Climate Tipping Points

INSIGHTS FOR EFFECTIVE POLICY ACTION

OECD

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Foreword

Climate change is creating adverse conditions for both ecosystems and societies that go beyond anything in the recorded history of humanity. If climate tipping points are crossed these trends could worsen exponentially, leading to profound changes in our planet and in the natural and socio-economic systems it sustains. This OECD report provides key insights for policy-makers on how to take account of the threat of tipping points in climate policy today. It also reviews the most recent scientific information, concluding that crossing tipping points is increasingly likely at even low levels of global warming, with the time remaining to avoid such disastrous outcomes rapidly running out.

There is indisputable evidence that the planet is approaching tipping points. Unexpectedly high melt rates of the Greenland and Antarctica ice sheets over the past three decades, the loss of Amazon rainforest resilience, the drastic slowdown of important ocean currents and the acceleration of Arctic permafrost melting are just some examples. If tipped over the edge, the changes in even one of these sub-systems can cascade, with deep and often irreversible global consequences for natural and human systems, for decades or centuries to come. We are rapidly approaching warming of 1.5°C, which modelling projections increasingly suggest will trigger some of these tipping points. This makes it imperative to take collective, ambitious and bold action to mitigate greenhouse gas emissions before the end of this decade.

In light of the mounting scientific evidence, this report argues that the earlier generally accepted advice – that the risk of crossing tipping points is low – can no longer be accepted. The dramatic impacts associated with tipping points mean that urgent action is needed to avoid crossing them, and to prepare for their effects if they are crossed. This means redoubling efforts to keep rising temperatures below 1.5°C. It also means that adaptation measures need to be transformational, necessitating stringent and even drastic action to minimise short-term losses and to build resilience in the medium-term. Moreover, Earth sub-systems susceptible to tipping points must be closely and urgently monitored.

Tipping points can be seen as inflection 'points of no return' in the Earth system. Unlike other climate impacts, crossing tipping points cannot be counteracted by more action later. The time for acting to protect our planet and the future generations which depend on us is now.

Jo Tyndall

Director

Environment Directorate

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Executive Summary

A tipping point is a critical threshold beyond which a system reorganises, often abruptly and/or irreversibly and a tipping element is an Earth system component that is susceptible to a tipping point. Key tipping elements include the collapse of the West Antarctic and Greenland Ice Sheets, the melting of the Arctic Permafrost, the collapse of the Atlantic Meridional Overturning Circulation and the dieback of the Amazon Forest. **The goal of this report is to review the state of knowledge on climate system tipping points and to make recommendations for a wide range of stakeholders, on how climate risk management strategies can adequately reflect the risks of crossing tipping points.**

The crossing of climate system tipping points may lead the climate to change regionally or globally, both by substantially affecting the Earth system and as a result of tipping cascades, leading to potentially catastrophic impacts. Tipping points impacts will 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, leading to severe effects on 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 would lead to world-wide impacts through e.g. contributing to additional greenhouse gas emissions into the atmosphere and temperature feedback loops or to faster sea-level rise.

Recent state-of-the-art research shows that important tipping points are already “possible” at current levels of warming and may become “likely” within the Paris Agreement range of 1.5 to 2°C warming, questioning the previously well-accepted notion that climate tipping points have a low probability of being crossed under low levels of warming. Despite marked improvements in the understanding of the high risks associated with climate tipping points, global policies explicitly targeting risks of tipping points remain virtually non-existent. Being traditionally classified as low-probability, climate system tipping points are often misinterpreted as having a high-probability of not occurring and therefore omitted from climate policy decision making. Yet, the current scientific evidence unequivocally supports unprecedented, urgent and ambitious climate action to tackle the risks of climate system tipping points.

In terms of climate mitigation, the existence of climate system tipping points means it is vital to limit the global temperature increase to 1.5°C, with no or very limited overshoot. This effectively reduces the number and shapes of possible emissions pathways towards 1.5°C and renders lenient interpretations of the Paris Agreement temperature goal incompatible with its resilience goal, as, in the face of tipping points, simply reaching the temperature target does not ensure a resilient planet and society. Committing to net-zero emissions by mid-century is not enough in itself; it is about achieving net-zero with urgent, early and deep reductions in emissions already this decade. Near-term policies in line with the mitigation targets in current Nationally Determined Contributions (NDCs), put limiting warming to 1.5°C without overshoot out of reach altogether. It is therefore critical that 2030 ambition in NDCs is considerably strengthened in the very near term, and that commensurate policies are implemented at relevant timescales to meet these revised targets.

Transformational adaptation is particularly important to build resilience and prepare for the potential severe impacts of crossing tipping points. Even if global warming levels are kept to 1.5°C with no or limited overshoot, some climate system tipping points and their associated impacts may already be unavoidable at current levels of warming. Transformational adaptation is that which leads to a change in the fundamental characteristics of human and natural systems so that the capacity of these systems to cope with potential hazards is increased. It could therefore necessitate stringent measures to reduce impacts, that have the potential to disrupt in the short-term current economic and social activities, but which have the ability to avoid drastic losses in the short- and mid-term and to generate a range of benefits to human well-being and to planetary health in the long-term.

Technological development and innovation have a crucial role to play in contributing to a better understanding of the climate system in general as well as in the development and implementation of approaches to reduce and manage the risks of crossing climate system tipping points. Indeed, technologies for better monitoring and modelling of the climate system, such as remote observation equipment, high computing power, mapping software and telecommunication systems, are and will remain essential for characterising how the risk of crossing of climate tipping points may evolve over time and space. In addition, carbon dioxide removal technologies play a key role in limiting warming to 1.5°C with no or very limited overshoot. This is through creating “negative emissions”, which can help accelerate – rather than displace – early deep emissions reductions and balance out harder-to-abate sectors that will continue to emit during the first half of the century. Concerns around CDR technologies however exist; investments are needed to enhance understanding of these trade-offs and to better evaluate the risks associated with, on the one hand overcoming barriers to scale-up these technologies, and on the other failing to employ them.

This report concludes that current scientific understanding of climate system tipping points challenges the generally accepted notion that tipping points have a low probability of being crossed under moderate levels of warming, which adds further urgency to the climate challenge and requires a shift in how tipping points are treated in climate policy today. For climate strategies to adequately reflect tipping-point risks, they need to drive drastic cuts in emissions this decade, including through enhanced NDCs and accelerated transformations towards net-zero, while also adapting to climate impacts. Scaling up and further developing technologies supporting these transformations and for monitoring tipping elements is also key. Given the potential for catastrophic impacts associated with climate system tipping points, missing the opportunity to implement such strategies could lead to immeasurable economic and ethical costs in the near-future.

1

Climate tipping points: a critical moment for action

This introductory chapter provides a short overview of current understanding of climate system points, including on how this knowledge has evolved over the years, and introduces some notions and definitions relevant for the remainder of the chapters. While uncertainties remain, the chapter alerts to the fact that there is high confidence that current levels of climate action fall far short from what is needed to avoid the dangerous impacts of crossing climate tipping points.

According to the Intergovernmental Panel on Climate Change (IPCC), a tipping point is “a critical threshold beyond which a system reorganises, often abruptly and/or irreversibly” and a tipping element is “a component of the Earth system that is susceptible to a tipping point” (Chen, 2021[1]). Climate system tipping points may lead the global or regional climate to change from one stable state to another stable state — one that is potentially much less suitable for sustaining human and natural systems — or may result in changes that occur non-linearly and faster than the rate of change expected from climate forcing [1] (Alley et al., 2003[2]; Lee, 2021[3]). Such abrupt and/or irreversible changes are particularly dangerous because they can occur on timeframes that are short enough to defy the ability and capacity of human societies to adapt to environmental pressures. As such, the impacts of crossing climate tipping points would be severe and widespread, with potentially catastrophic consequences for human and natural systems. The goal of the present report is to review the state of knowledge on climate system tipping points and to reflect on the implications for near-term climate action. The report does not aim to be comprehensive in its literature review of the different climate system tipping points. Rather it aims to provide to policy makers needed relevant information that can lead to development of climate strategies that directly integrate the threat of tipping points.

The issue of climate tipping points was first introduced by the IPCC about two decades ago when they were projected to possibly occur in “the next few centuries if greenhouse gas concentrations continue to increase” (IPCC, 2001[4]). However, more recent IPCC reports recognise the risk of crossing tipping points at much lower levels of warming and therefore at considerably shorter timescales (IPCC, 2018[5]; IPCC, 2019[6]). Indeed, the latest IPCC report recognises that low-likelihood outcomes, that is, outcomes with a low-probability of being crossed at low-levels of warming including the crossing climate tipping points, cannot be ruled out already this century and must be an integral part of risk management strategies (IPCC, 2021[7]). More recent research shows that current global warming of ~1.1°C above pre-industrial already lies within the uncertainty range of important tipping elements and that further tipping elements will become “possible” or even “likely” within the Paris Agreement range of 1.5 to <2°C warming (McKay et al., 2022[8]). These findings highlight the immediate danger of tipping points, and question whether it remains pertinent to continue classifying tipping points as low-likelihood outcomes.

There is evidence that a number of tipping points may already have been crossed or are close to being crossed. For example, it cannot be ruled out that West Antarctic Ice Sheet (WAIS) and the Greenland ice-sheet tipping points have already been crossed, while low-latitude coral reefs and the abrupt permafrost thaw tipping points are likely to be crossed if temperatures increase above 1.5°C (McKay et al., 2022[8]). In addition, the Atlantic Meridional Overturning Circulation (AMOC) has been slowing down in the last two decades (Good et al., 2018[9]) and is at its weakest for over a millennium (Caesar et al., 2021[10]; Boers, 2021[11]). If triggered, these tipping points could potentially lead to cascading global impacts, including triggering further tipping points, with dramatic effects on human and natural systems (Lenton et al., 2019[12]).

At the global scale, such cascading effects, where the crossing of one tipping point leads to the triggering of further tipping elements, could lead to a new ‘hothouse’ global climate that would be less suitable for human existence (Steffen et al., 2018[13]; Lenton et al., 2019[12]). 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 (Arias et al., 2021[14]). Given the dynamic interaction between these potential climate hazards and socio-economic systems, it is particularly important to better understand tipping point dynamics and their likely impacts in order to minimise and manage the risk of crossing tipping point thresholds.

However, uncertainties remain in understanding the climate risks associated with crossing tipping points. Climate risk can be understood as the result of the interactions between climate-related hazards and the exposure and vulnerability of the affected human and ecological systems to the hazard (IPCC, 2021[15]). Uncertainties in understanding the risk of climate tipping points stem therefore from these different determinants of risk. First, uncertainties arise from the complexity of earth and climate systems, with multiple stressors unfolding in parallel and the potential for cascading impacts across systems, making it impossible for singular climate related hazards to be predicted with accuracy with current knowledge (Ara Begum, 2022[16]). Second, uncertainties arise as vulnerability, exposures, socio-economic development and decision making may change over time (*Ibid*). Climate risk is a highly complex notion due to the dynamic nature of the interaction of its determinants, the behaviour of complex systems in which it operates, including non-linear responses and the potential for surprises, as well as the complex nature of the responses to climate risks themselves (*Ibid*).

There are also large uncertainties that arise when estimating the potential costs of crossing tipping points. A recent study estimated that climate tipping points increase the social cost of carbon (SCC), a common measurement of the economic impact of climate change, by approximately 25%, with positively skewed results indicating a 10% chance that the SCC is more than doubled (Dietz et al., 2021[17]). While uncertainties and ambiguities remain in the understanding of some aspects of how climate change will unfold, especially regionally or locally, they must not be a cause of inaction. Indeed, considering the very high level of confidence in the relationship between global greenhouse gas emissions and global average temperature rise, as well as on the severity of potential impacts, larger uncertainties generally imply the possibility of larger climate risks and should therefore amplify, rather than weaken, the case for early, ambitious and effective climate action (OECD, 2021[18]).

Scientific advances are systematically leading to higher confidence in the potentially catastrophic impacts of continued warming, including evidence that irreversible tipping elements in the Earth's systems could already be triggered this century, with long-lasting effects over a timeframe of centuries to millennia (Lee, 2021[3]). The Working Group II (WGII) contribution to the Sixth Assessment report (AR6) of the IPCC assesses that the risk associated with crossing critical thresholds or tipping points remains *moderate*[2] at current levels of warming of about ~1.1ºC (high confidence) (WMO, 2022[19]). Such risks are projected to transition to *high* with warming between 1.5–2.5ºC (medium confidence) and to *very high* with warming between 2.5–4.5ºC (low confidence) (O'Neill, 2022[20]). This prediction emphasises the increased risks associated with surpassing or overshooting 1.5 ºC of warming during this century, even if temperature levels are brought back down at the end of the century.

These advances underline the urgent need for strategies that specifically address the risks of tipping points. Despite this significant progress, global policy efforts and action explicitly targeting those risks, both on reducing GHG emissions and adapting to potential impacts, remain intangible and highly insufficient. Global collective action on mitigating greenhouse gas emissions falls far short of what is needed to meet the globally agreed temperature goal of the Paris Agreement of "holding global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels" (Paris Agreement, 2015[21]). If pledges made by COP26 including in the Nationally Determined Contributions (NDCs) submitted and mid-century long-term legally-binding targets (e.g. net-zero by mid-century targets) are met, end-of-century temperature increase would reach 2.1°C (CAT, 2021[22]). If *all* net-zero targets are fully achieved (i.e. those adopted and those under discussion), the resulting temperature increase by the end of the century would be 1.8°C. Emissions trajectories in line with current policies and actions are however not in line with NDCs and would lead to a 2.7°C increase in global average temperature by the end of the century. All the more concerning is that global CO_2 emissions have rebounded since the COVID pandemic to their highest levels in history, indicating that emissions are going in the opposite direction even relative to insufficient NDCs. This lays bare the considerable discrepancy between short- and long-term targets and action on the ground (CAT, 2021[22]).

At current levels of action, there is therefore a high risk that the Earth system will cross critical thresholds or tipping points as temperature increase is projected to surpass 1.5ºC. The existence of climate tipping points requires stringent early action on GHG emissions, limiting the permissible temporary overshoot beyond 1.5ºC and thereby the ways by which the Paris agreement goal can be met, and rendering the current low level of climate action considerably more dangerous.

Efforts to adapt to climate change are increasingly being implemented worldwide but, similarly to mitigation, the rate and scale of adaptation progress still falls short of what is needed to keep up with growing risks (UNEP, 2021[23]). The IPCC estimates that at present 3.3 to 3.6 billion people are highly vulnerable to climate change (IPCC, 2022[24]). Climate tipping points exacerbate these risks. Their systemic scale, dramatic impacts and abrupt[3] nature pose significant challenges for human systems to adapt. For example, after a tipping element has been triggered, severe impacts can occur in short timescales, too rapidly for effective reactive adaptation responses, imposing hard limits for human systems to be able to identify, develop and adopt solutions to adapt to these impacts. Thus, taking into account climate tipping points is crucial for a comprehensive analysis of climate risk, not just to inform mitigation pathways, but also for effective adaptation design and implementation.

The first part of the report provides an accessible digest of the most recent scientific information on selected climate system tipping points in terms of the type of impacts associated with the crossing of tipping elements and associated probabilities and timescales. While non-exhaustive, this review intends to better characterise the risks of tipping points and identify knowledge gaps and potential ways to overcome these. Building on this scientific knowledge, the second part of this report discusses courses of action for better reflecting the risks of tipping points in climate policies and strategies. Notably, it aims at providing insights on how the knowledge available today on the longer-term effect of tipping points can inform near-term policy planning for mitigation, adaptation and other areas of action.

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Notes

[1] Climate or radiative forcing is the change in energy flux in the atmosphere caused by natural or anthropogenic factors of climate change, such as greenhouse gas emissions or increased water vapour. It is a direct measure of the amount that the Earth's energy budget is out of balance by external drivers of change.

[2] This assessment takes into account the different drivers of risk, i.e. physical hazards and the vulnerability and exposure of communities and ecosystems, based on literature-based expert judgement (Pörtner et al., 2022[25])

[3] According to the IPCC, "a large-scale abrupt 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." (IPCC, 2021[15])

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.

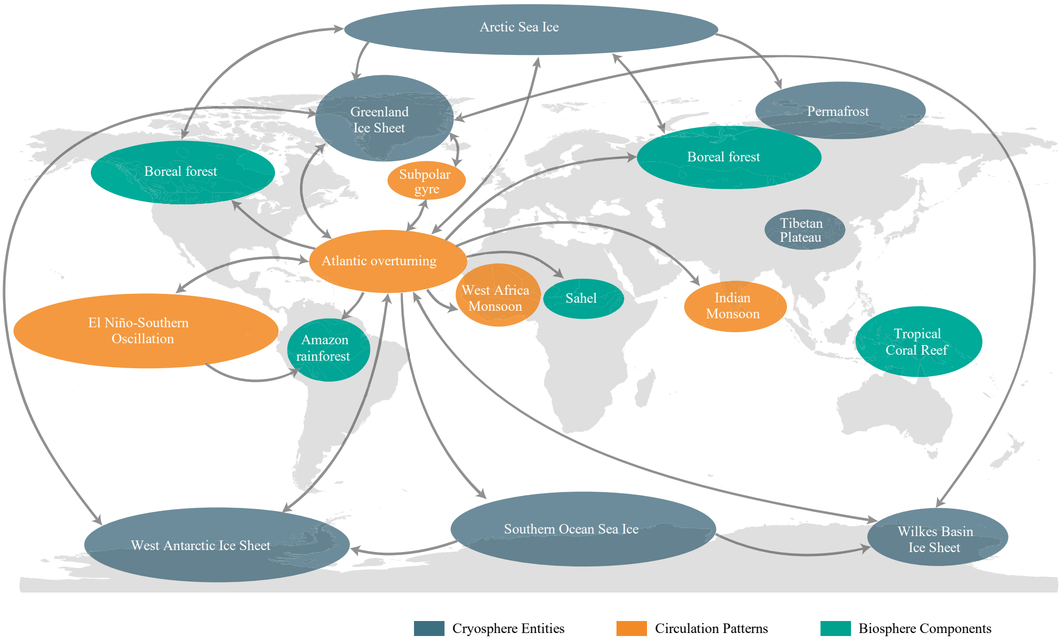
Recent findings suggest that many climate tipping points can be crossed, with a considerably higher probability and at much lower levels of warming than previously assumed and are an imminent threat today, challenging the previously well-accepted consideration that climate system tipping points are indeed 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]).

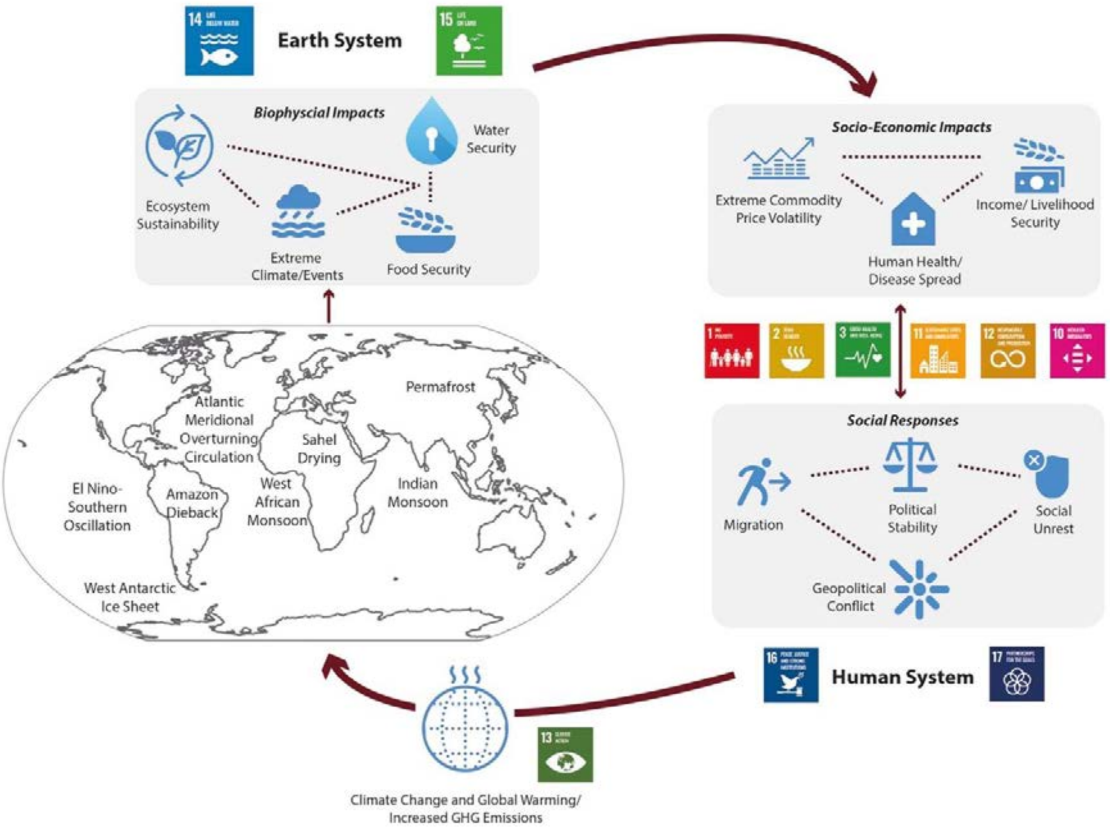
In the world today, shocks propagate quickly through sectors and international borders via international processes, such as global trade, financial flows and supply networks (Acemoglu et al., 2012[14]). These systemic risks remain poorly understood, making it a challenge to include them in risk assessment 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])

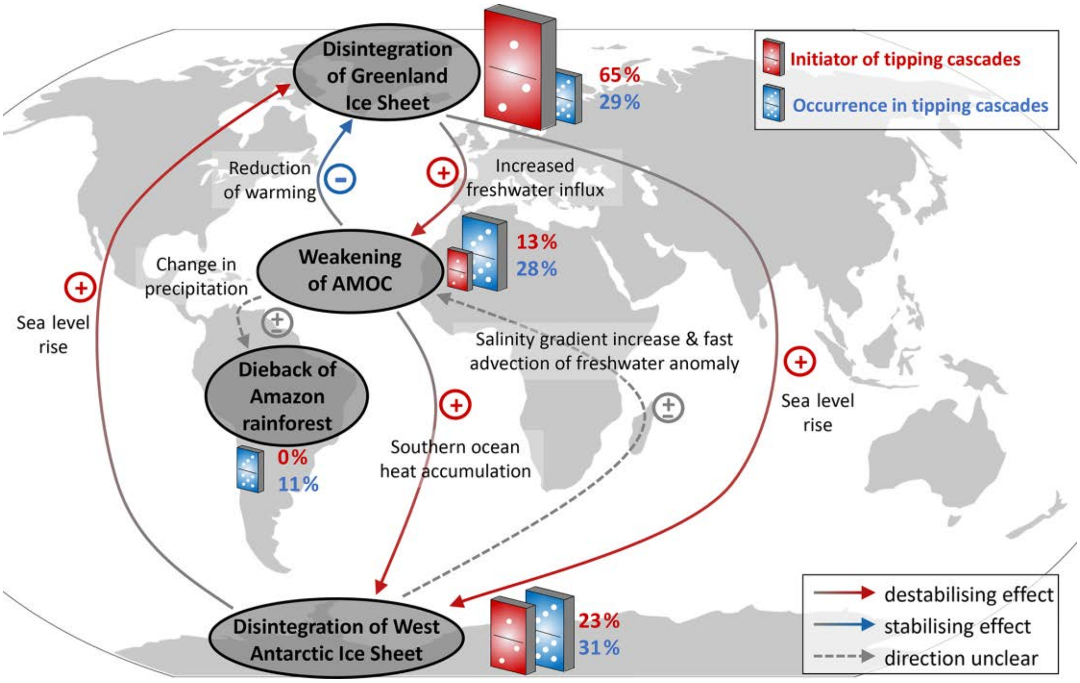
The potential for cascading impacts highlights the need for a better understanding of risk transmission mechanisms across sectors and international boundaries (Challinor, Adger and Benton, 2017[21]). Li et al (2021[22]) find that the “systemic risk induced by climate change is a holistic risk generated 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]).

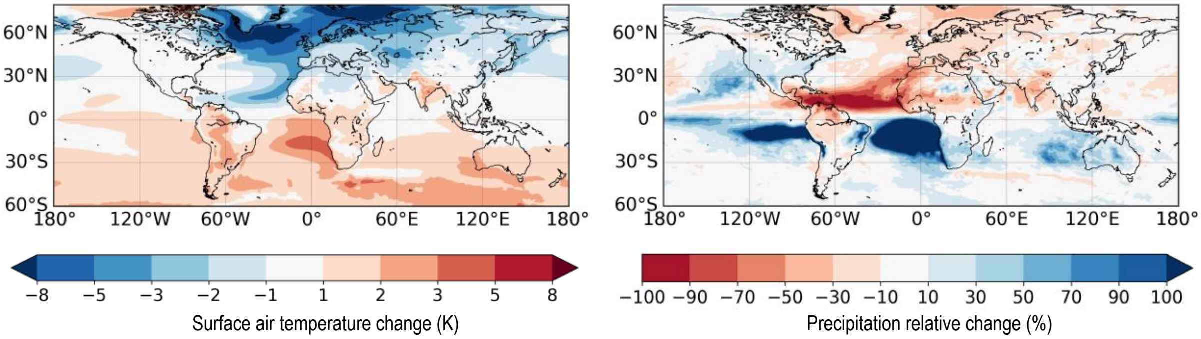
A recent analysis, synthesising paleoclimate, observational and model-based studies, gives a best estimate for a collapse of the AMOC at a threshold of 4°C (with a range of 1.4°C to 8°C). Observations suggest that the AMOC has weakened in 2004-2017 compared to 1850-1900. Reconstructions indicate the 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



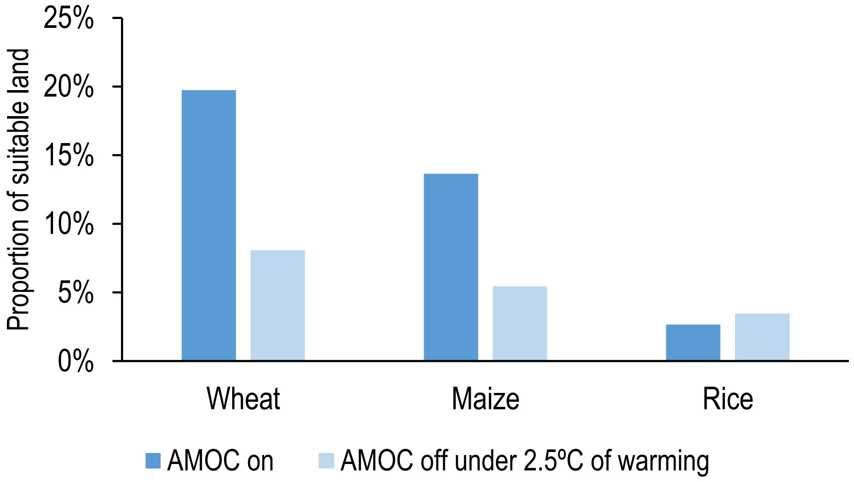
Note: Surface air temperature (left panel) and precipitation (right panel) response to AMOC-collapse scenarios. The analysis shows the impacts of an AMOC collapse under global warming using the future scenario SSP1-2.6 in the model HadGEM3-GC31-MM. The forcing scenario SSP1-2.6 refers to Shared Socio-economic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

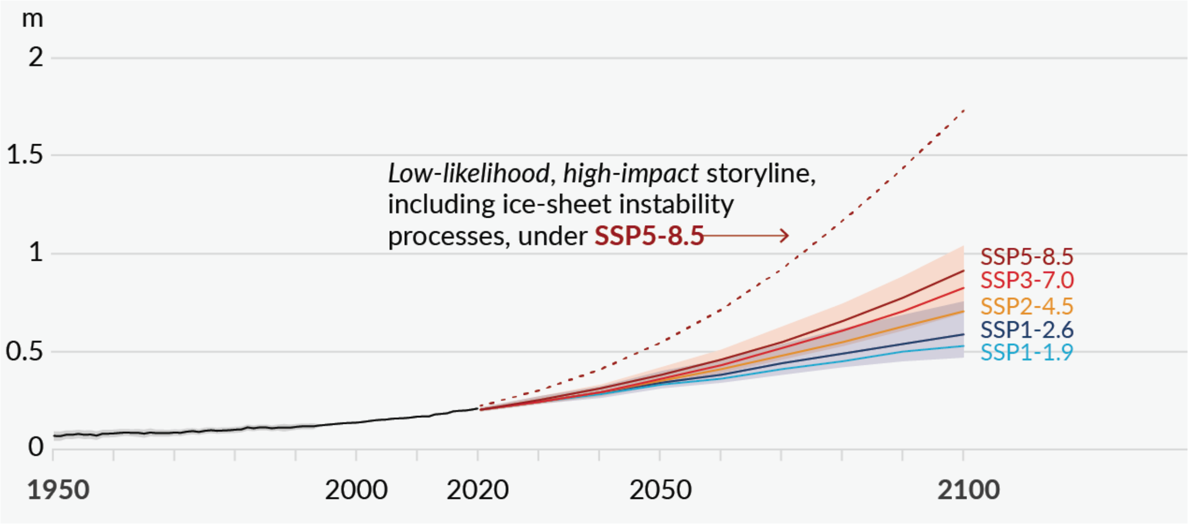
Impacts of ice sheets collapse

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.

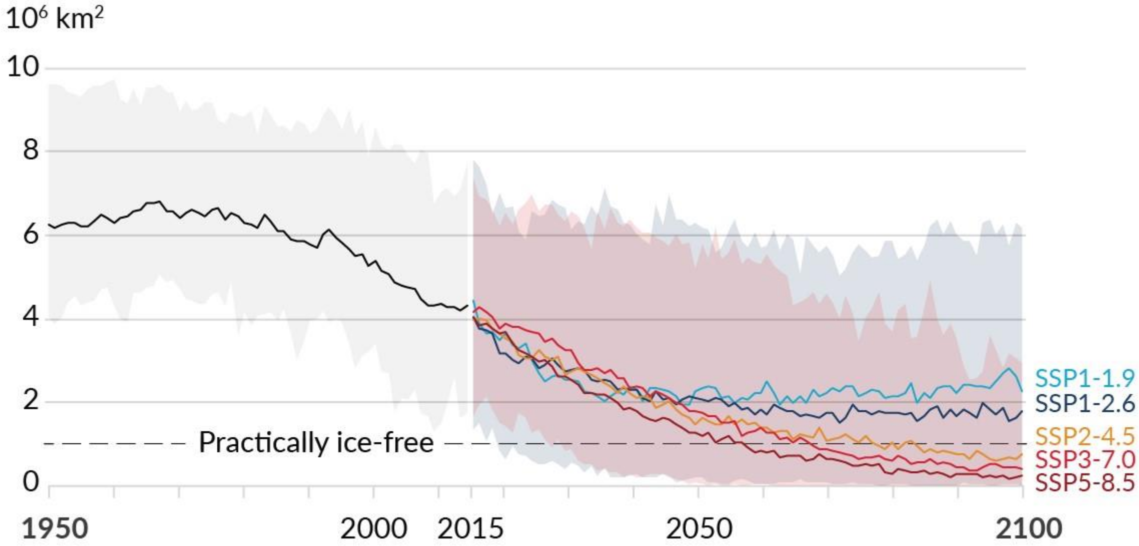
The currently observed decrease of Arctic sea ice is a key indicator of climate change. Satellite observations have established a 40% decrease in the Arctic sea ice area in September – the month of lowest annual extent - and a 10% decrease in March – the month of highest extent – between average levels 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.

3

Approaches to deal with the threat of crossing tipping points

While understanding of the risk associated with the crossing of climate system tipping points and the potential for cascading effects has considerably increased over the past decade (as reviewed in Chapter 2), mitigation efforts still fall far short of what is needed to avoid the crossing of these thresholds, nor are current adaptation efforts sufficient to manage them. Based on the evidence on tipping points reviewed in the previous chapter, the goal of this section is to provide policy recommendations and insights for climate strategies which appropriately reflect the risk of tipping points. It focuses on near-term policy measures and approaches, including net-zero transition strategies, strategies for building resilience to potential impacts of tipping points as well as on technological approaches to monitoring tipping element behaviour and how they can inform and contribute to mitigation and adaptation responses.

In Brief

Temperature increase must be kept under 1.5°C while adaptation measures foster transformation and technological solutions are more broadly applied and further developed

Fully integrating the risks associated with climate tipping points into climate risk management strategies requires a precautionary approach to mitigation. Considering that some tipping points may be crossed already between 1.5 and 2°C, such an approach means limiting the temperature increase to 1.5°C, with no or very limited overshoot. Indeed, an overshoot of the 1.5°C limit could result in considerably higher risk of crossing climate tipping points, even if temperatures returned to 1.5 °C levels by the end of the century.

The existence of climate system tipping points therefore effectively limits the number and the shape of emissions pathways towards 1.5°C and renders lenient interpretations of the Paris Agreement goal significantly more dangerous. Limiting warming to 1.5°C with no or very limited overshoot requires a rapid acceleration of near-term action and the transformations needed to reach net-zero CO_2 emissions. It is therefore no longer “only” about achieving net-zero emissions by mid-century; rather it is about achieving net-zero with urgent, early and deep reductions in emissions already this decade. Near-term policies in line with meeting current Nationally Determined Contributions (NDCs), put limiting warming to 1.5°C without overshoot out of reach altogether from a biophysical, geophysical, technological and economic feasibility perspective; it is therefore critical that NDCs are strengthened in the very near term, preferably before 2025, and that commensurate policies are implemented at relevant timescales to meet revised targets.

For some tipping elements, other climate and human disturbances, beyond GHG emissions, have the potential to interact with global warming and contribute to surpassing critical thresholds. For example, land use and hydrological changes alongside climate change could lead to widespread dieback of the Amazon forest in the near-term. In the Arctic, wildfires are increasingly contributing to abrupt permafrost thaw and carbon release from boreal forests. While also direct contributors to global warming, the mitigation of deforestation in the Amazon region as well as the management of wildfires in the Arctic region are key measures to reduce the risk of crossing these tipping points.

Given the lower levels of warming at which climate system tipping points may be crossed, some may not be avoided. Adaptation has a crucial role to play in reducing all three main drivers of climate risk, namely managing vulnerability and exposure of populations as well as managing physical hazards directly. Transformational adaptation consists in adaptation that leads to a change in the fundamental characteristics of human and natural systems. It may come with challenges in the short-term as it may disrupt current economic and social systems; in the mid- and long-term however it could generate a range of benefits to human well-being and to planetary health. For example, adaptation measures such as the ban of coastal development, relocation of houses or crop fields to safe areas will very likely need to be considered in order to harness transformation. In addition, transformational adaptation measures that are beneficial or low-cost even in the case where tipping points eventually do not occur can be identified and chosen as “no-regret” policies such as the investment in re-habilitating ecosystems and ecosystems services.

Technological development and innovation have an important role to play in reducing and managing climate risks associated with tipping points. The current understanding of the climate system in general has largely benefited from technological development over the past century, such as in space observation equipment, high computing power, mapping software and telecommunication systems. In particular, technologies for better monitoring and modelling of the climate system will remain essential for detecting early warning signals of the crossing of climate system tipping points. It is difficult to predict the thresholds at which tipping points are crossed, as the driving parameters which induce a shift often show only incremental changes before the system makes a sudden or persistent transition. Strong efforts are being made in climate modelling and remote sensing to improve the detection of early warning signals. Currently these new findings are mostly not yet feeding into risk management strategies and are not informing policy-makers. Greater efforts to systematically make this information available for decision-makers in a digestible manner, will be important to address the threat of tipping points.

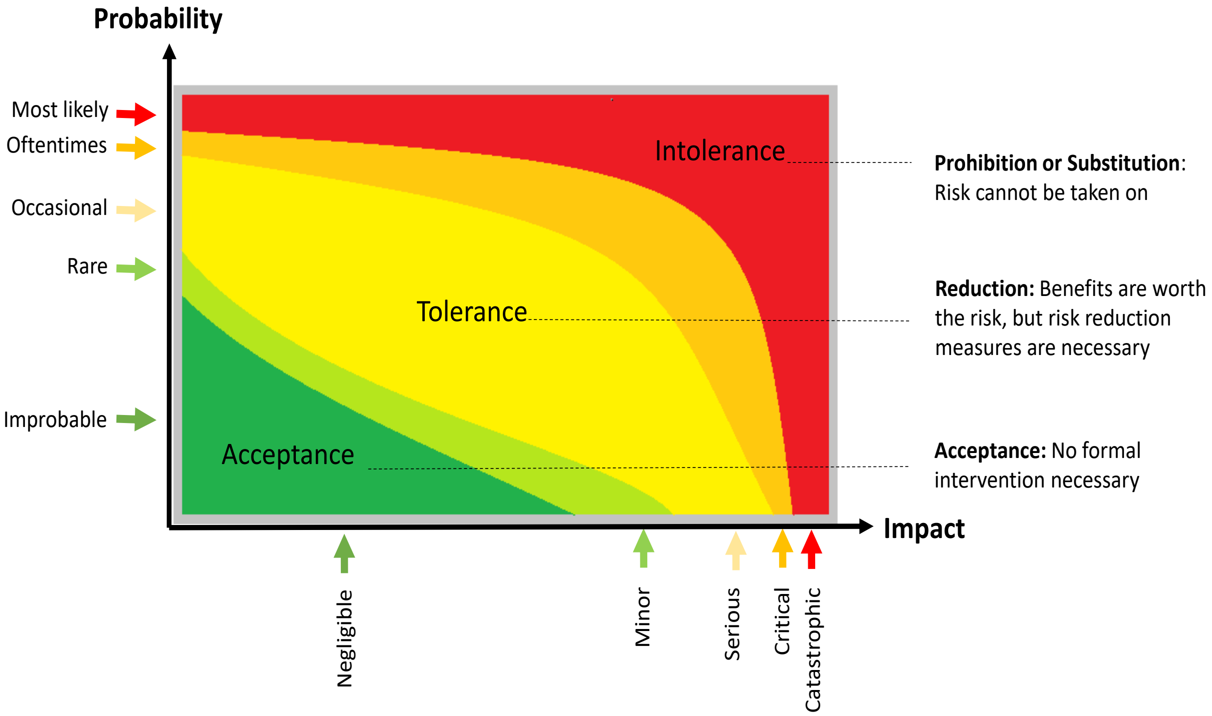
The risk of climate tipping points additionally implies a key role for Carbon dioxide removal (CDR) technologies, as scenarios that limit warming to 1.5°C,with no or very limited overshoot all include at least some deployment of CDR, even when stringent demand-side measures are adopted. These technologies are needed mainly in order to help accelerating early deep emissions reductions and to balance out harder-to-abate sectors that continue to act as sources of residual emissions during the first half of the century. There exist today legitimate concerns regarding CDR technologies, in particular relating to the risks associated with bioenergy with carbon capture and storage (BECCS), stemming primarily from its immense demand for land and resulting implications for land-use practices. The potential trade-offs between the risks of employing CDR technologies – and in particular BECCS - and the risks of crossing climate system tipping points, were CDR technologies not to be employed, are today poorly understood. Investments are needed to enhance understanding of these trade-offs and to better evaluate the risks associated with, on the one hand overcoming barriers to scale-up these technologies and on the other, failing to employ them.

3.1. Climate tipping points and climate risk management strategies

Risk management strategies involve “plans, actions, strategies or policies to reduce the likelihood and/or magnitude of adverse potential consequences, based on assessed or perceived risks” (IPCC, 2021[1]). Risks are assessed and evaluated based on their likelihood and potential for impact (Figure 3.1) and to inform risk management, low-likelihood but high-impact outcomes are considered to constitute material risks (IPCC, 2021[1]). Current policy practice has largely focused on higher-probability outcomes (usually lower-impact) and has therefore not effectively applied risk management approaches, despite increasing recognition that climate risk warrants careful risk assessment (King et al., 2015[2]; Sutton, 2018[3]). Given that climate tipping points are generally considered low-likelihood outcomes, they have virtually not been explicitly included in climate policy strategies.

When decisions are made under uncertainty, risk governance processes that facilitate continuous monitoring, evaluation and learning are useful (Klinke and Renn, 2012[4]). Such iterative processes to managing risk can be guided by three closely linked components, namely the characterisation of risks, their evaluation and finally, development, implementation and evaluation of approaches to reduce and manage risks (OECD, 2021[5]). The characterisation of risks is key to risk management strategies, providing direct information to decision makers on the different types of risks and potential impacts they may be facing and informing therefore policy responses to reduce and manage those risks. Having characterised the risk in question, risk evaluation assesses whether this risk is acceptable to the decision maker and their stakeholders[1], which is in turn determined by their understanding of the risks, influenced by their values and perspectives. For example, decision makers may consider the acceptability of given risks dependent on a combination of their likelihood and the severity of potential impacts (IRGC, 2017[6]). Figure 3.1 visualises such a framework for risk evaluation, categorising different levels of acceptability whereby; risks are deemed acceptable (where no formal intervention is necessary due to negligible impact and low-likelihood), tolerable (where risks are likely and reduction and risk management measures are available, but where these can be traded-off with non-action considering the costs of the impacts themselves) or intolerable (where potential impacts are too high regardless of their likelihood and risk reduction measures need to be implemented to avoid those risks).

Figure 3.1. Risk evaluation based on probability and potential impact of an outcome



Source: (OECD, 2021[5]), adapted from (IRGC, 2017[6])

As shown in Figure 3.1, impacts that are potentially “catastrophic”, even if “improbable”, are assessed as intolerable, meaning that decision-makers are not willing to risk them happening and should take measures to avoid them, regardless of cost[2]. The evidence reviewed in the previous section makes clear that crossing tipping points would entail catastrophic impacts at both regional and global scales, with further implications cascading throughout natural and human systems. In addition, the most recent scientific evidence suggests that important tipping points, including collapse of the Greenland and West Antarctic ice sheets, die-off of low-latitude coral reefs, and widespread abrupt permafrost thaw, may be close to tipping already at current levels of warming [(McKay et al., 2022[7]), Table 2.1 and Figure 3.2], suggesting even that they may not be “improbable” at all. Tipping points should therefore fall firmly within the “intolerable” risk category and should be managed accordingly.

Global policy efforts, however, are not commensurate with this risks. For example, as discussed in Section 2.4, climate projections informing economic models of potential climate damages only recently started to consider the possibility of tipping points, and thus the economic costs of climate change have often been largely underestimated. This has implications for policy, as policy makers informed by these assessments will choose response pathways that are inadequate for dealing with tipping point risks.

Uncertainties, likelihoods and confidence in results remain important factors determining how risk is perceived. In comparison to previous reports, IPCC AR6 pays special attention to a number of low-probability outcomes that may be associated with high levels of risk, such as low-likelihood high warming scenarios and low-likelihood high-impact events such as tipping points (Chen, 2021[8]). However, the IPCC uncertainty guidance, focusing on likelihoods (based on probabilities), and levels of confidence (based on an evaluation of evidence and agreement across models), are easily misinterpreted. For example, *low confidence*, in IPCC terms, does not provide confidence on the absence of the potential outcome; rather it provides an indication of the poor state of knowledge on this topic. In addition, an *unlikely* probability can be associated with high-impact outcomes and be therefore of high importance to risk assessments. Thus, even if climate system tipping points had low probability of being crossed lower levels of warming, which the more recent scientific literature suggests may not be the case, their uncontested potential for catastrophic impacts nonetheless necessitate their incorporation into risk assessments, even if confidence in these outcomes is low.

Historically, however, uncertainties have undermined government responses on climate change. With scientists wary of overstating confidence in their results, confidence levels and uncertainties have often been interpreted as implying climate change may not be an issue after all. In some cases this has been exacerbated by concerted lobbying efforts by vested interests to undermine trust in scientific results. Although Molina and Abadal (2021[9]) argue that stronger likelihoods have since “encouraged stronger action and greater commitment on the part of governments to the mechanisms of international cooperation designed to tackle climate change”, climate tipping points remain low-likelihood events and thus less conducive of action. However, likelihoods in the projection of climate hazards are not the same as climate risk, which is also determined by the vulnerability and exposure of human and natural systems. For effective risk management strategies, policy makers thus need to consider these likelihoods and confidence levels carefully and critically.

Public acceptance is influenced by how uncertainty, likelihood and confidence in results are communicated. Public perception often wrongly attributes higher levels of uncertainty with lower trust in the likelihood of a given outcome, leading to an underestimation of potential risk (Howe et al., 2019[10]). From a risk management perspective, when dealing with uncertainties, one needs to balance the possibilities and consequences of overestimating or underestimating the risk. It is therefore necessary to minimise both false alarms and missed warnings (Shepherd, 2019[11]). Finding a balance between these two extremes is not trivial. There is no single probabilistic threshold that can guarantee a risk is not being over- or underestimated, with multiple factors, including value judgements and risk tolerance, influencing this threshold.

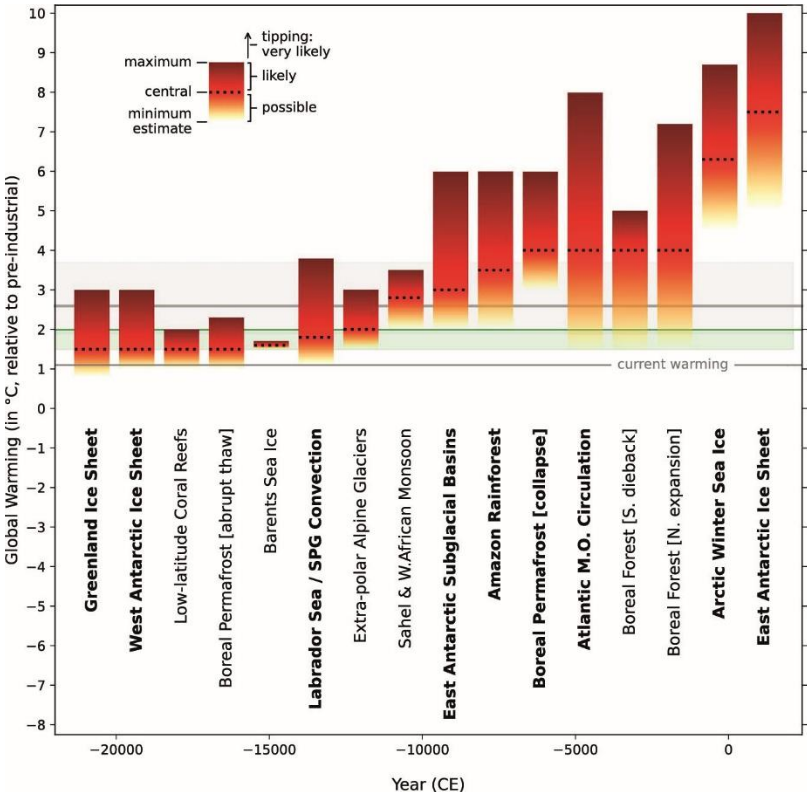
Interestingly, the likelihoods currently informing climate policy responses would be unacceptable in many other areas of life and of decision making. For example, climate pathways considered as consistent with the Paris Agreement are those that provide a “likely” chance, that is a ~67% chance, of meeting the Agreement’s temperature target, leaving a ~33% chance of not doing so. If an aircraft had only a ~67% chance of reaching its destination (and consequently 33% chance of not doing so), this would hardly be considered as an acceptable level of risk. Thus, as with the possibility of an aircraft crashing, low-likelihood, high impact climate outcomes deserve greater scrutiny by policy makers.

In summary, decision making and policy responses to climate change must therefore carefully consider how they address inevitable uncertainties arising from the dynamics of the physical climate system closely interacting with complex and equally dynamic social and economic systems. Uncertainties, likelihoods and confidence statements have been either ignored, not well-understood or misinterpreted in practice, leading often to an underestimating of the gravity of possible climate outcomes Importantly, the new scientific evidence showing that key climate system tipping points are already possible at current levels of warming and likely within the Paris Agreement range (McKay et al., 2022[7]) largely decreases uncertainties in relation to the timescale at which these abrupt changes could start happening. If interpreted correctly, and considering the short timeframe available for action, the uncertainties and ambiguities surrounding climate change projections should amplify – not weaken – the case for strong climate action.

3.2. The role of mitigation in avoiding the crossing of tipping points

Despite progress in collective mitigation plans over the past two decades (see section 3.2.1), even if all announced emissions reduction pledges for 2030 and 2050 are fully implemented, this highly optimistic scenario would still lead to 1.8 °C of temperature increase by the end of the century (Climate Action Tracker, 2021[12]; IEA, 2021[13]). In addition, emission trajectories in line with currently implemented policies are not on track to meet current NDCs and would lead to an increase of about 2.7°C by the end of the century. Despite being within the 1.5-2 C temperature target range of the Paris Agreement, the current level of warming that climate targets for 2030 and 2050 commit the world to, let alone those that currently implemented policies imply, would significantly increase the risk of crossing important tipping points in the climate system. Indeed, Figure 3.2 shows that some tipping elements may already be threatened at current levels of warming and that the probability of tipping elements being triggered increases significantly between 1.5 and 2°C (McKay et al., 2022[7]). This is supported by the IPCC, who project a transition from moderate to high risk for most tipping points at between 1.5-2.5°C of warming (Pörtner et al., 2022[14]). Limiting warming to 1.5°C is thus crucial for avoiding the most dangerous impacts of climate change (IPCC, 2018[15]; IPCC, 2021[16]).

Figure 3.2. Global warming threshold estimates for global core and regional impact climate tipping elements



Note: Shadowed in green is the 1.5°C-2°C Paris Agreement range of warming. The shadowed area in grey shows the estimated 21st century warming under current policies (horizontal line shows central estimates). Bars show the minimum (base, yellow), central (line, red), and maximum (top, dark red) threshold estimates for each tipping element (bold font, global; regular font, regional),
Source: (McKay et al., 2022[7])

Under current policy trajectories, projected warming could already exceed 1.5°C, or even 2°C, by mid-century. Indeed the IPCC states that it is “almost inevitable” that the world will exceed the temperature goal of 1.5°C (IPCC, 2022[17]), implying at least some level of overshoot is to be expected. Recent research estimates that if all conditional and unconditional Paris pledges are implemented in full and on time, peak warming could reach 1.9-2°C during the century (Meinshausen et al., 2022[18]). These temperatures could potentially be brought back down to 1.5°C with additional action towards the end of the century, e.g. through net-negative emissions. The overshoot, however, depending on its extent and duration, could still result in crossing irreversible climate tipping points, such as in the melting of the West Antarctica and Greenland ice-sheets and the loss of coral reefs, with severe and irreversible impacts in many natural and human systems [Table 2.1, Figure 3.2 and (McKay et al., 2022[7])].

Fully integrating the risks of climate tipping points into mitigation risk management strategies unequivocally means that a precautionary approach to mitigation should be taken, an approach where global average temperature increase is limited to 1.5°C, with no or limited overshoot. The existence of climate system tipping points limits therefore the number and the shape of emissions pathways towards 1.5°C and renders lenient interpretations of the Paris Agreement goal, as for example allowing for high-overshoot or for warming closer to 2°C at the end of the century, significantly more dangerous and simply incompatible with the Agreement’s resilience goal. This is because in the face of tipping points, simply reaching the temperature target by the end of the century does not ensure a resilient planet and society. The stark reality is that, in the presence of climate system tipping points, a just-below-2°C world could be dramatically different to one where today’s ambition gap is bridged and temperatures are kept at, or below, 1.5°C.

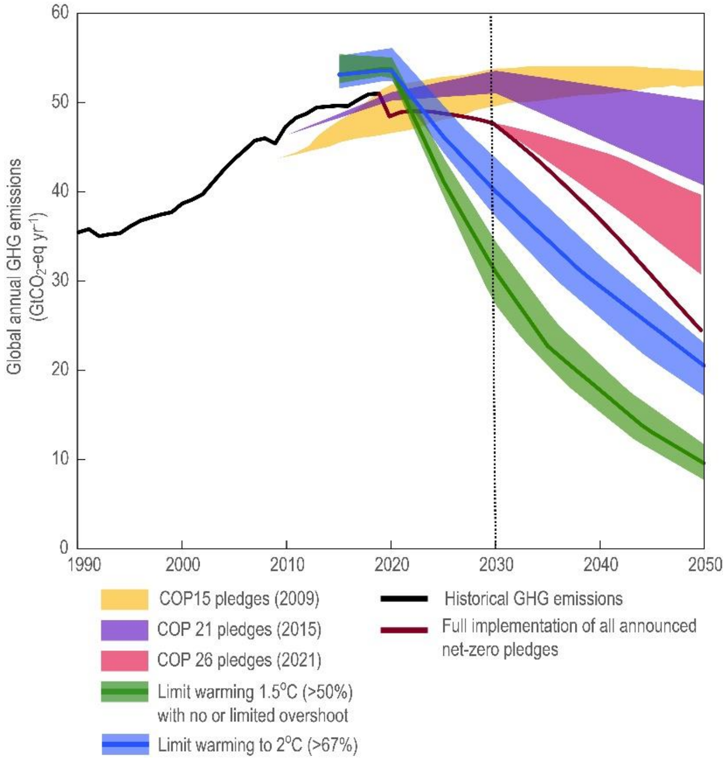
It is also important to note that, if crossed, some climate tipping points would effectively reduce the remaining carbon budget for reaching temperature objectives. Indeed, loss of sea ice and ice sheets leads to a decrease of solar radiation reflection, effectively acting as an amplifier of surface temperatures (see Section 2.3.5). If these tipping points are crossed, emissions reductions would need to be even larger than previously thought to meet stated temperature targets. In addition, permafrost carbon emissions (see Section 2.3.3) have already led to lowering the estimated remaining carbon budgets for achieving the 1.5°C and 2°C objectives (Canadell et al., 2021[19]), even without having reached the threshold for an abrupt tipping point. Since most of these tipping elements are likely to be tipped already within the 1.5°C-2°C range, temperature feedback loops further stress how crucial it is to avoid or limit an overshooting 1.5°C.

Indeed, the science is clear about the fact that collective ambitious climate action keeping warming levels below 1.5°C remains undoubtedly the least uncertain, safest and most cost-effective way to reduce the risks of losses and damages, including the potentially catastrophic impacts of crossing tipping points. As reviewed in Section 2.4, the latest economic assessments show that, when faced with the risk of cascading tipping points and their non-linear and irreversible impacts, the additional costs of implementing stringent climate policies earlier are worth paying. Rapid cuts in emissions now are made all the more necessary by the increasing evidence that some tipping elements may be triggered at lower levels of warming, increasing the urgency of meeting the 1.5°C target with limited or no overshoot. This has important implications for near-term policy, necessitating rapid and deep emissions reductions already this decade. Fully integrating tipping points and their risks within mitigation strategies thus requires countries to significantly increase their efforts, both advancing pledges to levels consistent with the Paris Agreement’s temperature target, and ensuring commensurate policies are implemented at relevant timescales to meet these target. Despite uncertainties and challenges, 1.5°C can still be achieved with very limited or no overshoot (see sub-section 3.2.2). However, as emissions continue to rise, this window of opportunity is closing swiftly.

3.2.1. Collective emissions mitigation efforts have improved but progress falls short

The mitigation of GHG emissions is key in climate risk management strategies, as this is the most direct way to reduce global temperature increase and thus the probability of physical hazards actually occurring. The world has seen a continuous rise in mitigation ambition since 2009, with countries collectively putting forward increasing emissions reductions pledges over the years. Figure 3.3 shows global emissions projections resulting from emissions reductions commitments put forward by countries at three different points in time: in 2009 at COP15 in Copenhagen (yellow wedge), in 2015 at COP21 in Paris (violet wedge) and the latest commitments put forward at COP26 in Glasgow (brown wedge). The figure shows that the level of collective ambition towards 2050 has seen an improvement over the years. In 2009, before any long-term commitment by mid-century was put forward, the so-called Copenhagen pledges were projected to lead to emissions as high as 53-54.5$GtCO_2$-eq by 2050 (Rogelj et al., 2010[20]). Intended Nationally Determined Contributions (INDCs) put forward by countries by COP21 led to emissions levels between 42-51$GtCO_2$-eq (Climate Action Traker, 2015[21]), while the latest assessments of NDCs put forward by COP26 in Glasgow show these emissions could be brought down to up to 25$GtCO_2$-eq, if all long-term targets announced by countries are fully implemented (Climate Action Tracker, 2021[12]).

Figure 3.3. Progression of GHG emissions reductions pledges and projections from 2009 to 2021

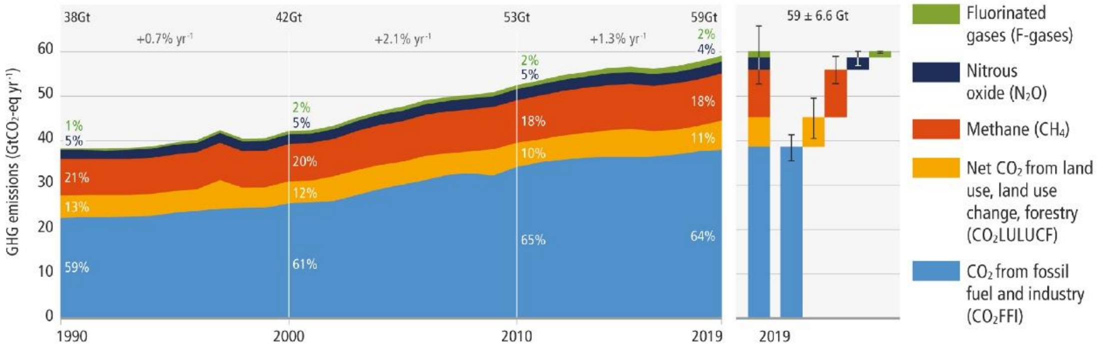


Note: Evolution of GHG emissions resulting from emissions reductions pledges and commitments put forward by countries since 2009. Emissions trajectories in line with pledges made by COP 15 (yellow wedge), COP21 (blue wedge), COP 26 (brown wedge and solid line) are taken from Rogelj et al. (2010[20]), Climate Action Tracker (2015[21]), Climate Action Tracker (2021[12]) respectively. Final historical emissions are taken from (Climate Action Tracker, 2021[12]). The upper end of the brown wedge corresponds to emissions projections based solely on NDCs by 2030 while the lower end also includes long-term binding commitments (Climate Action Tracker, 2021[12]). The brown solid line is considered an optimistic scenario that assumes full implementation of all announced net-zero targets and targets announced in long-emissions development strategies also when those are not yet binding in national law (Climate Action Tracker, 2021[12]). Shaded green and blue areas show GHG emission medians and 25th–75th percentiles for pathways that limit warming to 1.5°C with no or limited overshoot with a 50% chance and pathways that limit warming to 2°C with 67% based on immediate actions from 2020 onwards, respectively (M. Pathak, 2022[22]). Wedges and ranges start at different emissions levels as projections were made at different points starting from historical emissions levels available at the time of the assessment; updates in historical emissions over the years provide adjustments to previous years. This analysis refrains from doing any harmonisation as its goal is to show the progression of emissions reductions commitments over the years and does not make any direct assumption on emissions budgets and implications for resulting temperature increase.

Source: Authors based on data from Rogelj et al. (2010[20]), Climate Action Tracker (2015[21]), Climate Action Tracker (2021[12]) and M. Pathak, (2022[22])

Despite this steady progression of collective mitigation ambition, GHG emissions have continued to rise since 1990 in all major sectors of the economy and in all major groups of GHGs (IPCC, 2022[23]). Figure 3.4 shows that annual average GHG emissions during the past decade (2010-2019) have been higher than in any other previous decade. In addition, emission trajectories in line with currently implemented policies are not on track to meet current NDCs and would lead to an increase of about 2.7°C by the end of the century (Climate Action Tracker, 2021[12]).

Figure 3.4. Total anthropogenic GHG emissions between 1990 and 2019



Source: (IPCC, 2022[23])

Although recent emissions increases are in-line with legally binding targets set by countries for 2020, the 2030 targets set in the NDCs fall short of 1.5°C trajectories. Even under an optimistic scenario whereby announced net-zero targets are implemented in full (brown line in Figure 3.3), median warming would reach 1.8°C. Indeed, if 2030 targets pledged in the NDCs are not strengthened, very deep reductions would be required thereafter in order to return to 1.5°C by the end of the century (with a 50% chance), and a high-overshoot would be inevitable (IPCC, 2022[23]).

For indicative purposes only, a trajectory in line with full implementation of net-zero targets currently announced by countries could lead cumulatively to more than 1200GtCO$_2$-eq GHG emissions over the next three decades (M. Pathak, 2022[22]). The least ambitious realisation of COP 26 pledges could increase that cumulative budget to more than 1400GtCO$_2$-eq of GHG emissions. To put that into perspective, the remaining CO$_2$ budget in line with 1.5°C is estimated to be at around 400 [180-620] GtCO$_2$ with a 67% chance. While these budgets are not directly comparable (as the former budgets refer to GHG cumulative emissions and the latter only CO$_2$), it is fair to say that current pledges largely surpass what would be a safe trajectory to 1.5°C. All the more alarming is that emissions from the last decade are roughly the same size as the remaining 1.5°C budget, and emissions today are still increasing, showing that a drastic change in emissions trends this decade is needed (M. Pathak, 2022[22]).

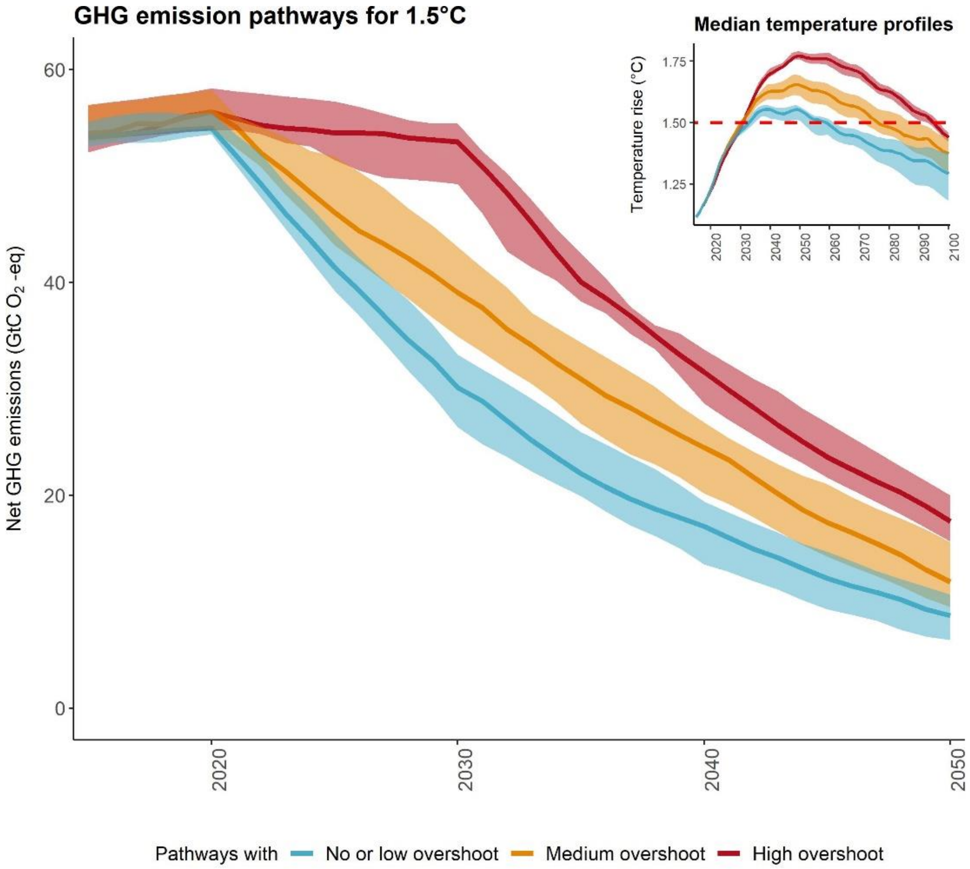
Given this evidence it is clear that mitigation ambition needs to be rapidly increased. With the Paris Agreement only mandating a revision of NDCs every 5 years (starting in 2020), further ambition increases are not expected until 2025. However, given the urgency of the climate problem, particularly in light of the evidence on climate tipping points, steepening emissions reductions trajectories to 2030 is fundamental to remaining within a safe operating space climatically. Governments should therefore step-up in their efforts to revise current climate policy targets immediately.

3.2.2. Key features of mitigation strategies in line with limiting warming to 1.5°C with no or very limited overshoot

In order to avoid the potential catastrophic impacts of crossing climate tipping points, global average temperature increase needs to be limited to 1.5^{o}C with limited or no overshoot. This section reviews key features of mitigation scenarios meeting this target, drawing on work by Riahi et al (2021[24]).

First, limiting warming to 1.5°C, with limited or no overshoot, requires a strong acceleration of near-term policy actions in line with transformations needed to reach net-zero CO_2 emissions by mid-century. Typically, net CO_2 emissions need to drop by 50% by 2030, and reach net zero in the 2050s (Riahi, 2022[25]). Figure 3.5 illustrates how early, strong action in this very decade becomes imperative for avoiding or limiting overshoot which could trigger tipping points, and emissions pathways that do not make deep cuts by 2030 are ruled out. Alongside reductions in CO_2 emissions, achieving rapid reductions in non-CO_2 GHGs in this decade, in particular in methane, are also key to constrain the overshoot of 1.5°C. Scenarios that reach 1.5°C of warming with no or limited overshoot reduce methane emissions on average by a third before 2030 and halve them by 2050 (Riahi, 2022[25]). Weak near-term policies, such as those implied by NDCs, put limiting warming to 1.5°C out of reach altogether. Pathways consistent with their NDCs imply higher fossil fuel development until 2030. Accelerated emission reductions after the 2030s would not be sufficient to avoid an overshoot of 1.5°C, and additionally would be made more challenging by the build-up of fossil fuel infrastructure resulting in carbon lock-ins. Considering the risk of crossing climate tipping points, it is crucial that emissions levels implied by current NDCs are not locked in.

Figure 3.5. Implications of global GHG emission trajectories by 2050 for overshooting 1.5°C



Note: Global net GHG emission pathways (main) and median temperature rise profiles (top right) of scenarios from the IPCC AR6 scenarios database that result in less than 1.5°C of warming in 2100 with a 50% likelihood. Scenarios are sorted into 3 overshoot categories depending on their associated median values of peak warming temperature over this century: no or low overshoot scenarios (median peak warming of 1.6°C or below), medium overshoot scenarios (median peak warming of 1.6°C to 1.75°C) and high overshoot scenarios (median peak warming of 1.75°C to 1.86°C). Lines represent median yearly values and shaded areas represent 25th-75th percentile yearly value ranges for each overshoot category. Net GHG emission values correspond to total Kyoto GHG emissions using the AR6 Global Warming Potential with a time horizon of 100 years (AR6-GWP_{100}) factors to convert emissions into CO_2-equivalent values. GHG emissions are calculated by AR6 WGIII using all available gas species reported by the scenario providers as well as infilled emissions species to comprise a more complete basket of Kyoto gases. The temperature rise profiles are assessed by AR6 WGIII using the climate emulator MAGICC. Temperatures refer to Global Surface Air Temperatures (GSAT) and warming refers to the temperature rise above 1850-1900 temperatures. Only scenarios that passed the AR6 vetting process and received a climate assessment are considered.
Source: Analysis made by the authors based on data from the IPCC AR6 scenarios database (Byers, 2022[26]).

Second, all scenarios compatible with 1.5°C with no or limited overshoot rely on achieving net negative emissions through the deployment of carbon dioxide removal technologies, in addition to rapid early emissions reductions already over the next decade. In the scenarios, afforestation, reforestation and BECCS are responsible for the bulk of these negative emissions. Typically, as part of current net-zero strategies, demand-side sectors such as transport, industry and buildings remain emissions sources, while the AFOLU and energy sectors act as sinks. This highlights the importance of considering demand-side mitigation measures in order to limit the level of negative emissions needed. For example, improved energy efficiency, behavioural change and wide-scale electrification will be key to meeting emissions reduction targets.

Third, in order to avoid overshoot, near-term mitigation costs will increase considerably requiring higher upfront investments, but also imposing some short-term costs. Modelling suggests that once net-zero emissions are achieved in the latter part of the century, however, these costs will ease, for example with carbon prices able to decrease to maintain emissions at net-zero balances. This is in turn accompanied by an increase in GDP, with modelling results indicating this rebound in GDP would be much larger than the near-term costs imposed by stringent mitigation policies. In fact, the accelerated near-term transformation in line with avoiding temperature overshoot would have benefits for long-term GDP compared with current policy trajectories, even without accounting for the benefits of avoided impacts, which in the case of tipping points, are very high (see Section 2.4). Importantly, the study finds that the relatively low costs of mitigation implied by NDCs are over-shadowed by considerably higher costs from 2040 onwards until the end of the century.

Fourth, there are large differences across regions regarding the timescales for reaching net-zero, or even net-negative, emissions, with some regions acting as sinks as others continue to emit. Importantly, although such regional differences would pertain the most efficient and effective means of reaching the required targets, these scenarios may not be politically feasible. In fact, achieving such an effective collective solution is challenging as it requires international collaboration as well as markets for cross-regional policy frameworks, which are currently not in place. It is encouraging, however, that net-zero targets in major countries/regions, such as China, the European Union and South Korea, are in line with the pace of transformation required, as depicted in Riahi et al (2021[24]).

The recent Working Group III contribution to the AR6 further highlights the key role systems transformation has to play in limiting warming to 1.5°C with no or limited overshoot. Major transitions in the energy sector are needed, including through the deployment of low-emissions energy sources, switching to alternative energy carriers, energy efficiency and conservation and halting the continued installation of unabated fossil fuel infrastructure. In general, effective mitigation strategies involve all sectors of the economy, and the role of demand-side management measures, including e.g. energy and material efficiency and consumption, electrification and circular material use, cannot be overemphasised. Indeed, all mitigation strategies face implementation challenges, for example technological risks, scaling, and costs. Many of these challenges are however considerably reduced in modelled pathways that assume resources are used more efficiently achieving low demand for resources or those that shift global development towards sustainability, including by reducing inequality (IPCC, 2022[23]).

3.2.3. Mitigation of other drivers and human disturbances contributing to climate system tipping points

As reviewed in Chapter 2, for some tipping elements, other climate and human disturbances have the potential to interact with global warming to contribute to surpassing critical thresholds. For example, land use and hydrological changes coupled with the impacts of climate change could lead to widespread dieback of the Amazon forest in the near-term. In the Arctic, wildfires are increasingly contributing to abrupt permafrost thaw and carbon release from boreal forests. Given there remains the possibility that some tipping points are crossed even at 1.5°C of warming, such additional drivers could prove critical in determining levels of climate risk. Thus, in addition to stringent emissions reductions, a better understanding of these other drivers and increased efforts to mitigate them is required in order to avoid crossing catastrophic tipping points.

As wildfires are expected to increase in severity and frequency in the Arctic, efforts to prevent, monitor and mitigate these will prove crucial in avoiding the risk of crossing tipping points in the Arctic permafrost and boreal regions. Tundra and boreal wildfires are now increasingly driving abrupt permafrost carbon release (Miner et al., 2022[27]), as well as boreal forest losses. Wildfires occurring above the Arctic polar circle in regions where they may not directly threaten human activities or settlements – such as the extensive wildfires observed this summer in Alaska which made 2022 one of the worst years on record (Copernicus EU, 2022[28]) – are usually allowed to burn without implementing monitoring or suppression attempts (Irannezhad et al., 2020[29]). Understanding of the role of the increasingly widespread types of fires in the region is only at its beginning, but their impact on the permafrost carbon feedback and on boreal forest carbon release is considerably larger than on local human activities. As such, Arctic wildfires will require international collaboration in order to better understand their role in crossing Arctic tipping elements, and international efforts to monitor and prevent them.

In the Amazon, deforestation is generating widespread degradation of the hydrological cycle, and could cause the Amazon to pass its tipping point much sooner than if only rising temperatures are taken into account. Additionally, the widespread use of fire to clear vegetation leads to greater vulnerability to fire in subsequent years. A better understanding of the negative synergies between deforestation, climate change and use of fire have led scientists to estimate that the Amazon forest is at risk of shifting to a savannah state at 20-25% of deforestation (Lovejoy and Nobre, 2018[30]). Curbing deforestation so as to keep the deforested area within a safety range is required to avoid crossing such a threshold, as is ambitious and accelerated reforestation in deforested regions of the basin (Lovejoy and Nobre, 2019[31]). Mitigation of deforestation and fire disturbances that could lead the Amazon to a tipping point would also rely on investment in fire control by property holders and governments as well as expanding protected areas (Nepstad et al., 2008[32]).

3.3. The role of adaptation in the context of threat of climate system tipping points

The IPCC defines adaptation in human systems as “the process of adjustment to actual or expected climate and its effects in order to moderate harm or take advantage of beneficial opportunities”. In natural systems, adaptation is “the process of adjustment to actual climate and its effects; human intervention may facilitate this” (IPCC, 2022[33]). Even if global warming levels are kept to 1.5°C with no or limited overshoot, some tipping points which are already possible at current levels of warming (McKay et al., 2022[7]) may be crossed and associated impacts unavoidable, so that even if stringent mitigation efforts to limit climate risk are pursued, adaptation will still be needed (Ara Begum, 2022[34]).

It is estimated that currently 3.3 to 3.6 billion people are highly vulnerable to climate change (IPCC, 2022[33]). This number would increase significantly if tipping points were crossed, with most regions and people affected in some way by the associated physical hazards including extreme temperatures, higher frequency of droughts, forest fires, unprecedented weather, food insecurity and faster sea-level rise to name a few (see Chapter 2). Adaptation has a crucial role to play in reducing all three main drivers of climate risk, namely managing vulnerability and exposure of populations as well as managing physical hazards directly, having a crucial role to play in responding but also preparing systems to the potential impacts of tipping points.

The systemic scope and severity of impacts associated with climate system tipping points may impose both soft and hard limits on possible adaptation responses, whereby “soft limits are those for which no further adaptation options are currently feasible but might become available in the future, and hard limits are those for which existing adaptation options will cease to be effective and additional options are no longer possible” (Pörtner et al., 2022[14]). For example, increased sea-level rise due to the tipping of cryosphere points rendering several small islands uninhabitable poses a hard limit to adaptation, and a soft limit to adaptation in other coastal areas where coastal livelihoods would be rendered unsustainable (Mechler et al., 2020[35]). What is more, the potentially abrupt nature of tipping point impacts could render the time available for human systems to adapt too short to allow communities or societies to identify, develop and adopt ad-hoc solutions to adapt to these impacts. Taking into account climate tipping points and the interactions and reinforcing dynamics among ecological, social, and climate processes is therefore crucial for effective and long-term adaptation planning and implementation (Cai et al., 2015[36]; Lontzek et al., 2015[37]; Steffen et al., 2018[38]; Dietz et al., 2021[39]).

This section considers how adaptation efforts can account for the risk of crossing climate tipping points, focusing on the following three aspects. First, the section considers the role of transformational adaptation in building systemic resilience to tipping point impacts. Second, the section considers the importance of monitoring and measuring progress in adaptation for informing adaptation efforts. Third, the section considers the need for new approaches for dealing with uncertainty in decision making.

3.3.1. The role of transformational adaptation in reducing the risks of climate tipping points

Transformational adaptation is that which leads to a change in the fundamental characteristics of human and natural systems so that the capacity of these systems to cope with potential hazards is increased (IPCC, 2022[33]). Considering the scale and magnitude of impacts associated with the crossing of tipping points, fundamental changes in systems will be unavoidable to adapt to those impacts. More effective however is to prepare to those impacts through changing these key fundamental attributes of socio-economic systems, through energy, land-use, infrastructure, industrial and societal systems transitions before, the occurrence of these impacts through transformational adaptation.

This report therefore argues that the scale and magnitude of tipping point impacts necessitate a transformational, beyond incremental, approach to adaptation. Incremental adaptation refers to measures that target specific systems components, safeguarding these from given climate risks, and ensuring system functioning into the future (Loginova and Batterbury, 2019[40]) (Kates, Travis and Wilbanks, 2012[41]). In comparison, transformational adaptation can be more effective in building resilience because it implies changes in the fundamental characteristics of the human and natural systems so that the capacity of these systems to cope with potential hazards is increased (IPCC, 2022[33]). The IPCC defines resilience as "the capacity of social, economic and ecosystems to cope with a hazardous event or trend or disturbance, responding or reorganising in ways that maintain their essential function, identity and structure as well as biodiversity in case of ecosystems while also maintaining the capacity for adaptation, learning and transformation" (IPCC, 2022[33]).

The latest Working Group II contribution to the IPCC AR6 considers transformational adaptation as "one component of climate resilient development in which adaptation, mitigation and development solutions are pursued together to exploit synergies and reduce trade-offs among these actions" (Ara Begum, 2022[34]) (Box 3.1 discusses in more detail some of these synergies and trade-offs). This is also reflected in the IPCC WGIII report on mitigation, in that, alongside its role for mitigation, the transformation of whole systems also has a key role to play in achieving transformational adaptation (Lecocq, 2022[42]). While transformational adaptation comes with challenges in the short-term by potentially disrupting current economic and social systems, in the long-term it could generate a range of benefits to human well-being and to planetary health (Schipper et al., 2022[43]) which could end up saving communities and the environment.

In light of the threat of climate system tipping points, transformational adaptation could necessitate stringent and even drastic measures to reduce impacts and avoid losses. Many responses in line with transformational adaptation are technological – for instance, implementing water capture and storage solutions in areas at risk of drying. They can also be behavioural, or alternatively include fundamental changes in institutional arrangements, priorities, and norms (Kates, Travis and Wilbanks, 2012[41]). In addition, transformational adaptation measures can target the spatial development of human activities, including through managed or strategic retreat of communities and settlements, relocation of assets and infrastructure or long-term spatial planning and urban and agricultural zoning. Other examples include cooperative governance such as international cooperation among governments to manage migrations, the deployment of Nature-based Solutions (NbS), and livelihood transformation in land systems (New, 2022[44]).

Concrete examples for transformational adaptation in response to the risk of crossing climate system tipping points have been explored in the literature. First, the disintegration of ice-sheets would result in considerable sea-level rise, posing an existential risk to low-lying coastal areas and countries, making stringent and transformational adaptation measures unavoidable. For regions with low tolerance to uncertainty, where key economic sectors are at risk, credible adaptation responses would need to consider these plausible high-impact scenarios of SLR and enforce drastic measures such as no-building zones and planned retreat from exposed areas (Haasnoot et al., 2019[45]). In another instance, studies suggest that energy planning and zoning in the Amazon region, which is currently heavily reliant on large-scale hydropower, needs to consider the potential impacts of a dry-state Amazon forest on the hydrological cycle of the region and plan for a decentralisation of energy production, a diversification of energy sources focusing on small-scale hydropower and solar power, and investing in energy saving (Lapola et al., 2018[46]). Taking a transformational approach to adaptation in that region would also mean protecting the agricultural sector through livelihood transformation by encouraging farmers to switch to crop varieties and livestock adapted to drier conditions (*ibid*).

Transformational adaptation measures that are beneficial or low-cost even in the case where tipping points do not occur can be identified and chosen as “no-regret” policies (Heltberg, Siegel and Jorgensen, 2009[47]). Some may come with large co-benefits by contributing to reductions in GHG, supporting the advancement of other sustainable development goals – e.g. energy and water access – and building systems’ and populations’ resilience to future climate shocks. This is especially the case for, the investment in re-habilitating ecosystems and ecosystems services and the implementation of NbS. For example, coastal ecosystem conservation helps ensure coastal protection against increased risk of SLR from ice sheet tipping points, but may also improve food access from fisheries, flood regulation, biodiversity conservation, as well as provide recreation and cultural benefits (Schipper et al., 2022[43]). Importantly, NbS are also effective in accelerating mitigation efforts. Forest maintenance and restoration is a key carbon sequestration measure, and has a range of potential sustainable development co-benefits, including food provision, fuel provision, job creation, biodiversity conservation, air quality regulation, and water and soil conservation (Schipper et al., 2022[43]). In addition, in the Amazon, investing in forest protection would contribute to mitigate the risk of a dieback tipping point (see Section 3.2.3). A further example of no-regret policy includes energy decentralisation which can help ensure universal access to energy while increasing resilience in the case of adverse impacts from a tipping point in the Amazon region.

Many adaptation initiatives today prioritise near-term climate risk reduction – also largely in line with short political cycles - which may constrain opportunities for transformational adaptation (IPCC, 2022[33]) and clearly indicates that much more needs to be done. Even if the Paris Agreement’s temperature target are met, it is likely that some transformational adaptation will be needed (Ara Begum, 2022[34]). Thus, in addition to pursuing stringent mitigation efforts to limit climate risk, transformational adaptation efforts must also be pursued to ensure resilience to unavoidable impacts, including those associated with the crossing of tipping points. If mitigation efforts fall short of the 1.5°C target, transformational adaptation will be all the more important as impacts become more severe, and the risk of crossing tipping points increases (Ara Begum, 2022[34]). Implementing transformative actions that also support sustainable development goals in response to the risk of climate tipping points being crossed provides a key opportunity for climate resilient development.

Box 3.1. Linkages between mitigation, adaptation and sustainable, climate-resilient development

The recognition and appropriate assessment of climate risks, including the risks of crossing tipping points can strengthen adaptation and mitigation actions that lead to the transformation of key systems, in line with sustainable development and with strengthening the resilience of ecosystems and society. Accelerated, effective and equitable climate action for both mitigation and adaptation is crucial for achieving sustainable climate-resilient development. If not addressed, climate change will negatively impact, directly or through its cascading effects, the achievement of sustainable development.

For example, climate change will have negative impacts on the health and livelihoods of people around the world and on ecosystem health and biodiversity, both of which are the heart of the Sustainable Development Goals (SDGs). Climate action, on the other hand, may lead to improved energy efficiency and the use of renewable energy, the reduction of air pollution, shifts to more balanced, healthier diets, reforestation or forest conservation and avoided deforestation, all of which are examples of synergies between climate mitigation and sustainable development. There are, however, also potential trade-offs here that are relevant when dealing also with the threat of climate system tipping points, particularly considering land-use based mitigation such as re- and a-forestation, in terms of employment and the affordability of food, energy and water. Carbon capture and storage technologies also entail potential negative impacts on clean water and sanitation. While synergies largely outweigh trade-offs, the latter need to be managed through careful planning and implementation of climate policies. Maximising synergies and avoiding or managing trade-offs pose particular challenges for developing countries and vulnerable populations. Indeed, there is a strong link between sustainable development, vulnerability and climate risk.

Limited economic, social, and institutional resources often lead to higher vulnerability and lower adaptive capacity in particular in developing countries. Even if global mitigation targets are achieved, there will be a large need for financial, technical and human resources for adaptation. In addition, some mitigation options can lead to reduced adaptive capacity as for example, in the large-scale or poorly planned deployment of bioenergy and afforestation of naturally unforested land. By contrast, there are a range of response options that maximise both mitigation and adaptation, such as sustainable urban planning and infrastructure design including green roofs and facades, agroforestry, and the restoring natural vegetation and rehabilitating degraded land. Coordinated and coherent policies integrating mitigation and adaptation policies across sectors can maximise synergies and therefore enhance support for climate action, but this requires resources in social and institutional systems.

Enhanced mitigation and action in line with sustainable development will have distributional consequences within and across countries. Countries vary in their level of development, but also in their social, economic, cultural, environmental and political contexts. Sustainable development must take into account these differences and their resulting needs as regards development outcomes. Rapid and broad mitigation actions may result in disruptive changes with distributional consequences including the shift of employment and income from emissions intensive sectors to low-emissions activities. Low-emissions development can however create opportunities to build skills and create jobs. Applying just transition principles and integrating equity, justice and gender-equality considerations into policy packages at all scales can reduce challenges associated with the necessary shift towards low-emissions pathways.

Source: (IPCC, 2022[23])

3.3.2. The importance of measuring progress on adaptation

There is sparse evidence that existing adaptation actions actually reduce climate risk (O'Neill, 2022[48]). As with mitigation efforts, although adaptation actions are increasingly implemented worldwide, the rate and scale of adaptation progress falls short of what is needed to keep up with mounting climate risks (UNEP, 2021[49]). National-level adaptation planning has seen progress over the recent years, with an increase in the development of adaptation planning instruments and positive trends across almost all criteria of adequate and effective adaptation planning (UNEP, 2021[49]). Data on the effectiveness of implemented adaptation activities in actually reducing climate risk, however, is limited. Current adaptation implementation rates are unlikely to keep pace with mounting impacts from climate change (UNEP, 2021[49]). While progress on adaptation planning and implementation has been observed in all sectors and regions, that progress is also unevenly distributed across households, geographies and income levels with most observed adaptation being fragmented, small in scale, incremental and sector-specific (IPCC, 2022[33]).

This highlights the need to strengthen the understanding of how adaptation actions contribute to effective policy outcomes, with the support of robust monitoring and evaluation frameworks at project, local, national and international levels. Indeed, Article 7 of the Paris Agreement requests countries to engage in "monitoring and evaluating and learning from adaptation plans, policies, programmes and actions" (Paris Agreement, 2015[50]). According to the IPCC, in the context of adaptation, M&E consists of "systematic process of collecting, analysing and using information to assess the progress of adaptation and evaluate its effects - e.g., risk reduction outcomes, co-benefits and trade-offs - mostly during and after implementation" (New et al., 2022[51]). M&E is particularly important as climate change and associated impacts are dynamic processes that will change in the future. Hence, identifying successes and failures enables learning, and continuous monitoring or adaptation measurement allows efforts to be adapted to changing circumstances (Box 3.2). Moreover, under deep uncertainty, there is growing evidence that effective implementation strategies require M&E in order to judge outcomes against possible futures scenarios (OECD, forthcoming). This is particularly relevant in the context of the risks of climate system tipping points. In order to adequately consider the risk of climate tipping points, M&E systems need be informed by the best available science on tipping points, including information on potential hazards associated with crossing tipping points. Particularly important here is information on the early detection of tipping points and the thresholds beyond which they are triggered [(Bloemen et al., 2017[52]), further explored in Section 3.4.1].

Box 3.2. Adaptation Measurement – knowing when to adjust adaptation actions in an uncertain future climate

Adapting to a changing climate inherently deals with significant uncertainty. It is an ongoing process of adjustment to the evolving impacts of climate change. These impacts are characterised by uncertainty in the response of the climate system to greenhouse gas emissions, in the feedback loops produced in environmental, economic and social systems, as well as in the interconnected and cascading effects, such as those produced by tipping points, that may require unprecedented adaptation, or even demonstrate the limits of adaptation. Adaptation measures that may be effective at a given point in time might be insufficient at another, especially considering mounting climate impacts. As future impacts from climate change, including those resulting from the crossing of climate system tipping points, are difficult to predict, regularly measuring whether adaptation policies are sufficient and effective in reducing climate risk is critical to mitigate losses and damages.

Although progress has been slow, countries increasingly adopt adaptation measurement as part of implementing National Adaptation Strategies (NAS) and Plans (NAPs). Today, 19 OECD countries measure progress in the implementation of adaptation policies. Adaptation measurement entails setting objectives that can be linked to adaptation policy efforts, and can be measured in terms of inputs (e.g. human, financial and technical resources) and outputs (e.g. the deliverables resulting from a policy action). More advanced measurement efforts seek to evaluate whether these actions are effective in reducing climate risk and can be attributed as a result of the roll-out.

For example, in the **United Kingdom**, the Climate Change Committee, an independent body, conducts the Independent Assessment of UK Climate Risk. It analyses key current and future climate risks, documents the efforts of building climate resilience to date and recommends adaptation actions needed in the coming five years. Its analysis is based on current and planned policies as well as on economic sectors in which most impacts are expected (e.g. infrastructure or the natural environment). Every year, based on the risk assessment, the Committee measures progress in the implementation of adaptation actions. The annual progress report identifies the extent to which adaptation planning is taking place, whether implemented plans consider the key climate risks identified as well as trends in factors contributing to climate risks. Its work is based on adaptation indicators, including vulnerability, exposure, adaptation actions and impact to help assess the effectiveness of the UK's National Adaptation Plan, in response to the widening adaptation gap identified in the climate risk assessment process.

Over time, adaptation measurement can iteratively inform decision-making, as an adaptive management practice that enables countries to be alerted when adaptation action is insufficient, to protect communities and economics from unfolding climate risks, including any unexpected cascading impacts, or impacts associated with certain tipping points. For this to work, the constant monitoring of the level and distribution of climate risks is necessary as well as an understanding of the effectiveness of current adaptation measures.

Note: Based on the IPCC's framework, climate risk is composed of exposure, vulnerability and hazard.
Source: (IPCC, 2022[33]); (OECD, 2015[53]); (Noltze et al., 2021[54]); (OECD, 2023 (forthcoming)[55]); (Leiter, 2021[56]); (OECD, 2022[57]); (Defra, 2022[58]); (CCC, 2021[59])

3.3.3. Dealing with scientific uncertainty when developing adaptation strategies

Global Climate Models can be highly effective tools that provide a range of valuable information for adaptation in light of the threat of tipping points. As reviewed in Chapter 2, such models provide information that can strengthen collective understanding of potential futures and therefore of how decisions today can contribute to reducing the risk of climate change tomorrow (OECD, 2021[5]). However, they entail considerable uncertainties in relation to the projection of climate impacts that risk being misinterpreted by decision makers. As reviewed in section 2, the projection of impacts and cascading effects associated with climate tipping points are also subject to considerable uncertainties which only addto the adaptation challenge.

Approaches to decision-making under uncertainty have been developed and have been characterising adaptation planning and decision making. One example is the use of "narratives" which treat uncertainty in less rigid frameworks than traditional risk assessment methods and provide scientifically sound qualitative descriptions of plausible low-likelihood, high-impact future world evolutions and are particularly important in providing a better understanding of the risks and potential impacts associated with climate system tipping points. Dessai et al. (2018[60]), for example, use an approach, informed by climate processes and expert elicitation, to build six narratives of future regional precipitation change applied to the Indian Summer Monsoon. The authors show that climate process-based expert elicitation of narratives have the potential to inform regional and local risk assessments and adaptation decisions when future climate uncertainty is large[3]. Shepherd et al. (2018[61]) argue that this narrative or 'storyline' approach is an effective way of linking the physical and human aspects of climate change. They suggest four main reasons supporting their use:

- improving risk awareness by moving away from a probabilistic framing of climate impacts towards an event-oriented framing, which captures more directly how people perceive and respond to risk;
- strengthening decision-making by allowing policymakers to work backward from a particular vulnerability or decision point and combining climate change information with other relevant factors to address risk;
- allowing the use of more credible regional models in a conditioned manner by providing a physical basis for partitioning uncertainty, and;
- avoiding false precision and surprise by exploring the boundaries of plausibility.

Such storyline approaches have also been suggested as ways to improve the contributions of the IPCC on informing climate risk assessments, particularly for low-likelihood, high-impact events such as tipping points (Sutton (2018[3]). One example explored is the potential for abrupt change in the AMOC during the 21st century (among others). While low-probability, policymakers should nonetheless concretely consider the potential for high-impact hazards associated with an abrupt transition of the AMOC during this century in climate risk assessment which are explored in these storylines (Sutton, 2018[3]). Indeed, the latest WGI contribution to the AR6 explicitly assesses low-likelihood high-impact outcomes by using physical storylines, in particular in the context of "high-warming scenarios" (Arias et al., 2021[62]). These scenarios consider the low-likelihood, high-impact outcome that expected warming levels at given concentrations of GHG are surpassed (OECD, 2021[5]). Such a scenario would lead to far more severe global and regional impacts than projected, including higher risks of crossing tipping points (Arias et al., 2021[62]). Through detailing such a future through a storyline approach, the IPCC report highlights the importance of such scenarios despite associated uncertainties, and thus enables them be taken into account into climate risk assessment informing adaptation responses.

Another effective approach of decision-making under uncertainty, the Dynamics Adaptation Policy Pathways (DAAP), takes into account the multitude of uncertainties decision makers need to consider, e.g. in how climate change will unfold or how societies and economies will evolve (Haasnoot et al., 2013[63]). This approach is based on the establishment of a framework for action that is informed by a strategic vision of the future and guided by short-term, flexible actions that can be adjusted to reflect changing circumstances. DAAP is therefore a proactive decision support method, where decisions are taken to prevent, rather than to respond to, critical changes. As such, DAAP supports the development of adaptation plans where measures can be adjusted before crossing a tipping point (Franzke et al., 2022[64]).

3.4. The role of technology in addressing the risks of climate system tipping points

Technology has a key role to play to reduce and manage climate risk. Risk governance processes need to include mechanisms facilitating continuous monitoring, evaluation and learning, particularly when decisions are made under uncertainty (OECD (2021[5]) (Klinke and Renn, 2012[4]). Since there is no prior experience in dealing with climate system tipping points risks, such processes need to rely on emerging understanding of risks. This can be guided by the following components (OECD, 2021[5]): (1) characterisation of the risks; (2) evaluation of the risks and (3) development, implementation and evaluation of approaches to reduce and manage the risks. As discussed in previous sections, these are key components for incorporating the risk of tipping points within both mitigation and adaptation policies. Technology has a crucial role to play here and this section provide an overview of how different technologies can support each of these components specifically when dealing with the risks of tipping points.

3.4.1. Role of technology in informing the characterisation of risks of crossing climate system tipping points

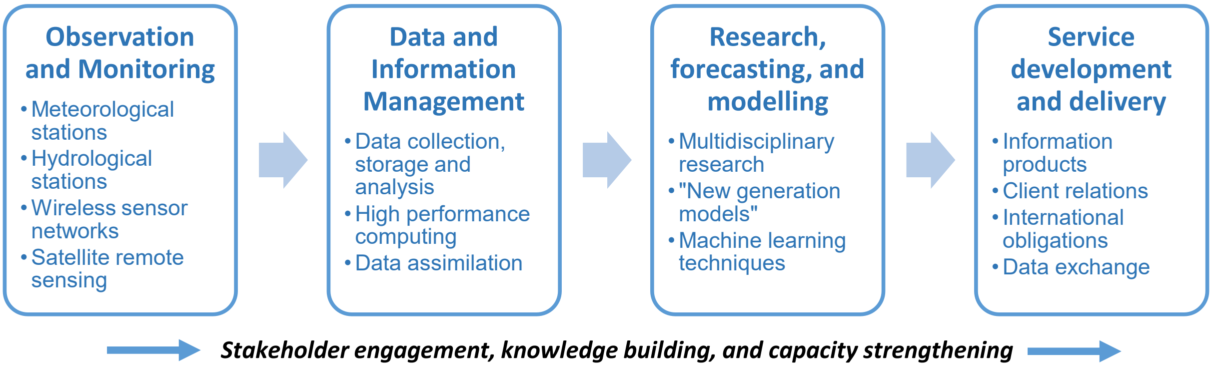
As reviewed in Chapter 2, understanding and characterising the risk of crossing tipping points, their potential impacts and cascading effects, is a complex scientific problem. The current understanding of the climate system as whole has largely benefited from technological development over the past century. In particular, advances in space observation equipment, high computing power, mapping software and telecommunication systems, provided essential tools to advance observational data collection and climate modelling. These tools are and will remain essential for the identification of climate system tipping elements and their behaviour under different warming scenarios.

In order to quantitatively understand features of the Earth's system relevant to climate system tipping points, physical theories and Earth observations are turned into models that represent these key features and their interactions. Earth is more extensively and systematically observed today than at any other time, benefitting from advances in satellites and remote sensing (Agapiou, 2016[65]; Reichstein et al., 2019[66]). The resulting data is crucial for the calibration and evaluation of climate models and therefore contributes to characterising risks associated with climate change, including the risks of climate system tipping points.

Weather and climate information services (WCIS) provide information on past, present and future states of the atmosphere and so inform climate policy decision-making (Allis et al., 2019[67]). In the presence of climate system tipping points, such services are crucial for monitoring the potential approach of tipping points and the impacts resulting from their crossing. WCIS are also essential for identifying and assessing options for reducing and managing risks as well as for monitoring the performance of implemented measures. Research suggests that, while weather services are well established, climate services informing longer timescales are less so, despite major progress in recent years (Hewitt et al., 2020[68]). Continued investments in the WCIS value chain (Figure 3.6) are necessary to ensure reliable delivery of weather and climate information. It is crucial that these products remain relevant, accessible and credible to a wide audience of decision makers, clients and communities (WMO and GFCS, 2019[69]).

Earth observations from satellites provide information on climate and climate change, relying on a complementary mix of satellite- and surface-based measurements. Such data are also crucial for supporting early warning systems (EWS) in the context of climate system tipping points, which are further discussed below. For instance, the World Meteorological Organization Global Observing System (WMO GOS) encompasses both surface- and space-based observations essential for understanding the Earth system and for the production of WCIS. Indeed, satellite data from the WMO GOS provide 90% of the data for Global Numerical Weather Prediction, which underpins most Earth system modelling approaches (ITU, 2020[70]).

Figure 3.6. Weather and climate information service value chain



Source: (OECD, 2021[5]), adapted from (WMO, 2015[71]; CIF, 2020[72]).

The physical hazards resulting from the crossing of tipping points interact with the vulnerabilities of exposed communities and natural systems to determine risk. In this sense, technologies for the collection of data on exposure and vulnerability are crucial for the characterisation of risks. Understanding societal vulnerability requires granular socio-economic data and assessments of the impact of climate hazards on people's livelihoods and health, which is often not directly quantifiable. Geospatial data, analysis and visualisation tools, including satellite imagery, aerial or unmanned aerial vehicle (UAVs or drones) images, mobile communications, and social media can provide valuable information on exposure and vulnerability (OECD, 2021[5]). The use of such technology, however, requires real-time capabilities to monitor the exposure of people as well as advanced data processing capacities. Coupling high-resolution geospatial data on the patterns of exposure and vulnerability with artificial intelligence capabilities may thus help guide response design and implementation (OECD, 2021[5]).

At the international level, Shared Socio-economic Pathways (SSPs) have been developed to describe different potential development pathways making assumptions on variables such as level of economic growth, poverty and demographic change which are closely linked to vulnerability and exposures. While they are scenarios and by no means direct predictions of the future, in conjunction with climate scenarios, they provide a good indication of how the three drivers of risks can interact to determine impacts (O'Neill et al., 2017[73]).

Early warning systems for characterising the risks of tipping points

Technologies for better monitoring and modelling of the climate system will be essential for characterising how climate-related hazards resulting from the crossing of climate system tipping points may evolve over time and space. Thus, they can more broadly identify features of systems approaching a tipping point. In this sense, high-quality scientific data in an appropriate frequency and resolution are key to understand, monitor allow for early warning of tipping elements. Due to the need to assess the complex interactions between natural variability and anthropogenic forcing (Swingedouw et al., 2020[74]), detecting early warning signals is challenging but any information provided is invaluable for the understanding of how the Earth system is approaching some of these critical transitions (Ditlevsen and Johnsen, 2010[75]; Lenton, 2011[76]; Swingedouw et al., 2020[74]; Bury, Bauch and Anand, 2020[77]; Rosier et al., 2021[78]). The current state of early warning systems for climate system tipping points and potential avenues for improving them are reviewed below.

It is difficult to predict the state at which tipping points are crossed as the driving parameters which induce a shift often experience only incremental changes before the system in question makes a sudden or persistent transition. One method to help detect early loss of system resilience consists in Early warning indicators (EWI), which are statistical methods that can quantify the loss of temporal or spatial resilience, signalling the approach of crucial thresholds (Gsell et al., 2016[79]; Lenton, 2011[76]; Boulton and Lenton, 2015[80]; Boers, 2021[81]). Recent analysis shows that deep-learning, or artificial intelligence algorithms, can find more reliable early warning signals than more established methods as they use extra information from patterns in the data (Bury et al., 2021[82]).

Another method that has proven to be successful in detecting early warning signals of abrupt shifts in climate state in climate modelling and observational datasets is a machine-vision approach to automatically detect edges (Bathiany, Hidding and Scheffer, 2020[83]). This approach can quantify abruptness, provide details to help understand the causes of the shift, and assess some uncertainties of climate events. This method has proven to be effective in identifying “climate surprises” (Bathiany, Hidding and Scheffer, 2020[83]), showing, for example, abrupt shifts related to the loss of sea ice and permafrost in the Arctic (Bathiany, Hidding and Scheffer, 2020[83]).

Almost all existing methods for monitoring early warning signals rely on data on the present state of the climate through direct and remotely sensed observations and play a crucial role in the characterisation of tipping point risks. While remotely sensed observations have been significantly improved over the years (Guo, Zhang and Zhu, 2015[84]; Reichstein et al., 2019[66]), better monitoring technologies are needed to improve high-level observation of disturbances in spatial patterns related to fragile transitions in systems. Ideally, an international scientific programme could focus on monitoring, modelling and developing potential EWIs for a range of tipping elements. Progress in this direction seems to be underway. In early 2021, for example, the ESA Climate Office convened a forum on Remote Sensing of Tipping Points in the Climate System; the forum was hosted by the International Space Science Institute (ESA, 2021[85]). Participants recognised that while the spatial resolution of satellite datasets and the resolution across the frequency spectrum are both improving, these improvements have associated challenges, such as the need to bridge scale differences between observations and models. Participants also noted the importance of methodologies to take advantage of the high resolution imagery available in remote sensing datasets to study spatial patterning and nonlinear disturbance effects.

Observational data on abrupt climate changes that occurred in the geological past is also needed to improve the ability of models to characterise, and therefore predict, couplings and feedbacks in the Earth system and the potential for tipping points (Lenton et al., 2019[86]). Constraining, for example, current ice sheet models with new historical data will progressively allow reanalysing past ice sheet mass loss. This can contribute to enhancing our understanding of the underlying processes of ice sheet melting and improve the ability for models to reproduce past changes, increasing the reliability of their projections (Lenton et al., 2019[86]; Swingedouw et al., 2020[74]; Brovkin et al., 2021[87]).

In general, there are a number of valuable efforts by the climate modelling community and remote sensing experts in improving the detection of early warning signals. It is less evident how these new findings feed into risk management strategies, informing courses of actions contemplated by policy-makers. Greater efforts to systematically make this information available, in a digestible manner, for decision-makers need to be made if the threat of tipping points are to be addressed.

3.4.2. Role of technology in informing the evaluation of risks of crossing climate system tipping points

Technology has an important role to play in risk evaluation (Figure 3.1). Risk evaluation involves a broad range of values, including societal values, economic interests and political considerations, which influence perceptions of risk. Given differences in values across individuals, communities and cultures, it is crucial that the approach to risk evaluation is participatory through, for example, the creation of community risk assessment tools. They can create an exchange of information that informs decision makers on how society judges risks and brings to light communities’ perspectives on increased climate risks to livelihoods and systems (van Aalst, Cannon and Burton, 2008[88]). The methodology may involve a range of hard and soft^4 technological tools, including risk mapping, focus group meetings, surveys and discussions, and interviews.

As an example, digital community risk maps facilitate risk-knowledge co-generation informing the evaluation of climate risk in general and also generating information that is useful for managing the risk of crossing climate system tipping points. For example, the Risk Geo-Wiki portal established by the International Institute for Applied Systems Analysis, provides a two-way information exchange between local knowledge and expert-sourced knowledge of risk (Geo-Wiki, n.d.[89]). It allows for a community-based participatory mapping process where community members can provide, for instance, hand-drawn maps of the locations of critical infrastructure, emergency shelters and other community resources. The information is then digitalised and can be further updated developed by local stakeholders. These digitalised maps can be overlaid with satellite imagery to better visualise and aid in planning, designing and developing initiatives. The portal has been used in Nepal, Peru, Mexico (Mechler et al., 2018[90]).

With advances in geospatial technologies, qualitative local knowledge can now be translated into mathematical models to evaluate quantitatively potential outcomes of climate change (Hemmerling et al., 2019[91]). The process can therefore incorporate localised knowledge into usable quantitative datasets that can serve multiple purposes in the planning process. Such quantification can, for example, be used to identify particularly vulnerable or exposed social or cultural groups, and provide useful information for reducing and managing risks in geographically targeted evidence-based planning strategies. This allows policy makers to make informed decisions, such as on the adoption of new adaptation and resilience plans, even where traditional quantitative data informing risk assessments is lacking (Cornforth, Petty and Walker, 2021[92]).

3.4.3. Role of technology in the development and implementation of approaches to reduce and manage risks of crossing climate system tipping points

Technology has a crucial role to play in climate strategies, helping to avoid and reduce risks through mitigation and adaptation. Without aiming to be comprehensive, this section discusses the role of technology for some mitigation and adaptation options, reflecting specifically on how these contribute to tackling the risk of climate tipping points. The section also discusses the potential use of geoengineering, and in particular the use of Solar Radiation Modification technologies, as a response to the risks of crossing climate system tipping points.

Technologies needed for limiting warming to 1.5°C, with no or limited overshoot

Strategies that limit warming to 1.5°C with no or limited overshoot require accelerated near-term economic transformation, entailing rapid and deep emissions cuts worldwide. The ability to achieve these unprecedented levels of emissions reductions depends on technologies and the strength of reinforcing feedbacks. For example, the energy system is one of the key systems requiring transformation for a low-carbon world. Renewable power generation technologies including solar, wind and hydro technologies, are key for achieving that transition. The development of these technologies over the past decade led to a considerable decrease in the cost of energy from renewable sources and a significant scaling-up of renewable deployment and generation (IEA, 2021[13]). This new energy economy is the product of a virtuous cycle combining policy action and technology innovation, with momentum sustained by ever decreasing costs (IEA, 2021[13]). In every plausible low-carbon future where the crossing of climate system tipping points is avoided, these efforts need to be considerably accelerated, especially within the next decade (see section 3.2.for further detail).

The risk of climate tipping points also implies a key role for Carbon dioxide removal (CDR) technologies, as scenarios that limit warming to 1.5°C, with no or limited overshoot, all include at least some CDR. They serve three main purposes throughout the century: they help accelerating early deep emissions reductions, they balance out harder-to-abate sectors that continue to act as sources of residual emissions and they allow for reducing warming after peak temperature (Riahi et al., 2021[24]). It is important to note however that, since an overshoot could lead to the crossing of tipping points, the well-known argument that delayed emissions reductions can potentially be compensated by negative emissions during the latter part of the century is no longer valid.

CDR options in energy-system modelling pathways are mostly land-based biological CDR, including bioenergy with carbon capture and storage (BECCS), afforestation or soil-carbon sequestration and direct air CO_2 capture and storage (DACCS) (M. Pathak, 2022[22]). While afforestation and soil-carbon sequestration have been practiced for decades to millennia (although not necessarily with the intention to remove carbon from the atmosphere), experience with BECCS and DACCS, whilst growing, is still limited (M. Pathak, 2022[22]). There remain today many legitimate concerns regarding BECCS, stemming primarily from its immense demand for land and resulting implications for land-use practices, trading-off available land for food production and impacting natural ecosystems and biodiversity (Creutzig et al., 2021[93]). It is argued that these risks may be best avoided by demand-side measures driving rapid decarbonisation in place of land-intensive carbon dioxide removal technologies (Creutzig et al., 2021[93]). Given that all scenarios in line with 1.5°C, with no or limited overshoot, include CDR, even when stringent demand-side measures are adopted, not employing CDR at all could result in the crossing of tipping points. The risks associated with BECCS can therefore no longer be considered in an isolated manner and need to be weighed against the risk of crossing tipping points. These potential trade-offs remain poorly understood and could greatly benefit from further research.

Knowledge transfer/sharing supporting transformational adaptation and M&E processes

Identifying technologies supporting climate change adaptation is a complex process that cuts across all sectors of the economy and at different scales. This section does not aim at providing a list of potential technologies, rather it focuses on key aspects identified in Section 3.3 and potential ways technology can harness their development. First, transformational adaptation approaches are still in their infancy. Supporting policy-makers in achieving transformational adaptation strategies may require both soft and hard technologies. For example, knowledge creation and transfer, a soft-technology, is key to informing decision-makers and ensuring transformational adaptation is possible. Boon et al., (2021[94]) argue that transformational adaptation may require the transformation of climate services in a process that simplifies and aggregates climate system knowledge, and then integrates it with knowledge about the physical, economic and social systems of cities and regions. The authors identify four knowledge requirements: "(1) system knowledge to identify the root causes [of climate risk] and solutions; (2) inspirational and cross-disciplinary knowledge to develop a long-term vision; (3) a clear climate message and guiding principles to mainstream the vision; and (4) design principles that are connected to the priorities and interests of the stakeholders." (Boon et al., 2021[94]).

Scientific and modelling advances can also support adaptation approaches that are effective and in line with transformational adaptation, especially in the context of high-uncertainties associated with climate system tipping points. Palmer and Stevens, (2019[95]) argue that greater and more co-ordinated investments into climate modelling capabilities could reduce uncertainties in climate projections. While there are clear benefits from greater coordination and investments in climate modelling, the notion that simply increasing computational effort will necessarily reduce uncertainties of modelling output is disputed, particularly in relation to regional model responses (Stainforth and Calel, 2020[96]).

Geoengineering: the potential use of Solar Radiation Modification technologies

Solar geoengineering, and in particular, Solar Radiation Modification (SRM) approaches have been proposed as a potential strategy to reduce future climate impacts, as well as reducing the risk of crossing climate system tipping points (Irvine, Sriver and Keller, 2012[97]; Curry et al., 2014[98]; Heutel, Moreno-Cruz and Shayegh, 2016[99]). One well-known SRM approach consists of injecting sulphate aerosols in the stratosphere, thereby reducing the amount of solar radiation reaching the Earth's surface. Such approaches have the potential to offset warming, even without a reduction in GHG emissions, however, their effectiveness and political feasibility of such approaches is debated (Barrett et al., 2014[100]; Irvine, Schäfer and Lawrence, 2014[101]).

In particular, there are concerns regarding risks associated with the use of SRM technologies. The latest IPCC report cautions that there remains little understanding of the potential of these technologies to actually reduce risk, and that they may also introduce novel risks to people and ecosystems (Pörtner et al., 2022[14]). The report highlights that SRM could result in substantial residual climate change by altering regional and global climate patterns (*Ibid*). In addition, because SRM does not change trends in emissions, climate impacts that are not directly related to temperature would not be avoided, such as ocean acidification under continued anthropogenic emissions. The report highlights there is high agreement in the literature that addressing climate change risks with SRM should only be a supplement to mitigation strategies, and should be used solely to reduce residual risks. The report also highlights considerable knowledge gaps, with low confidence in projected benefits of SRM as well as in risks to crop yields, economies, human health, or ecosystems. Finally, the report recognises that co-evolution of SRM governance and research provides a chance for responsibly developing SRM technologies, guarding against potential risks and harms relevant across a full range of scenarios. Other types of risks consist in the so-called "termination shock", whereby a potential sudden stop of deployment of a particular SRM technology could lead to rapid and damaging rise in temperatures with potentially very dramatic impacts (Parker and Irvine, 2018[102]).

Despite the uncertainties and potential risks surrounding SRM, Heutel, Moreno-Cruz and Shayegh, (2016[99]) argue that, considering the risk of climate tipping points, solar geoengineering should be included as a policy option in an optimal climate policy strategy. This is because SRM approaches have the ability to reduce temperatures much faster than mitigation, and thus may reduce the risk of reaching a tipping point even if mitigation responses are insufficient (Heutel, Moreno-Cruz and Shayegh, 2016[99]). The authors, however, also argue against using such approaches after a tipping point has been reached. It has been highlighted that decision-making concerning SRM needs to take a risk-risk framework approach, where risks of SRM are analysed against other risks such as risks associated with e.g. climate change itself, emissions reductions, CDR or adaptation (Tyler Felgenhauer et al., 2022[103]) and that opportunities to increased investments in research for atmospheric climate interventions need to be rapidly ramped up (Silverlining, 2019[104])

All considered, given the limited level of research on geoengineering technologies, low confidence in their effectiveness and the considerable risks they are associated with, this report concludes that they are not today a feasible policy option for reducing the risk of crossing tipping points. Since mitigation strategies continue to face implementation challenges, in particular in terms of technological risks, scaling and costs, investments in technologies that can deliver 1.5°C through GHG mitigation need to be prioritised over more uncertain, and potentially riskier, geoengineering technologies.

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Notes

[1] This report does not discuss or prejudge whether stakeholder engagement processes are effectively put in place, but acknowledges that these are also important factors of risk evaluation.

[2] In this risk evaluation framework, how a risk is perceived is independent and prior to costs and/or cost-benefit considerations. However, even if the costs are considered, as reviewed in section 2.4, the costs of climate tipping points are projected to considerably outweigh mitigation costs.

[3] A direct application of such an approach for the design of long-term adaptation pathways is given in Bhave et al (2018[105]).

[4] Both soft and hard technology encompass scientifically ordered knowledge to develop goods or services that enable human adaptation. Hard technologies involve technological equipment such as example satellites, whereas soft technologies refers to technological knowledge, non-tangible material, administrative or organizational use.

Climate Tipping Points

INSIGHTS FOR EFFECTIVE POLICY ACTION

This report reviews evidence that overshooting 1.5°C may push the earth over several tipping points, leading to irreversible and severe changes in the climate system. If triggered, tipping point impacts will rapidly cascade through socio-economic and ecological systems, leading to severe effects on human and natural systems and imposing important challenges for human adaptation. Of particular concern are the likely collapse of the West Antarctic and Greenland ice sheets and the abrupt melting of permafrost grounds in the Arctic, which would result in additional sea-level rise and greenhouse gas releases, leading to more warming.

Based on the most recent science and consultations with renowned experts, *Climate Tipping Points: Insights for Effective Policy Action* argues that it is no longer appropriate to consider the risk of crossing tipping points as low-probability. Overshooting 1.5°C may likely lead to irreversible and severe impacts, which must be avoided, heightening the urgency to drastically reduce emissions within this decade. The report calls for a shift in how tipping points are treated in climate policy today and provides recommendations on how climate risk management strategies can better reflect the risks of tipping points in the areas of mitigation, adaptation and technological innovation.

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Climate and economic resilience in a changing world

LOSSES AND DAMAGES FROM CLIMATE CHANGE

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