economic systems. For example, even a moderate level of warming a tipping the Atlantic Meridional Overturning Circulation leads to a climate less suited to humans in Europe and parts of South America (OECD, 2021[5]).

Table 2.3. Overview of recent economic analyses incorporating the risk of tipping points

Study reference	Tipping element(s) considered	Modelling framework and representation of tipping points and damages	SCC outcomes	Key results** – Increase in economic cost / Optimal warming level***
(Cai et al., 2015[90])	Single stylised tipping point	Use the DSICE* model (stochastic IAM based on the DICE* model) with relative price effects. The tipping point risk is represented as an abrupt and permanent loss of welfare – a 5% reduction in the value of market and nonmarket goods and services. The probability of tipping depends on warming levels (5% annual probability at 4°C).	Introducing the possibility of a future stochastic tipping point increases the initial carbon tax by more than a factor of 3 to USD 154 per tCO_2 (compared to a DICE with relative price effects).	+200% 2°C
(Lontzek et al., 2015[91])	Single stylised tipping point	Incorporate a stochastic potential tipping event into the DSICE* model, with a cumulative probability of tipping of ∼2.5% in 2050, ∼13.5% in 2100 and ∼48% in 2200. Assumed damages from the tipping point are a 10% reduction in global GDP, taking 50 years to unfold.	Despite conservative default assumptions, the prospect of an uncertain future tipping point causes an immediate increase in the initial SCC by ∼50% to USD 55.6 per tCO_2.	+50-100% 2.4°C
(Lemoine and Traeger, 2016[92])	Three stylised tipping points: One climate feedback tipping point (representative of permafrost, ocean clathrates and loss of reflective ice); one tipping point reduces carbon sinks (e.g. Amazon forest dieback, saturation of the ocean CO_2 sink); the last tipping point only affects the economic damages	Stochastic version of the DICE* model. The hazard of crossing each tipping point increases with temperature. Overall the expectation of first crossing one of the thresholds is 2.5°C. The first two tipping points modify the climate dynamics in the model: climate feedback tipping point increases the warming response to a doubling of CO_2 from 3°C to 5°C. The weakened carbon sinks tipping point reduces the rate of atmospheric CO_2 removal by 50%. The third tipping point modifies the damage function of the model: if it occurs, then doubling anthropogenic warming increases damages eightfold rather than fourfold.	The SCC in 2015 nearly doubles to USD 11 when taking all three tipping possibilities and their interactions into account (compared to a DICE model where the ad hoc damage adjustments are removed). The economic damage tipping point has the strongest individual effect, increasing the optimal SCC by 30%. The feedback tipping point increases the optimal emission tax by 14%, and the carbon sink tipping point increases it by 8%.	+100%
(Cai, Lenton and Lontzek, 2016[7])	Five interacting tipping points: AMOC collapse, disintegration of the Greenland ice sheet, collapse of the West Antarctic ice sheet, dieback of the Amazon rainforest, and shift to a more persistent El Niño regime.	Stochastic version of the DICE* model (DSICE). Each tipping point results in a percentage reduction global GDP (from 5 to 15%), The combined reduction in GDP if all five tipping events occur is 38%. Each tipping point is also given a hazard rate which depends on temperature and on other tipping points being passed. Damages unfold over a transition time which is different for each.	The prospect of multiple future interacting climate tipping points increases the 2010 SCC nearly eightfold to USD 116 per tCO_2. The corresponding optimal policy involves an immediate, massive effort to control CO_2 emissions, which are stopped by mid-century, leading to climate stabilization at <1.5 °C above pre-industrial levels.	+700% 1.4°C
(Diaz and Keller, 2016[93])	Disintegration of the West Antarctic Ice Sheet	Stochastic version of the DICE* model (DICE-WAIS). Additional damages occur through the coastal impacts of SLR.	Because the full impacts unfold far in the future, the average SCC only increases by USD 2 to USD 21 per tCO_2 (about 10% increase).	+10%
(van der Ploeg and de Zeeuw, 2018[94])	Single stylised tipping point.	Ramsey economic growth model. The tipping point is modelled as a catastrophic shock that would result in a 30% loss of GDP. The hazard of the shock rises with global warming (1.2% probability at 2.5°C, 6.8% probability at 6°C). The impact of the shock unfolds over either a decade, half a century or a century.	If precautionary savings to prepare for the climate catastrophe are made, the long-run optimal carbon tax grows from USD 85 to only USD 91 per tCO_2 in the case of fast impacts, and even lower in the case of slower impacts (half a century or a century).	+7%

(Nordhaus, 2019[87])****	Disintegration of the Greenland ice sheet (GIS)	DICE* model with an additional module – a simplified version of more complex models of GIS equilibrium and dynamics. The volume of the GIS depends on temperature, and the GIS fully melts at 3.4°C. Damages occur through SLR, with a linear damage function (1% of global output lost for each 1 m of SLR). Therefore complete disintegration of the GIS would lead to ≈7% loss in global income each year.	Adding the risk of GIS disintegration, the increment to the SCC is close to zero at moderate discount rates and as high as 5% at very low discount rates and high melt rates. This can be explained by the very long timescale over which damages from the GIS meltdown occur.	+0-5%
(Yumashev et al., 2019[95])	Nonlinear Arctic feedbacks: permafrost feedback and surface albedo feedback from decreasing sea ice and land snow.	PAGE-IC IAM with permafrost and albedo feedback modules – simplified versions of complex climate models. Both tipping points lead to additional warming over the entire period in the model.	Adding the nonlinear effect of permafrost and surface albedo effects on temperatures, the total economic effect of climate change (mitigation costs, adaptation costs and climate-related economic impacts aggregated until 2300) is increased by USD 24.8trillion for the 1.5 °C target, USD 33.8 trillion for the 2.0 °C target, USD 50.3 trillion for the 2.5 °C target and USD 66.9 trillion for the NDCs scenario.	+4-5.5% 1.5°C
(Taconet, Guivarch and Pottier, 2021[96])	Single stylised tipping point	The tipping point is introduced in a DICE-like IAM as a stochastic risk whose hazard rate depends on temperature, leading to a permanent drop in GDP (between 0% and 50%).	Depending on other parameters, for a 10% productivity shock induced by the tipping point, the SCC triples from USD 34 to USD 103 per tCO_2.	+200%
(Dietz et al., 2021[88])	Eight tipping points: Permafrost carbon feedback, Ocean methane hydrates, Arctic sea ice/Surface Albedo Feedback, Amazon dieback, GIS disintegration, WAIS disintegration, AMOC slowdown, Indian summer monsoon variability.	Meta-analytic IAM that includes replicas of each tipping point module in the literature. The modelled impact channels of the tipping points are the following: CO_2 and CH_4 emissions (permafrost), CH_4 emissions (ocean hydrates), changes to warming (Arctic sea ice loss), CO_2 release (Amazon forest dieback), increased SLR (GIS and WAIS disintegration), change in the relationship between global and national mean surface temperatures (AMOC slowdown), GDP per capita in India (Indian monsoon). The model aggregates country-level damages from temperature changes and SLR, as well as damages from the summer monsoon variability in India, based on recent high-resolution empirical evidence and modeling.	Collectively, the eight tipping points increase the SCC by ∼25%, with a ∼10% chance of more than a doubling the SCC. Economic losses are increased almost everywhere globally. The largest effects are due to the dissociation of ocean methane hydrates and thawing permafrost. Results are probable underestimates, given that some tipping points, tipping point interactions, and impact channels are not covered.	+25%-100%

Note: : This table presents a selection of recent studies based on (Riahi, 2022[86]) and on authors' judgment, but a more complete list of over 50 economic analyses incorporating the risk of tipping points can be found in (Dietz et al., 2021[88]). The Dynamic Integrated Climate and Economy (DICE) model is a deterministic (i.e. not integrating randomness) IAM that is widely used in climate change research and policy. The Dynamic Stochastic Integration of Climate and Economy (DSICE) model is a stochastic (i.e. integrating uncertainty with probability distributions) IAM that is based on the DICE.

** The numbers presented in the column 'Key results" are not directly comparable, considering that they result from studies modelling different types and numbers of tipping points with large variations in assumptions. Additionally, authors have selected here an approximate key result for each of the studies considered, but these typically provide a range of estimates of the change in economic costs with varying parameters. *** Increase in the economic cost refers to the increase in SCC when incorporating tipping point(s) except for (Yumashev et al., 2019[95]) where it refers to the increase in the total economic effect of climate change. Optimal warming level refers to the optimal temperature warming level in 2100 found in the study when taking into account the risk of tipping point(s). This result is reported here if it is provided by the study considered. **** These results have been strongly debated in the scientific literature, including on issues such as the choice of discount rates and the estimates of climate damage. See for example (Hänsel et al., 2020[97]).

Because governments are more likely to adopt climate policies only if their intended benefits justify their costs, the social cost of carbon constitutes a key metric that informs national and international climate policy on the optimal level of carbon taxes and of regulation. Estimates are regularly provided to governmental agencies through ad-hoc working groups – for example the Interagency Working Group on Social Cost of Carbon in the USA (Interagency Working Group on Social Cost of Carbon, U.S. Government, 2016[98]). The fact that the estimates informing climate policy have until very recently failed to take into account tipping points means the cost of carbon has so far been very severely underestimated, justifying a much weaker and slower response to climate change than needed. Indeed, economic analyses of climate change have mostly supported policies with delayed action, no peaking of emissions in this century, and with optimal warming levels that go far beyond 2°C by the end of century, generally reaching 3°C or 4°C (Cai et al., 2015[90]). Analyses that incorporate the risk of tipping points, and especially the risk of multiple interacting tipping points, show that the cost of delayed action is much higher than previously estimated. Incorporating more realistic projections of the physical science of climate change in economic models results in a much more stringent optimal policy trajectory, one that keeps warming to well-below 2°C, requiring emissions peaking early in the 21st century. The latest attempts at modelling the economic cost of tipping points thus show that these are hugely important for determining the optimal ambition of climate policy and support a well-below 2°C temperature goal. Therefore these latest estimates of the social cost of carbon should be taken account by policy makers and inform updates of NDCs and of national policy ambitions.

There remain methodological challenges in integrating tipping points in IAM frameworks. It is crucial to improve the connection between the physical science basis and economic models by better capturing the dynamics of Earth System Models and their associated uncertainties in economic models and moving beyond highly stylised representations of these components. Importantly, while many studies incorporate a tipping element into their modelling framework, physical scientists have highlighted the need to account for all tipping elements and for their interactions so as to capture the risk of cascading tipping points (Lenton et al., 2019[3]). Key open issues in this area of research were discussed at the expert workshop on climate tipping points (OECD, 2021[99]) and are presented in Box 2.1. Overall, there needs to be continued research in the field to improve and mainstream the representation of tipping points into economic assessments (Lenton and Ciscar, 2012[100]), especially since existing estimates still overlook some tipping point impacts and possible interactions and are thus likely still too optimistic.

Box 2.1. Summary of the Expert Workshop on climate tipping points

Main outcomes and key open issues discussed at the workshop

As part of the on-going OECD Horizontal Project on *Climate and Economic Resilience*, the OECD organised an Expert Workshop in October 2021 to discuss the current state of scientific understanding surrounding climate and economic tipping points. Acknowledging that models underpinning most economic analyses of climate change rarely take into account abrupt changes and climate tipping points, even though such changes are a major determinant of the optimal levels of policy effort, the workshop investigated, ways to better assess the economic consequences of climate tipping points with existing models as well as new modelling approaches taking into account the risks from climate tipping points. In this regard the workshop considered progress in understanding the climate emergency, and in determining policy pathways to avoid the potential for catastrophic outcomes.

Climate tipping points and early attempts to incorporate them into policy analysis

During the workshop presentations and discussions, Tim Lenton, Director of the Global Systems Institute and Chair in Climate Change and Earth System Science at the University of Exeter, stressed that several tipping points could be crossed with significant probability in the near- and medium-term if the current emissions trajectories are upheld. Therefore, he argues that respecting the Paris Agreement's temperature target range is crucial to avoid crossing several of the tipping points. To achieve this, it is urgent to incorporate climate system tipping points in economic analyses. Elizabeth Kopits, Senior Economist at the National Center for Economic Analysis at the US Environmental Protection Agency, showed that early modelling efforts that attempted to include large-scale singular effects into Integrated Assessment Models (IAMs) used ad-hoc parameters without empirical bases and without considering the adequate multi-decade time horizons. She highlighted the need to better capture the dynamics of Earth System Models and their associated uncertainties into economic models and to cover all potential earth system changes and tipping elements, instead of assessing one in isolation, to account for potential cascading effects.

Recent attempts to model the economic impacts of climate tipping points

As pointed out by Shardul Agrawala, Head of the Environment and Economy Integration Division at the OECD Environment Directorate, cost-benefit analysis incorporating climate tipping points to determine optimal mitigation and adaptation policies requires a better estimation of tipping point-induced economic damages, including their quantifications, magnitude, timescales and geographies. Historically, such studies have failed to accurately capture the timescales, dynamics, and uncertainties associated with the biophysical aspects of tipping points, to consider coupling between tipping points, and to model welfare losses in a non ad-hoc way.

Simon Dietz, Yongyang Cai and Christophe Traeger were invited to present their recent work modelling the economics of interactive tipping points (see Table 2.3 for a summary of their methodologies and results). William Nordhaus stressed the need to improve coupling of economic and geophysical models, particularly by introducing better and more complex geophysical modelling into economic models. Another significant issue raised by Nordhaus is that most existing studies are global and mask potentially large heterogeneity within countries. A corollary from this discussion is the need for higher resolution economic data, which can be better integrated with disaggregated geophysical data. Nordhaus further brought to light the issue surrounding the relationship between temperature and economic growth. Modelling this relationship as either a one-off shock to output or as a permanent decrease in the growth rate has immensely different implications for projecting the costs of future climate change. The discussion that followed stressed the importance of considering adaptation to climate change and innovation in current modelling frameworks.

Directions for future work

The workshop's discussions stressed that progress has been made in past decades in incorporating the risk of climate tipping points into economic analyses. They highlighted the importance of including the possibility of interacting and cascading tipping points, and of providing a unified framework in which to include tipping points of varying sources. A key priority identified for research going forward is the need to improve the link between economic and geophysical modelling. Another important recommendation that emerged from the workshop was to account for several impact channels other than mean temperature change (e.g. sea-level rise, extreme weather events).

Source: Expert workshop on Economic Modelling of Climate and Related Tipping Points: Workshop Report (OECD, 2021[99])

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Notes

[1] Under a RCP8.5 scenario with warming above 3°C in 2300.

[2] To measure the changing resilience of the Amazon rainforest, the authors use a stability indicator to predict the approach of a dynamical system towards a bifurcation-induced critical transition.

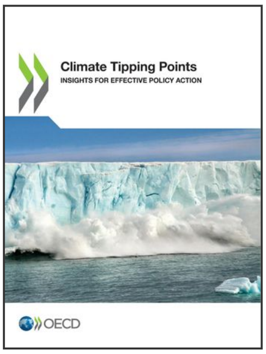
[3] Or 143 $GtCO_2$-eq

[4] IPCC's remaining carbon budgets from 2020 onwards for maintaining warming below these levels by the end of the century with a 67% chance.

[5] According to the IPCC, storylines are "a way of making sense of a situation or a series of events through the construction of a set of explanatory elements. Usually, it is built on logical or causal reasoning. In climate research, the term storyline is used both in connection to scenarios as related to a future trajectory of the climate and human systems and to a weather or climate event. In this context, storylines can be used to describe plural, conditional possible futures or explanations of a current situation, in contrast to single, definitive futures or explanations" (IPCC, 2021[1]).

[6] Proposed explanations are large internal variability and opposing trends between regions of the Antarctic. There is additionally very low confidence in the projections of a decrease of the Antarctic sea ice, because of a lack of consistency across model simulations and satellite observations, and a lack of paleo-records and reconstructions before the satellite observations began in the 1970s (Gulev et al., 2021[72]).

[7] TCR differs from Equilibrium climate sensitivity (ECS) as it refers to the amount of warming that occurs at the time the CO_2-eq concentration doubles following a linear and steady increase in emissions (having increased gradually by 1% each year), as opposed to when the system has reached equilibrium. TCR is more closely related to the way cumulative GHG emissions have changed in the more recent past.



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