Natural system impacts of overshoot pathways

Global consequences of climate overshoot pathways: Annex 5

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CS-NOW
Climate services for a net zero resilient world

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Key messages

1. Some natural system tipping elements may already have been triggered

Parts of the West Antarctic ice sheet may have already passed a tipping point, and there are early indications about the Greenland ice sheet, the Amazon rainforest and the Atlantic Meridional Overturning Circulation. For the AMOC, there is medium confidence that the ongoing decline will not become an abrupt collapse during the 21st century.

2. Other tipping elements will pass their thresholds between 1.5–2.0 °C of warming

A number of other tipping elements have best-estimate temperature thresholds between 1.5–2.0 °C of warming, including: (a) warm water corals (1.5 °C); (b) boreal permafrost (1.5 °C); (c) Barents Sea Ice (1.6 °C); (d) Labrador-Irminger seas/Subpolar gyre convection (1.8 °C); and (e) mountain glaciers (2.0 °C). For ocean acidification, sensitive regions, such as the Arctic, will pass critical chemical thresholds even under 1.5 °C warming. But each of these temperature thresholds have wide ranges that reflect the high uncertainty.

3. Overshooting 1.5 °C substantially increases the risk of catastrophic wildfires

The risk of catastrophic wildfires could increase, especially in regions already vulnerable to wildfires, if temperature overshoot exceeds 1.5 °C of warming for an extended period. A subsequent reduction in temperature and return to previous climate conditions would not necessarily reverse any ecosystem changes that occur as a result of increased wildfires.

4. Overshooting 1.5 °C substantially increases the risk of biodiversity loss

The risk of biodiversity loss is generally moderate with no overshoot but at the transition between high and very high with overshoot to 2 °C of warming. While even 1.5 °C warming is projected to cause substantial local losses for many species, the risk doubles for many species at 2 °C warming. The local extinction tipping point varies depending on region and group of species: insects have the lowest tipping point (1.5–2 °C), followed by plants (2–3 °C) and then vertebrates (>3 °C). However, some parts of Africa and Amazonia have a lower tipping point (<1.5 °C). As this is not full extinction, individual species ranges would be expected to slowly recover over time. However, changes to communities of species could lead to long-term and possibly permanent disruption of ecosystem functioning.

About this report

The “Global consequences of climate overshoot pathways” study has examined the natural and human system consequences of the world overshooting 1.5 °C, but then using carbon dioxide removal technologies to return the global temperature to 1.5 °C by 2100.

The final report summarises the findings from the study. Six annexes present the technical evidence that underpin the final report:

- Annex 1: Development of overshoot pathways.
- Annex 2: The feasibility of deploying CDR at the rate required for overshoot pathways.
- Annex 3: Economic implications of climate overshoot.
- Annex 4: Hysteresis and tipping points analysis using the UK Earth System Model.
- Annex 5: Natural system impacts of overshoot pathways.
- Annex 6: Human system impacts of overshoot pathways.

Around 40 scientists have contributed to these annexes and more than 900 literature sources are cited.

This annex, Annex 5, considers how both global and regional natural systems might be affected by an overshoot, and in particular the potential for hysteresis or tipping points to occur.

About CS-N0W

Commissioned by the UK Department for Energy Security & Net Zero (DESNZ), Climate Services for a Net Zero Resilient World (CS-N0W) is a 4-year, £5 million research programme, that uses the latest scientific knowledge to inform UK climate policy and help us meet our global decarbonisation and resilience ambitions.

CS-N0W enhances the scientific understanding of climate impacts, decarbonisation and climate action, and improve accessibility to the UK's climate data. It contributes to evidence-based climate policy in the UK and internationally, and strengthens the climate resilience of UK infrastructure, housing and communities.

The programme is delivered by a consortium of world leading research institutions from across the UK, on behalf of DESNZ. The CS-N0W consortium is led by **Ricardo** and includes research **partners Tyndall Centre for Climate Change Research**, including the Universities of East Anglia (UEA), Manchester (UoM) and Newcastle (NU); institutes supported by the **Natural Environment Research Council (NERC)**, including the British Antarctic Survey (BAS), British Geological Survey (BGS), National Centre for Atmospheric Science (NCAS), National Centre for Earth Observation (NCEO), National Oceanography Centre (NOC), Plymouth Marine Laboratory (PML) and UK Centre for Ecology & Hydrology (UKCEH); and **University College London (UCL)**.

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Acronyms

AMOC	Atlantic Meridional Overturning Circulation
AOGCM	Atmosphere-Ocean General Circulation Model
AR5	IPCC's Fifth Assessment Report (2013-2014)
AR6	IPCC's Sixth Assessment Report (2021-2022)
CO_2	Carbon Dioxide
CS-N0W	Climate Services for a Net Zero Resilient World
CTI	Community Transformation Index
CTP	Climate Tipping Point
DESNZ	Department for Energy Security and Net Zero
ESA	European Space Agency
ESM	Earth System Model
GMST	Global Mean Surface Temperature
GSAT	Global Mean Surface Air Temperature
Gt	gigatonne
Gt-C	gigatonne as carbon
Gt-CO_2	gigatonne as carbon dioxide
H^+	Hydrogen Ion
IPCC	Intergovernmental Panel on Climate Change
IUCN	International Union for Conservation of Nature
MHW	Marine Heatwave
MICI	Marine Ice Cliff Instability
MISI	Marine Ice Sheet Instability
NO	No Overshoot pathway
NTE	Non-tipping Element
PFAT	Permafrost Abrupt Thaw
SPM	Summary for Policymakers

SR1.5	IPCC Special Report on “Warming of 1.5 °C”
SROCC	IPCC Special Report on “Ocean and Cryosphere in a Changing Climate”
SSP	Shared Socioeconomic Pathway
TE	Tipping Element
TP	Tipping Point
TS	Technical Summary
UKESM	UK Earth System Model
UNEP	United Nations Environment Programme
VHO	Very High Overshoot pathway
WAM	West African Monsoon
WG-I/II/III	IPCC Working Groups I, II and III
Ω_{Arag}	Aragonite Saturation State

Executive Summary

This annex reviews the potential impacts of overshooting 1.5 °C on natural systems, with a particular focus on tipping points, high impact events and hysteresis in the climate and natural systems. It examines five parts of the Earth system:

1. Atmosphere: (i) changes in the West African and Indian monsoon; (ii) changes in the frequency and reversibility of extreme events (e.g. heatwaves, intense rainfall).
2. Ecosystems: (i) loss of boreal forests (fires and pests); (ii) loss of the Amazon and other Tropical Rainforests (fire and drought); (iii) greening of the Sahel; (iv) lock into dust-bowl conditions.
3. Biodiversity: (i) loss of biodiversity, including insects; (ii) changes in ranges, phenology, physiology and morphology of terrestrial and freshwater species.
4. Oceans and coastal regions: (i) collapse of the Atlantic Meridional Overturning Circulation (AMOC); (ii) cooling of the subpolar gyre; (iii) frequency and of intensity of ocean heatwaves; (iv) frequency and of intensity of ocean deoxygenation and hypoxic events; (v) change in the rate of ocean acidification; (vi) loss of coral reefs.
5. Cryosphere: committed loss to the ocean of the ice stored within (i) the Greenland Ice Sheet; (ii) Antarctic ice sheets; and (iii) mountain glaciers; (iv) loss of perennial Arctic Sea ice; (v) permafrost thaw.

Approach of this study

The Earth system comprises a number of interconnected domains (atmosphere, oceans, land and cryosphere), involving a large number of physical, chemical and biological processes. Earth system models (ESMs), such as the UK Earth System Model (UKESM), represent many of these processes and the complex interactions between them.

Tipping points in the Earth system refer to critical thresholds that can be passed in response to human-induced climate change, and lead to changes in components of the Earth system ("tipping elements") that are abrupt, high-impact (on human societies or the natural world), and often irreversible. Hysteresis refers to changes in the state of the Earth system that are potentially reversible, but depend on the history of the state. Hysteresis occurs when a return in a forcing agent (e.g. atmospheric CO_2 concentrations rising and then falling) causes the impact to remain “locked” in a potentially undesirable state. However, there is potential reversibility if the driver is reduced sufficiently.

The latest IPCC assessment and recently published literature indicate that the tipping points in some tipping elements are lower than previously considered. The focus of this annex is on those tipping points or cascade of tipping points, high impact events and hysteresis that could occur in the overshoot pathways under investigation in the wider study. Specifically, there is interest in:

- Which tipping points may be crossed with warming of between 1.5–2.0 °C?
- Which of these tipping points are reversible, with or without hysteresis, following a temperature ‘overshoot’ and subsequent cooling after a few decades?

Bespoke runs using the UKESM were undertaken for two pathways developed in Annex 1: (1) a “No Overshoot” (NO) pathway, which achieves the aim of the Paris Agreement to limit the global temperature increase to 1.5 °C by 2100; and (2) a “Very High Overshoot” (VHO) pathway, which reaches 1.9 °C of warming before returning to 1.5 °C by 2100. The UKESM scenario runs of these two pathways are described in Annex 4.

The overall methodology is to compare existing literature for a 1.5 °C rise and a 2 °C rise, especially since the publication of the IPCC Sixth Assessment Report (AR6), supplemented by initial analysis of the UKESM scenario runs to identify potential natural system impacts and/or hysteresis of overshooting. In the time available for preparation of this annex, the use of the output from the UKESM runs was limited to the ecosystem and biodiversity domains. This annex draws on the results for the atmosphere domain in Annex 4. A more complete analysis of the UKESM runs could be undertaken in the future.

A number of tipping points have best-estimate temperature thresholds between 1.5 °C and 2 °C. Overshoots not exceeding 2 °C may keep warming below the temperature thresholds of several other important tipping points. It may be possible to safely overshoot tipping points in slower elements such as ice sheets, but the allowable overshoot times need further research.

Atmosphere

Tropical monsoon systems have a large impact on human and natural systems. For the West African Monsoon, current literature suggests a tipping point occurs at a threshold of ~2.8 °C (2 to 3.5 °C) (low confidence), over a timescale of 50 years (10 to 500 years) (low confidence), with uncertain Earth system impacts (regional warming) (medium confidence). Annex 4 presents results that the end-of-century precipitation could be lower in the tropics, particularly in the Sahel and Indian monsoon regions, in the VHO pathway. However, none of the differences are currently statistically significant, as the ensemble spread is larger than the difference in the ensemble means between the VHO and NO scenario runs.

Temperature and precipitation extremes: The IPCC AR6 assessment contains new evidence which strengthens previous conclusions that even relatively small incremental increases in global warming (e.g. +0.5 °C) cause statistically significant changes in extremes on the global scale and for large regions for atmospheric variables such as temperature and precipitation (high confidence). Even for pathways without overshoot, it remains an active area of research whether the temperature distribution as a whole move to higher temperatures or the high temperature end of the distribution expands with global warming.

Ecosystems

Amazon and Boreal Forests: The tipping point on Amazon forest dieback has a proposed threshold of ~3.5 °C (2 to 6 °C), notwithstanding deforestation (which would likely lower the threshold) (low confidence), with timescales of 100 years (50 to 200 years) (low confidence). Boreal forests are considered to be a regional impact tipping element with two potential climate tipping points associated "with abrupt dieback at its southern edge" (medium confidence, a threshold of ~4 °C (1.4 to 5 °C) (low confidence)) and "abrupt expansion at its northern edge (tundra greening)" (medium confidence, a threshold of ~4 °C (1.5 to 7.2 °C) (low confidence)).

Fire: Climate change is already causing substantial shifts in fire regimes over much of the world's ecosystems. The extent of the changes increases with the level of global warming. In some regions, such as the Arctic, the increase in the frequency and intensity of wildfires may still be substantial even with a 1.5 °C warming because of the susceptible nature of this region. In other regions, such as the Mediterranean and notably tropical forests, more extreme temperature changes could increase the frequency of extreme wildfires. The impacts on wildfires could become more severe if an overshoot above 1.5 °C of warming is prolonged. While there is little research available on hysteresis in the context of overshoots, research on the warming and speed of forest losses suggest they can respond quickly and early. Even at current levels of warming, there are significant losses in carbon from forest fires, which could reduce the allowable anthropogenic emissions to achieve 1.5 °C of warming by 20%. An additional 40 $GtCO_2$ might need to be removed should there be an overshoot. Although the version of the UKESM used to create the scenario runs does not include a representation of vegetation fires, UKESM outputs are able to reproduce the trends in the bioclimatic variables relevant to fire. The UKESM analysis is consistent qualitatively with the above.

Biodiversity

Species changes: The typical response of species to climatic changes over time has been one of range changes. However, this usually takes a long period of time, even in species with rapid population cycling. The IPCC AR6 assessment concluded that there is now *very high confidence* that poleward and upward movements of species is attributable to climate change, across a large number of species types and across the globe. Such adaptation is only possible if the rate of change matches the ability of the species to track its suitable climate. If the rate is too fast, or the magnitude of change too great, then local extinctions are likely to occur, becoming overall extinctions if the change is great enough or a species has a very small range.

Although an extensive literature has been published on the potential impacts of climate change on species, few of the publications consider overshoot pathways. Figure 2-11 of IPCC AR6 WG-II shows the global risk of biodiversity loss is moderate at the temperatures associated with no overshoot, but at the transition between high and very high risk at the temperatures associated with the VHO (2 °C) pathway considered in this study. The risks to biodiversity and ecosystems are high with no overshoot and very high with overshoot for Africa; the loss and degradation of coral reef ecosystems is already very high even with no overshoot; sea ice ecosystems owing to loss of sea ice in the Arctic is high with no overshoot and very high with overshoot.

Range changes: Taken globally, at 2 °C (overshoot), range losses of >50% are projected for 18% of insects but only 6% at 1.5 °C. For plants, with 2 °C warming, range losses >50% projected for 16% of the plants but only 8% at 1.5 °C. Thus, avoiding overshoot prevents two thirds of the risks associated with warming of 2 °C for insects and half the risks associated with warming for plants. A key issue is that the models used, like most species distribution models, are based on long-term changes in the mean climate and do not take into account extreme events that increasingly occur. Incorporating changes in the frequency of extreme events in large-scale species modelling is an active area of current research.

One of the biggest risks of overshoot on biodiversity is the degree to which ecological communities may potentially transform over time. As climate changes, regions will gain some species and lose others. This mixing is likely to be underestimated for an overshoot pathway because the dispersal rates of some species may not keep pace with the temperature increase and subsequent temperature reduction. The regions showing the greatest potential risk are in Southern Amazonia/Cerrado (South America), Miombo Woodlands (Africa), Southern Europe, India, parts of Australia, and the Kamchatka Peninsula and surrounding areas in Russia. Considering pollinators (some of which can disperse to track the climate) and flowering plants (that generally have dispersal rates too small to track the climate changes), an overshoot pathway is projected to potentially impact pollinator/flowering plants (including insect pollinated crops) in Amazonia, Southern Africa and much of Europe.

Oceans and coastal regions

The oceans play a critical role in the Earth's climate system by storing large amounts of heat and carbon, transporting heat from warm to cold regions, and regulating the global climate.

Atlantic Meridional Overturning Circulation (AMOC): The AMOC is a core global tipping element (medium confidence) with a best estimate threshold of ~4 °C. The few available studies suggest that there is no evidence that the weakening of the AMOC will be significantly different for 1.5 °C or 2 °C of global warming. There is a lack of scientific literature about the AMOC response to overshoot pathways. There are many uncertainties arising from (a) missing processes in both models and measurements used for evaluation of AMOC trend and variability, and (b) a lack of understanding how ocean circulation is changing with warming, especially the role of vertical mixing, deep ocean processes, currents, and their impact on weather patterns on a regional scale, and (c) any potential hysteresis in AMOC.

Sea-level rise: There are few studies focusing on sea level rise for warming of 1.5 °C or 2 °C, including a small overshoot, leading to a lack of consensus between reported ranges of global mean sea level rise. Nevertheless, there is an agreement that the median of global mean sea level in 2100 would be 0.1 m higher in a 2 °C warmer world compared to a 1.5 °C. Other studies have reported an increase in the magnitude and frequency of extreme sea level events in coastal regions, associated with sea level rise under the 1.5 °C and 2 °C warming, compared to the present day.

Marine heatwaves (MHWs): Since the 1980s, MHWs have approximately doubled in frequency (high confidence) and have become more intense and longer (medium confidence). MHWs are projected to further increase in duration, intensity, frequency and spatial extent with global warming. This will lead to mass mortalities of coastal species and large-scale bleaching of coral reefs, as well as shifting fish stocks with reduced fisheries results.

Ocean Acidification: The global ocean has become about 40% more acidic since pre-industrial times. While there are few studies that focus on acidification differences between 1.5 °C and 2 °C warming, studies have shown that acidification is directly related to CO_2 concentration and uptake into the ocean and will continue as emissions rise. Even as CO_2 concentrations decline again, there will be a decadal to centennial level delay in recovery in the ocean carbonate system. Even under 1.5 °C warming, sensitive regions, such as the Arctic, will pass critical chemical thresholds for acidity (or pH), causing the breakdown of calcium carbonate minerals such as aragonite, which are used by many marine calcifying organisms such as calcifying plankton, corals, molluscs and crustaceans.

Marine Ecosystems: Warm water coral reef ecosystems are considered to be a regional tipping element (high confidence). New and multiple lines of evidence indicate the transition from high to very high risk now occurs at a lower temperature threshold (1.5–2.0 °C of warming) than previously considered.

Cryosphere

Greenland and Antarctic Ice Sheets: Observations have revealed that the Greenland Ice Sheet and parts of the West Antarctic Ice Sheet may have already passed a tipping point. An increase in warming from 1.5 °C to 2 °C increases the likelihood of the collapse of these ice sheets. As the ice sheet response timescale is long, passing of this tipping point could be avoided with post-overshoot cooling to 1.5 °C by 2100, provided that the uncertain critical threshold beyond which the Greenland ice sheet would tip lies at the upper end of the estimated temperature range of 1.5–3 °C).

Sea ice: Perennial sea ice in the Arctic is likely to be lost under sustained warming exceeding 1.5 °C. The Arctic summer sea ice system as a whole exhibits no hysteresis and no tipping point, with losses reversible 'within years to decades' under a cooling climate. There are early warning signs about regional-scale tipping points for sea ice in the Barents Sea.

Permafrost thaw: Loss of permafrost carbon due to thaw is irreversible at centennial time scales (*high confidence*). Armstrong McKay *et al.* (2022) identify permafrost abrupt thaw as a potential tipping point as a 'regional impact' (but not global) and conclude that "*going from 1.5 to 2 °C increases the likelihood of committing to … abrupt permafrost thaw*".

Glaciers: The likelihood of triggering the loss of more than 50% of extra-polar glacier ice is non-negligible as the temperature exceeds 1.5 °C and such loss becomes likely by ~2 °C. Mountain glaciers are considered to be potentially susceptible to tipping with an overshoot of any magnitude. Given the lack of information, uncertainties and regional variability in feedback mechanisms, such tipping points are described as *potentially* avoidable and *probably* reversible with subsequent cooling.

1. Introduction

Overshooting a 1.5 °C rise in the global surface average temperature compared to pre-industrial times could have substantial impacts on natural and human systems. This annex reviews the evidence for potential impacts on natural systems, with a particular focus on tipping points and elements, high impact events and hysteresis in the climate and natural systems. Five Earth system domains are analysed: the atmosphere, ecosystems, biodiversity, oceans and coastal regions, and the cryosphere.

The report considers a "Very High Overshoot" (VHO) pathway that reaches 1.9 °C of warming around 2065 before returning to 1.5 °C of warming in 2100, as this is likely to have the most substantial impacts of the three overshoot pathways developed in Annex 1. Where appropriate, the impacts of this pathway are compared with the impacts from a counterfactual "No Overshoot" (NO) pathway, in which the Paris Agreement target of limiting the increase in the global mean surface temperature to no more than 1.5 °C is achieved.

While there is a large body of literature available on the impacts of a 1.5 °C rise and a 2 °C rise in global mean surface temperature (IPCC, 2018, 2019, 2021, 2022a), there is less literature on the impacts of an overshoot to warming of ~2 °C followed by a reduction to 1.5 °C. As hysteresis is expected in some natural systems, the impacts would not necessarily reduce as the global temperature is reduced.

Annex 4 describes how the UK Earth System Model (UKESM) was used to produce scenario runs for the VHO and NO pathways. Each pathway was run four times to account for natural variability.

The overall approach adopted for the work presented in this annex is:

1. To review existing literature for a 1.5 °C rise and a 2 °C rise in global temperature, especially since the publication of the IPCC Special Reports (IPCC, 2018, 2019) and its Sixth Assessment Report (AR6) (IPCC, 2021, 2022a, b).
2. To supplement the literature review with an initial analysis of the UKESM runs described in Annex 4 (where available to the authors of this Annex), to identify potential natural system impacts and/or hysteresis of overshooting.

In the time available for preparation of this annex, use of the UKESM runs is limited to the atmosphere, ecosystem and biodiversity. A more complete analysis of the UKESM runs would require more time and resource.

1.1 Definition of tipping point and tipping element

The IPCC AR6 WG-I report (IPCC, 2021) defines a tipping point as "*a critical threshold beyond which a system reorganizes, often abruptly*[1] *and/or irreversibly*[2]", and a tipping element as "*a component of the Earth system that is susceptible to a tipping point*" (see Glossary at the end of this Annex Report). From Armstrong McKay *et al.* (2022), a climate tipping point (CTP) occurs when "*change in large parts of the climate system - known as tipping elements - become self-perpetuating beyond a warming threshold*". Armstrong McKay *et al.* (2022) consider a self-perpetuation mechanism to be critical to the existence of a tipping point and that the change may continue to occur, even if the forcing of the system is removed. In their analysis, Armstrong McKay *et al.* (2022) also include tipping points (e.g. in ice sheets) where "*the resulting qualitative change is slower than the anthropogenic forcing causing it, i.e. not abrupt in the sense defined as faster than the cause*".

Figure 1 shows the tipping elements of current concern, with estimates of their global warming temperature thresholds. Table 1 provides more information on these tipping elements and associated tipping points: temperature thresholds, timescales, reversibility or irreversibility, with confidence intervals, and the projected change during the 21st Century, where available. It should be noted that the confidence levels (low, medium and high) used by Armstrong McKay *et al.* (2022) are subjective and differ from those used by the IPCC.

There is concern that exceeding a tipping point in one tipping element could possibly trigger tipping points in other tipping elements, often referred to as a cascading transition (Kriegler *et al.*, 2009, Lenton *et al.*, 2019). For example, Arctic sea-ice loss could weaken the Atlantic

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[1] From the Glossary (at the end of this annex), a system change is **abrupt** if it occurs substantially faster than the typical rate of the changes in the history of that system. An abrupt climate change is 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.

[2] 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.

Ocean current that warms Europe, reduce rainfall in the Amazon, weaken the East Asian monsoon and accelerate Antarctic ice loss.

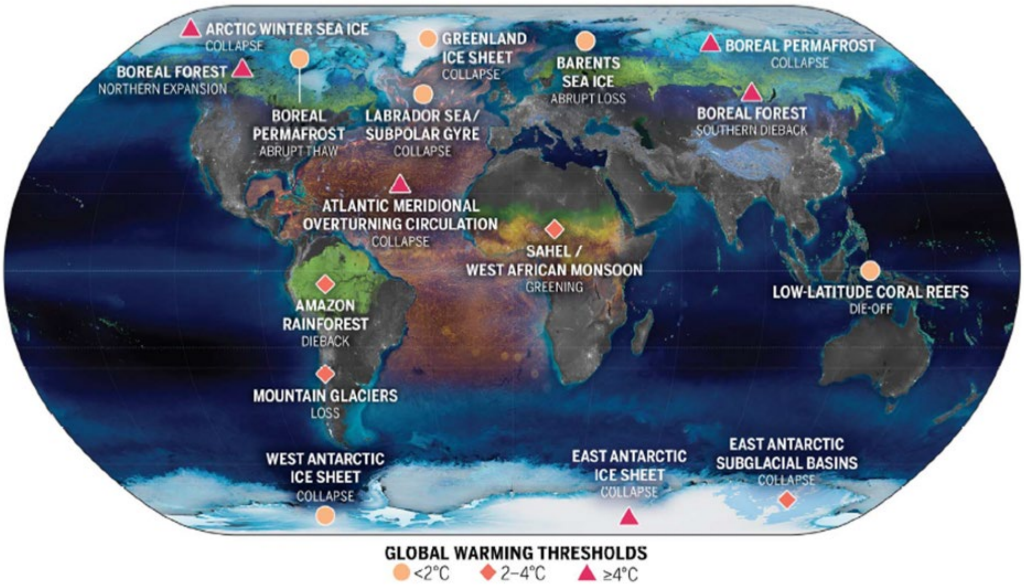


Figure 1. Tipping elements and estimates of global warming temperature thresholds at which their tipping will be triggered. Source: Armstrong McKay *et al.* (2022). Reproduced with permission from Springer Nature.

IPCC AR6 WG-I (IPCC (2021), Chapter 4) and Armstrong McKay *et al.* (2022), highlight the findings of many earlier papers that the temperature threshold of tipping points in some tipping elements may be lower than recognised at the time of the IPCC fifth assessment. Further, they also show that overshoots not exceeding 2 °C may still keep warming below the temperature thresholds of many tipping elements. However, observations have revealed that parts of the West Antarctic ice sheet may have already passed a tipping point and there are early warning signs about other tipping elements (the Greenland ice sheet, the Amazon rainforest and the Atlantic Meridional Overturning Circulation). A critical knowledge gap is understanding and quantifying the amount of temporary resilience climate tipping elements might have to a period of temperature overshoot. Key questions related to this are thus the magnitude and duration of the temperature overshoot, and whether the change induced by the tipping point is reversible (with a possible time lag), as the temperature is reduced to the target warming level.

Table 1. Climate tipping elements, temperature thresholds and timescales, with best estimate, range of estimates (minimum-maximum), confidence levels and projected 21st Century change. Sources: Armstrong McKay *et al.* (2022), with reversibility (R) or irreversibility (I) and Projected 21st Century change from IPCC AR6 WG1 (IPCC, 2021). Where irreversibility or reversibility was not assessed, it is indicated by '-'.

Climate Tipping Element (and tipping point)	Potential Abrupt Change (with IPCC confidence level)	Temperature threshold (°C)		Timescale (years)[3]		Reversible (R) / Irreversible (I)	Projected 21st Century Change
		Est. (Min-Max)	Confidence level	Est. (Min-Max)	Confidence level		
GLOBAL							
Greenland Ice Sheet (collapse)	No (high)	1.5 (0.8–3.0)	High	10k (1k–15k)	Medium	I, for millennia	Note (2a)
West Antarctic Ice Sheet (collapse)	Yes (high)	1.5 (1.0–3.0)	High	2k (500–13k)	Medium	I, for decades to millennia	Note (2b)
Labrador–Irminger Seas /Subpolar gyre Convection (collapse)	-	1.8 (1.1–3.8)	High	10 (5–50)	High	-	-
East Antarctic Subglacial Basins (collapse)	-	3.0 (2.0–6.0)	Medium	2k (500 10k)	Medium	-	-
Amazon Rainforest (dieback)	Yes (low)	3.5 (2.0–6.0)	Low	100 (50–200)	Low	I, for multi-decades	Note (2c)
Boreal Permafrost (collapse)	-	4.0 (3.0–6.0)	Low	50 (10–300)	Medium	I, for centuries	

[3] From Armstrong McKay et al., 2022, timescale is the time over which the transition to a new state occurs and is determined by the climate (sub) system itself. The resulting (often irreversible) changes may take centuries to millennia to be realized.

Climate Tipping Element (and tipping point)	Potential Abrupt Change (with IPCC confidence level)	Temperature threshold (°C)		Timescale (years)[3]		Reversible (R) / Irreversible (I)	Projected 21st Century Change
		Est. (Min-Max)	Confidence level	Est. (Min-Max)	Confidence level		
Atlantic M.O. Circulation (collapse)	Yes (medium)	4.0 (1.4–8.0)	Low	50 (15–300)	Medium	R, for centuries	Note (2d)
Arctic Winter Sea Ice (collapse)	Yes (high)	6.3 (4.5–8.7)	High	20 (10–100)	High	R, years to decades	Note (2e)
East Antarctic Ice Sheet (collapse)	-	7.5 (5.0–10.0)	Medium	Min 10k	Medium	-	-
REGIONAL	-						
Low-latitude Coral Reefs (die-off)	-	1.5 (1.0–2.0)		10 (–)		-	-
Boreal Permafrost (abrupt thaw)	-	1.5 (1.0–2.3)	Medium	200 (100–300)	Medium	-	-
Barents Sea Ice (abrupt loss)	-	1.6 (1.5–1.7)		25		-	-
Mountain Glaciers (loss)	-	2.0 (1.5–3.0)	Medium	200 (50–1k)	Medium	-	-
Sahel and W. African Monsoon (greening)	-	2.8 (2.0–3.5)	Low	50 (10–500)	Low	R, years to decades	-
Boreal Forest (southern dieback)		4.0 (1.4–5.0)	Low	100 (50–)	Low	I, for multi-decades	-

Climate Tipping Element (and tipping point)	Potential Abrupt Change (with IPCC confidence level)	Temperature threshold (°C)		Timescale (years)[3]		Reversible (R) / Irreversible (I)	Projected 21st Century Change
		Est. (Min-Max)	Confidence level	Est. (Min-Max)	Confidence level		
Boreal Forest (northern expansion)		4.0 (1.5–7.2)	Low	100 (40–)	Low	I, for multi-decades	-

Notes: (1) Confidence levels (low, medium and high) for temperature thresholds and timescales from Armstrong McKay *et al.* (2022), which differ from those used by the IPCC; (2) Projected 21st Century Change Under Continued Warming (IPCC, 2021): (a) Virtually certain mass loss under all scenarios; (b) Likely mass loss under all scenarios; deep uncertainty in projections for above 3 °C; (c) Medium confidence of increasing vegetation carbon storage depending on human disturbance; (d) Very likely decline; medium confidence of no collapse; (e) High confidence in moderate winter declines.

In a recent review, Wang *et al.* (2023) explore 10 global and regional candidate tipping elements, based on several criteria: strong evidence for or active ongoing debate regarding the risk of tipping behaviour; high potential impacts upon climate system feedbacks or ecosystems; and particularly intense discussion of a system in the context of tipping elements even if the system is not thought to be subject to tipping behaviour. As shown in Table 2, Wang *et al.* (2023) classified the 10 candidate tipping elements as a tipping or non-tipping element and whether the tipping point is reversible or irreversible.

Table 2. Classification of 10 candidate global and regional climate tipping elements, as tipping elements or non-tipping elements and whether the tipping point leads to a reversible or irreversible change. Based on Wang *et al.* (2023).

Climate tipping element	Tipping or non-tipping element	Reversible or irreversible
Disruption of tropical monsoons	Non-tipping	Reversible
Stratocumulus cloud deck breakup	Tipping	Irreversible
Boreal forest ecosystem shifts	Tipping	Uncertain
Amazon rainforest dieback	Tipping	Irreversible
Atlantic Meridional Overturning Circulation	Tipping	Potentially irreversible
Loss of shallow tropical coral reefs	Tipping	Irreversible
Greenland & Antarctic ice sheets	Tipping	Irreversible
Loss of Arctic Sea ice • Summer • Winter	 Non-tipping Tipping	 Reversible Reversible
Permafrost carbon release	Tipping	Irreversible
Marine methane hydrate destabilisation	Non-tipping	Irreversible

These are broadly consistent with the IPCC analysis of reversibility/irreversibility presented in Table 1.

1.2 Reversibility, irreversibility and hysteresis

There are concerns that the climate system may have a highly nonlinear response to increases in atmospheric greenhouse gas (GHG) concentrations. A linear response is where the magnitude of a climate change impact increases in proportion to a change in atmospheric GHG gas composition. A nonlinear change is where relatively small additional increases to GHGs generate a disproportionate alteration to an impact of interest or concern – and this is a prerequisite of situations that are frequently referred to as Tipping Points (TPs). The nonlinearity and especially TPs manifest as a new state towards which part of the Earth system moves. Crossing tipping points are a concern in the context of “overshoot”. First, there may be an inertia that may delay the move towards any new state (or impact state). While such inertia may initially be beneficial for adaptation purposes, its existence also means that when lowering GHGs (i.e. the return part of “overshoot”), the system or impact may take a substantial time to return to its original state. This delay is a form of hysteresis (Figure 2). Furthermore, some TPs may be such that a small increase in GHG concentrations cause a jump that actually locks part of the climate system or impact in a new state. In some circumstances, decreasing GHGs may be unable to release from this new state unless GHG concentrations are reduced substantially. If such TPs exist, and the new state is difficult for society to adapt to, then this suggests an overshoot approach to climate change is a high-risk activity. Mathematically such a situation is described as a “sharp hysteresis loop”.

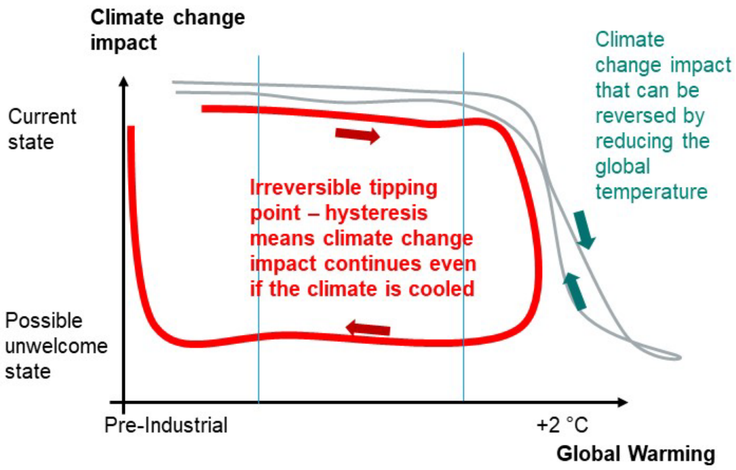


Figure 2. Schematic illustrating reversible impacts, irreversible tipping points and hysteresis. In this figure, we imagine an increase in global warming, followed by a decrease (moving along the "*x*"-axis and return). The "y" axis slows a decline from a current climatic state to an undesirable state. The red curve shows major hysteresis, with a return to the desired state only upon return to a pre-industrial warming level. The green curve shows negligible hysteresis (Manuscript in preparation).

Wang *et al.* (2023) denote a change either as reversible, if "*reversion to the original system state can occur within a century upon applying the opposite forcing*", or irreversible, if "*reversion to the original system state requires centuries or longer, and/or different opposite forcing of a significantly larger magnitude than the original change in forcing applied to achieve the altered system state)*".

In Figure 3, we illustrate schematically a set of five potential options that may represent an increasingly difficult and unpredictable response; the feature of each is described in Table 3. For options 4 and 5, where a tipping point affects the impact of concern, we note the recent study by Ripple *et al.* (2023), which presents and analyses an extensive list of climate feedbacks. With additional resource, there is scope to extend their analysis to address "overshoot" impacts: Does the feedback act directly and make a local impact worse? As illustrated in Figure 3, does a feedback act as a closed system, but there are indirect connections on to impacts of concern?

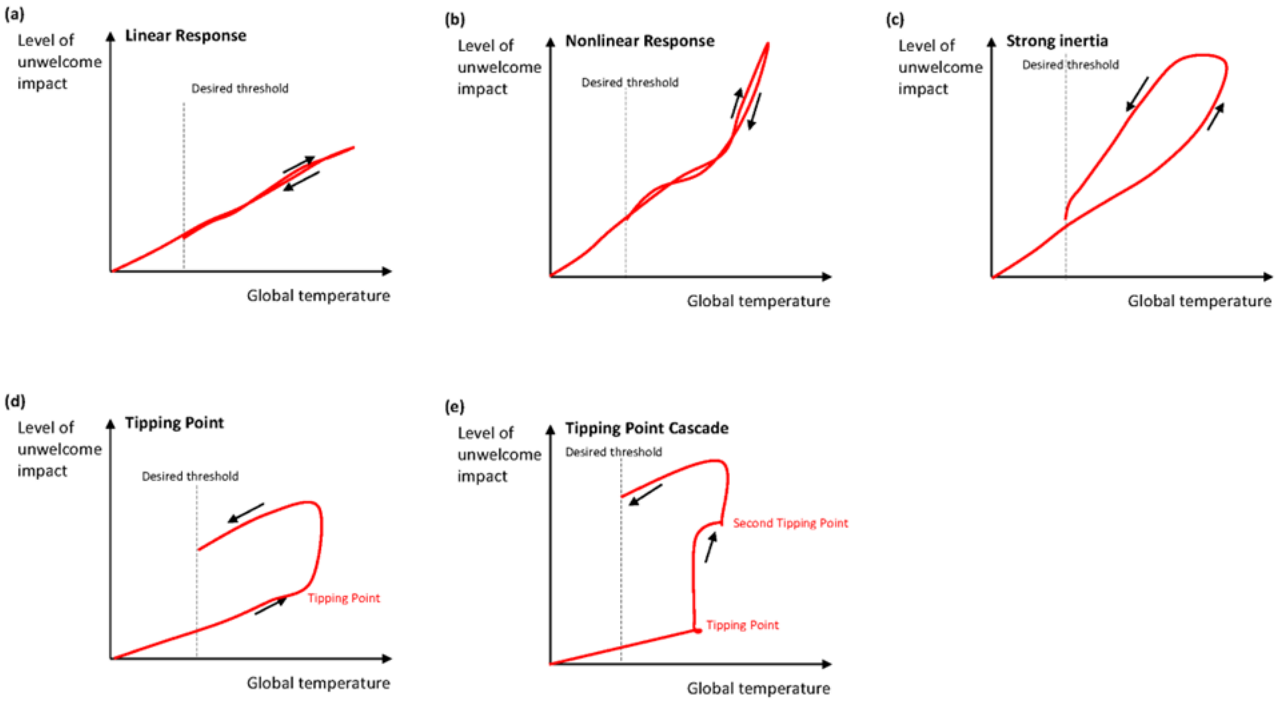


Figure 3. Schematic of different potential responses to global temperature overshoot. The 'x' axis is global temperature, and in each example the red curve takes 'x' values that increase, then decrease back down to a desired threshold. The "y" axis represents a generic impact, where a high value represents increasingly adverse impacts on society. The range of possibilities becomes increasingly nonlinear between panels (a) to (e). The examples in (e) and (f) are irreversible. So as the forcing declines (x-axis), the quantity in the "y"-direction stays high. (Manuscript in preparation).

If there is a cascade of tipping points, it only needs one of the simultaneous tipping points to be irreversible to make the entire change irreversible.

Table 3. Advantages and disadvantages of 5 idealised impact responses to an overshoot pathway. The cases are for increasing levels of nonlinear and related complexity (Manuscript in preparation).

Type of Impact Response	Advantages	Disadvantages
Linear (Figure 3a)	• Very easy to understand and predict response to "overshoot". • Represents a general degrading of conditions for some impacts, which are predictable.	• May cause reluctance to lower global temperatures, and instead just accept unwelcome impacts.

Type of Impact Response	Advantages	Disadvantages
Nonlinear but no hysteresis (i.e. reversibility) (Figure 3b)	• Very easy to understand and predict response to "overshoot"	• Although recovery is possible, this may take us to a strong nonlinear response and severe impacts for the temporary overshoot period. This could represent a tipping point (i.e. jump to a new state), but with reversibility.
With substantial inertia (Figure 3c)	• Possibility that a short overshoot may not trigger tipping points.	• Will take longer to recover from any unwelcome impacts that occur during the overshoot period.
Tipping point occurs during overshoot period (Figure 3d)		• Jumps to a new state that might be difficult for society to adapt to. • Strong hysteresis implies may stay in an unwelcome state as global temperatures decrease.
"Cascade" of tipping points occurs during overshoot period (Figure 3e)		• A cascade may force additional tipping points to occur for lower temperature values. • Sequence of changes in quick succession will be especially difficult to adapt to. • Crossing multiple tipping points raises the risk of complex and long-term hysteresis. • May never return to low impacts even if global T were stabilised.

1.3 Structure of this annex

Following a scoping workshop held in July 2022 and subsequent engagement with representatives from DESNZ and other Government Departments, the scope of the activity was confirmed (see Table 4). There was an emphasis on those tipping elements that are likely to be triggered at thresholds between 1.5 to 2 °C of warming. Are there tipping points avoided by keeping to 1.5 °C of warming (i.e. not overshooting)? If 1.5 °C of warming is exceeded, are the changes reversible or not? Do the changes depend on the duration of the overshoot and when it occurs?

Table 4. The tipping points and high impact events in each domain identified for exploration, as agreed with the Department for Energy Security and Net Zero following a scoping workshop.

	Atmosphere (Section 2)	Ecosystems (Section 3)	Biodiversity (Section 0)	Oceans and Coastal regions (Section 5)	Cryosphere (Section 6)
Tipping points (TP)/High Impact event (HI)	• TP: Changes in the West African Monsoon and Green Sahel • TP: Changes in Indian Monsoons • HI: Frequency and reversibility of extreme events (heatwaves, intense rainfall)	• TP: Loss of Boreal forests (fires and pests) • TP: Loss of Amazon and other Tropical Rainforests (drought) • Lock into dust-bowl conditions	• TP: Loss of insect species • TP: Loss of other biodiversity • TP: Changes in ranges, phenology, physiology and morphology of terrestrial and freshwater species	• TP: Collapse of Atlantic Meridional Overturning Circulation (AMOC) • TP: Subpolar gyre cooling • Ocean heatwaves • Ocean deoxygenation and hypoxic events • TP: Ocean acidification • TP: Loss of coral reefs	• TP: Loss of Greenland ice sheets • TP: Loss of Antarctic ice sheets • TP: Loss of Arctic winter sea ice • Loss of Arctic summer sea ice • TP: Permafrost thaw • TP: Melting of glaciers

Passing a tipping point in a tipping element can lead to direct impacts, potentially high, on both human and natural systems e.g. changes in the patterns and intensities of tropical monsoons. Triggering a tipping point can also lead to indirect "high" impacts e.g. impacts from sea-level rise caused by loss of either or both of the Antarctic and Greenland ice sheets. However, a high impact event does not necessary result from triggering a tipping point i.e. an impact whose severity increases with global warming and to which human or natural systems would find difficult to adapt. An example of this would be the increasing frequency and severity of heatwaves with global warming.

In this annex, we assess the current state of scientific knowledge on tipping elements, tipping points and high impact events (see Table 4). The annex is structured as follows: Sections 2 to 6 cover the domains listed in Table 4; Section 7 is a Conclusion section; Section 8 contains a bibliography of the literature cited. The annex concludes with a QA statement, a glossary and a list of acronyms.

2. Impacts on the atmosphere

2.1 Monsoon systems and Green Sahara

The tropical monsoon systems, occurring over Africa, Asia, the tropical Americas and Northern Australia, are critically important for both human and natural systems, providing food security and water availability. In these regions, extreme precipitation events usually result from storms embedded within the continental-scale monsoon winds, causing flooding and landslides that often inflict significant loss of life and property. Conversely, the lack of precipitation can lead to significant drought conditions.

Wang *et al.* (2023) find that much of the research to date, including analysis of the ensemble of CMIP5 and CMIP6 models, suggests that "*the global monsoon domain will experience a gradual increase of seasonal mean precipitation and a gradual weakening of low-level mean winds in response to warming*". They (re)classify tropical monsoon systems as uncertain climate tipping elements, because of a lack of evidence for a warming-related threshold behaviour. Wang *et al.* (2023) have concerns about cascading tipping elements: "*Monsoons might undergo abrupt changes not because of their own internal, nonlinear dynamics, but because they are forced by large amplitude, abrupt changes in some other element of the Earth system. A canonical example is the abrupt variation of monsoons during the last ice age, thought to occur synchronously across multiple continents in response to rapid temperature variations in the Northern Hemisphere*".

The analysis of the UKESM runs presented in Annex 4 suggests that there are many regions that have changes in total precipitation of the order of ±20%, including the South Atlantic Ocean, the Western Pacific, the Sahel and the Indian subcontinent. Although the End-century rainfall is lower in the tropics, particularly in the Sahel and Indian monsoon regions, in the VHO pathway, these changes are not are statistically significant as the ensemble spread is larger than the difference in the ensemble means between the VHO and NO scenario runs.

For the West African Monsoon (WAM), paleo-evidence indicates that there have been multiple abrupt shifts into and out of African Humid Periods, with associated greening of the Sahara, in response to gradual changes in orbital forcing (Armstrong McKay *et al.*, 2022). Weakening of the Atlantic Meridional Overturning Circulation and the consequential warming of the Equatorial East Atlantic has also caused past collapses of the WAM. Armstrong McKay *et al.* (2022) find that there is contrasting model behaviour between global and regional model predictions with "*some global models predicting strengthening of the West African Monsoon and wetting and northward expansion of the central and eastern Sahel (as well as drying in coastal West Africa)*" but in some regional climate models "*the WAM instead collapses*". Armstrong McKay *et al.* (2022) conclude that the existence of a future tipping threshold for the WAM and Sahel remains uncertain, including whether it strengthens or weakens. However, "*given multiple past abrupt shifts, known weaknesses in current models, and huge regional impacts*", they retain the Sahel/WAM as a potential regional impact tipping element (low confidence) with "*a threshold of ~2.8 °C (2 to 3.5 °C) (low confidence), a timescale of 50 years (10 to 500 years) (low confidence), and uncertain Earth system impacts (regional warming) (medium confidence)*".

2.2 Surface temperature

The evolution of the global mean surface temperature (GMST) for the UKESM NO and VHO scenario runs is presented in Annex 4. The difference between the VHO and NO pathways is greatest in 2060–2070 ("mid-century"). The VHO pathway has 0.5–1.0 °C extra warming over most land areas and even larger warming (2.5–4.5 °C) over the Arctic region. The oceans otherwise have little surface temperature warming. By end-century (2090–2100), when both have a GMST of 1.5 °C above pre-industrial, land temperatures in the VHO pathway reduce to a similar level to the NO pathway except at high northern latitudes, where there is some hysteresis. The differences are especially clear in the Arctic region, where temperatures in the VHO pathway remain substantially higher than in the NO pathway.

2.3 Extremes weather events

Chapter 11 of IPCC AR6 WG-I (IPCC, 2021) covers Weather and Climate Extreme Events in a Changing Climate. The chapter finds "*It is an established fact that human-induced greenhouse gas emissions have led to an increased frequency and/or intensity of some weather and climate extremes since pre-industrial time*." Regional changes in the intensity and frequency of climate extremes are found to scale with global warming. Chapter 11 includes new evidence that strengthens the conclusion in the IPCC Special Report on "Warming of 1.5 °C" (SR1.5, IPCC

(2018)) that even relatively small incremental increases in global warming (+0.5 °C) cause statistically significant changes in extremes on the global scale and for large regions (high confidence). In particular, this is the case for temperature extremes (very likely), the intensification of heavy precipitation (high confidence), including that associated with tropical cyclones (medium confidence), and the worsening of droughts in some regions (high confidence).

Table 11.2 of IPCC (2021) provides a synthesis of projected changes in extreme temperatures, heavy precipitation events, agricultural and ecological droughts, heavy precipitation associated with tropical cyclones, severe convective storms and compound events, for +1.5 °C, +2 °C and +4 °C of warming. Relative to present day conditions, changes in the intensity of temperature extremes would be at least double at 2 °C, and quadruple at 3 °C of global warming, compared to changes at 1.5 °C of global warming. Research into changes in the statistical distribution of temperature extremes however remains an ongoing activity. Even for the investigation of pathways without reversal, there continues to be a debate as to whether temperature extremes increase with global warming as a simple shift in the temperature distribution by the amount of background global warming or not (Thompson *et al.*, 2022). There is some evidence that the upper tails of the temperature distributions expand faster than local global warming, making new extreme levels higher than might be expected if only considering background average temperature changes. This might occur for instance, due to land-atmosphere feedbacks in a more arid environment (Berg *et al.*, 2014). The increase in the frequency of heavy precipitation events will be non-linear with more warming and will be higher for rarer events (high confidence), with a likely doubling and tripling in the frequency of 10-year and 50-year events, respectively, at 4 °C of global warming compared to the recent past.

3. Impacts on ecosystems

3.1 Amazon rainforest

The Amazon Forest biome stores ~150 to 200 GtC and historically has been an important sink for human CO_2 emissions. This sink has declined since the 1990s and ~17% of the Amazon Forest has been lost to deforestation since the 1970s (Armstrong McKay *et al.* (2022) and references therein). A combination of a climate change-induced drying trend, unprecedented droughts, and anthropogenic degradation in the south and east has led to the biome as a whole becoming a net carbon source. The Amazon Forest is also important for the global and regional water cycles as the Amazon Forest recycles about a third of the Amazon basin's rainfall on average. According to Armstrong McKay *et al.* (2022), "*this and localized fire feedbacks mean that ~40% of the Amazon forest is estimated to currently be in a bi-stable state, increasing to ~66% on an RCP8.5 trajectory, and rainforest loss could initiate self-reinforcing drying that tips this portion into a degraded or savanna-like state*".

Armstrong McKay *et al.* (2022) also note that widespread Amazon dieback was originally projected at 3 or 4 °C of warming. "*Given the size of the region affected by even partial dieback and its global impacts*", Armstrong McKay *et al.* (2022) classify the Amazon Forest as a global core tipping element (medium confidence). Their best estimates are a temperature "*threshold of ~3.5 °C (2 to 6 °C) independent of deforestation (likely lower with deforestation) (low confidence), timescales of 100 years (50 to 200 years) (low confidence), and partial dieback of 40% (i.e. current bistable area) leading to emissions of ~30 GtC*".

3.2 Boreal forests

The Arctic is warming faster than the global average (IPCC, 2021), causing perturbations to the terrestrial water and carbon cycles in this region. Warming may have already shifted some ecosystems from net carbon sinks toward carbon-neutral or carbon sources, although it remains a challenge to determine the net ecosystem response across the circumpolar scale (Schuur *et al.*, 2022). Analysis of long-term observations indicate rapid regional temperature increases, more frequent occurrence of wildfires, and intensification of pest-driven tree mortality (Wang *et al.* (2023) and references therein).

Armstrong McKay *et al.* (2022) classify the boreal forest as a regional impact tipping element with two potential climate tipping points: (1) Forest dieback at the southern limit (medium confidence) and (2) Expansion at the northern limit ("tundra greening") (medium confidence). As a result of global warming and feedbacks from changes in hydrology, increased fire frequency and bark beetle outbreaks, there is decline in forests (on the order of 100 km) and a transition to a grass-dominated steppe or prairie state. For dieback of Boreal forests at their southern limit, Armstrong McKay *et al.* (2022) estimate "*a threshold of ~4 °C (1.4 to 5 °C) (low confidence), timescales of 100 years (50+ years) (low confidence), and partial (~50%) dieback leading to emissions of ~52 GtC, which—along with countervailing biogeophysical feedbacks such as increased albedo and reduced evapotranspiration—leads to a net GMST feedback of ~−0.18 °C (medium confidence) [regional ~−0.5 to 2 °C (low confidence)]*". For expansion of Boreal forests at their northern limits, they estimate "*a threshold at ~4 °C (1.5 to 7.2 °C) (low confidence), timescales of 100 years (40+ years) (low confidence), and partial (~50%) uptake of ~6 GtC which along with countervailing biogeophysical feedbacks (decreased albedo, increased evapotranspiration) leads to a net GMST feedback of +0.14 °C per °C (regional ~+0.5 to 1 °C) (low confidence)*". Wang *et al.* (2023) also note large uncertainties. "*The potential for boreal forests to exhibit tipping element behaviour remains uncertain*", with knowledge gaps about "*the critical thresholds, extent of change, and climatic impacts of large-scale boreal ecosystem shifts*".

3.3 Ecosystems & fire

Climate change is already causing substantial shifts in fire regimes over much of the world's ecosystems (Forkel *et al.*, 2019, Kelley *et al.*, 2019, Jones *et al.*, 2022, UNEP, 2022). Global warming of 1.5 °C or more would increase the frequency and intensity of wildfires in some regions compared to pre-industrial levels (IPCC, 2018, 2022a). In some regions, such as the Arctic, the increase in the frequency and intensity of wildfires may still be substantial even with a 1.5 °C warming, because of the susceptible nature of the region to climate change. The recent UNEP report "Spreading Like Wildfire" (UNEP, 2022) projected up to 20 times more wildfire occurrence in some Arctic areas by 2100, even if emission reductions are implemented to limit warming to 1.5 °C. The extent of these changes is greater if global warming were to exceed 2 °C of warming. In other regions, such as the Mediterranean and notably tropical forests, more extreme temperature changes would also increase the frequency of extreme wildfires (UNEP, 2022).

Adapting to the impacts of climate change and investing in fire prevention and response measures will remain critical to reducing the impact of wildfires, even under a 1.5 °C pathway (UNEP, 2022). However, if the overshoot is more prolonged or temperatures exceed 1.5 °C for an extended period, the impacts on wildfires could be more severe. The risk of catastrophic wildfires could increase, especially in regions already vulnerable to wildfires. For example, wildfires can change ecosystems, when introduced, damaging or killing species not adapted to fire, making them more vulnerable to other stresses associated with future environmental change (Bowman *et al.*, 2009). Introducing fire into forest ecosystems that do not typically experience burning, or shifting to more intense fires in areas where burning occurs, can cause or accelerate forest degradation (Archibald *et al.*, 2018). By itself, this may cause a shift to shrubby and herbaceous vegetation, which is more fire-adapted – vegetation that also tends to burn more easily (van Nes *et al.*, 2018). This is because forest ecosystems tend to contain more moisture in live fuel loads and dead, thicker woody materials dry out more slowly. Conversely, degraded systems have fuel loads that dry out more rapidly (Lenihan *et al.*, 1998, Thonicke *et al.*, 2010, van Nes *et al.*, 2018, Kelley *et al.*, 2019). A subsequent reduction in temperature and return to previous climate conditions would not necessarily undo these changes, as newly degraded ecosystems continue to promote this increased burning (Lasslop *et al.*, 2016, Drüke *et al.*, 2023).

While there is little research on these hystereses in the context of overshoots, research on the warming and speed of these forest losses suggest they can respond quickly and early to changes in fire regime. For example, Burton *et al.* (2022) found substantial forest carbon loss in the Amazon between 2–3 °C above pre-industrial levels, mainly insensitive to emissions scenarios. This suggests that even in the rapid SSP5-8.5 scenario, losses happen almost immediately after the temperature threshold is reached. Meanwhile, Burton *et al.* (submitted) found significant loss in global forests and carbon occurring at 1.1–1.3 °C of warming (i.e. close to current levels of warming). The substantial carbon loss from these events may reduce our allowable emission to 1.5 °C of warming by 20%, and add 40 $GtCO_2$ to the negative emissions we must achieve to bring global temperatures down again should we overshoot.

3.3.1 Analysis of UKESM runs

The version of the UKESM used in this work does not include a representation of vegetation fires. However, Burton *et al.* (2022) demonstrate that UKESM outputs are able to reproduce the trends in the bioclimatic variables relevant to fire, thereby enabling an assessment of the long-term changes in fire and fire impacts.

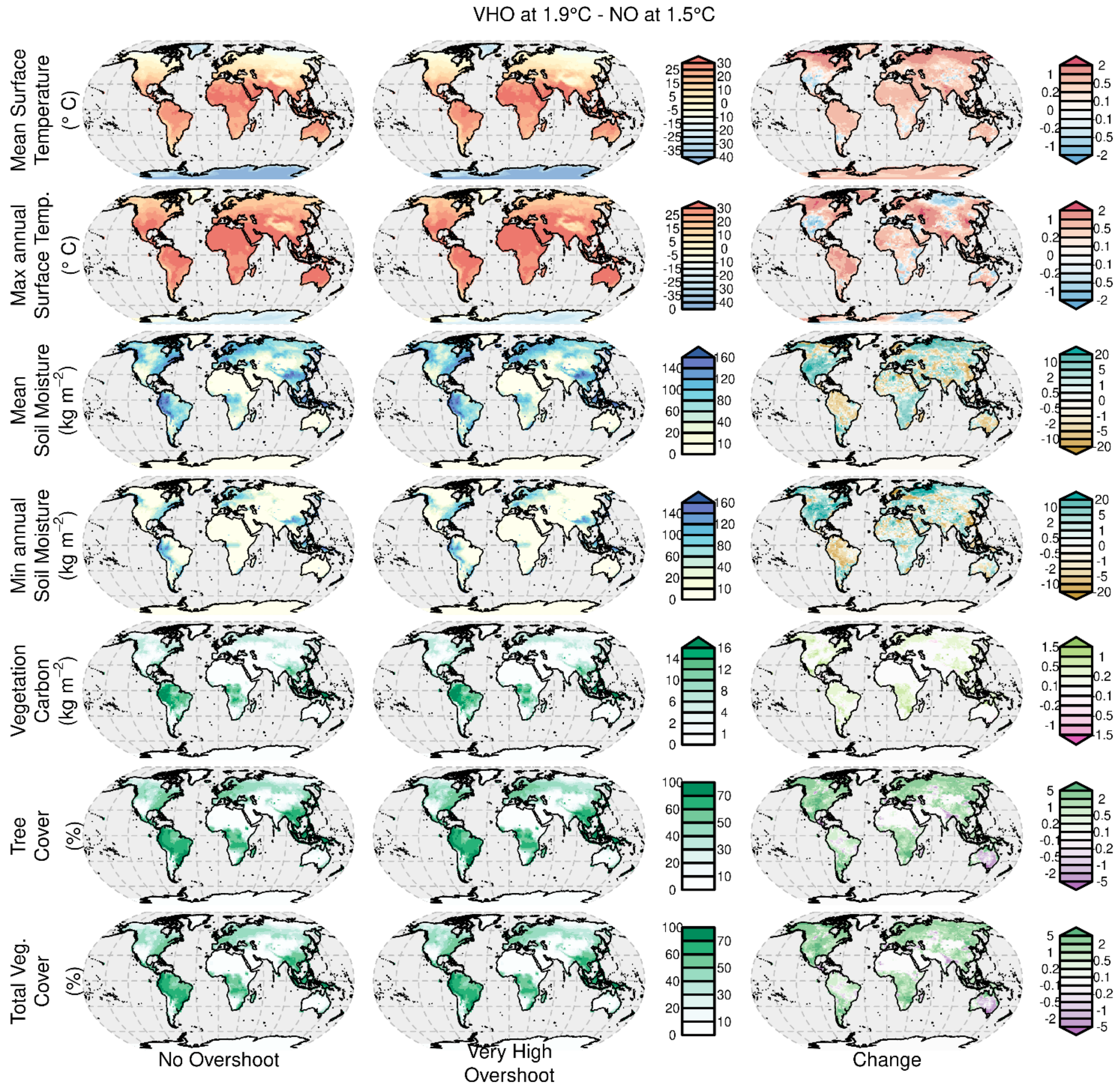


Figure 4. Temperature, soil moisture, vegetation carbon, tree cover and total vegetation cover changes between the VHO and NO UKESM scenario runs for mid-century (2065), when the temperature difference is greatest (1.9 °C and 1.5 °C, respectively). The left-hand and middle columns show the NO and VHO pathways, respectively. The right-hand column shows the corresponding difference in temperature, soil moisture, vegetation carbon, tree cover and total vegetation cover, between the pathways, as VHO minus NO.

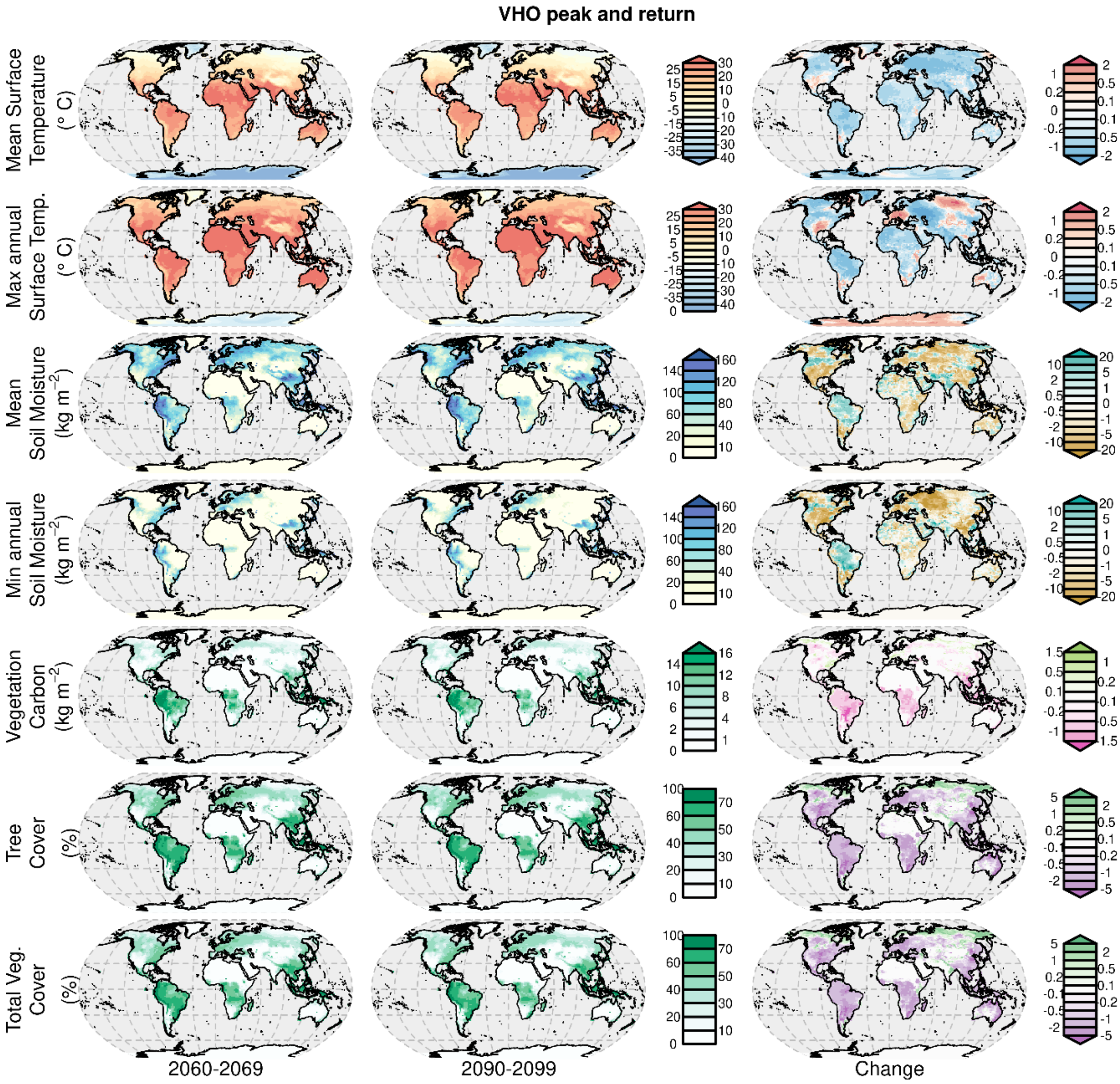
Soil moisture is a proxy for fuel moisture which governs how likely a fire will start and spread, while vegetation carbon is a proxy for fuel load available for burning (Bistinas *et al.*, 2014, Forkel *et al.*, 2019, Kelley *et al.*, 2019). Low soil moisture (i.e. dry soils) and high vegetation content is therefore associated with high burnt area, noting that in Boreal regions, ignition availability also becomes important (Kelley *et al.*, 2019, UNEP, 2022). Seasonal high temperatures are also related to extreme high intensity fires (UNEP, 2022).

As global temperatures peak at 1.9 °C above pre-industrial in the mid-century, the UKESM VHO simulation suggests soil moisture content will increase relative to a world stabilising at 1.5 °C over much of the world (Figure 4). In arid and semi-arid regions, such as central USA, seasonal regions in the Cerrado, Caatinga (Brazil) and in Southern Africa, the associated increase in vegetation carbon will increase fire risk, as there will be higher fuel loads. In seasonal dry forests, such as coastal US, temperate woodlands could lead to higher moisture content and a decreased fire risk. Similarly, increased tree cover, shifting to slower drying thick fuels, would retain a higher moisture content, although this could have the effect of increasing the severity of wildfire when they do occur (UNEP, 2022).

Of concern, Amazonia and tropical forests of East Asia show a drying trend, particularly at the driest times of the year (Figure 4, fourth row), which may compound the increases in burning and carbon loss to fires already in these regions (Silva *et al.*, 2020, Kelley *et al.*, 2021). This will likely be exacerbated as temperatures return to 1.5 °C, and some of the increased soil moisture over much of the world will diminish, especially in carbon rich high-latitude peatland, making it flammable and prone to carbon loss (Figure 5).

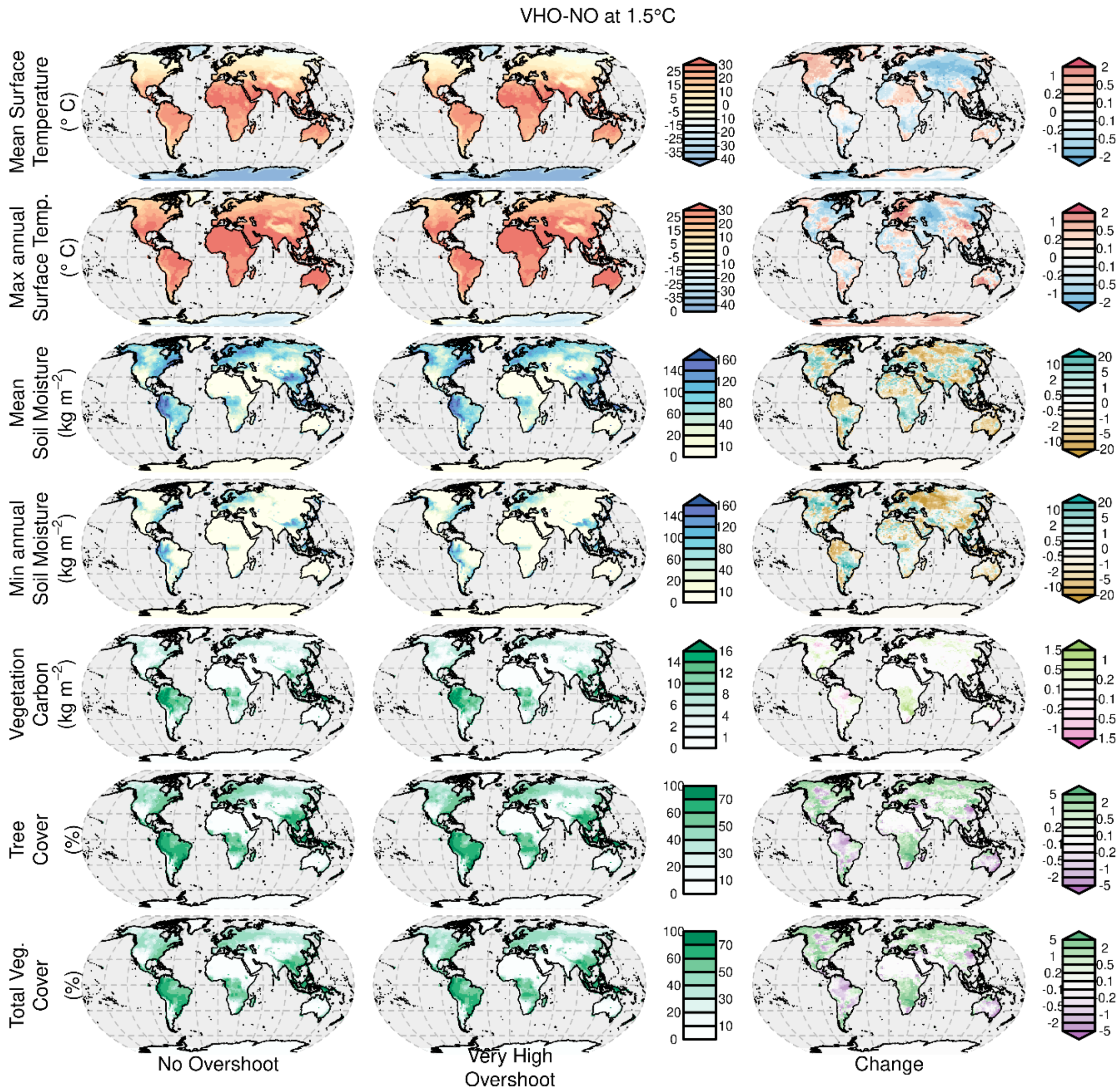
Some high latitude boreal regions in Canada, where fires occur when temperatures are very high, will also see a substantial increase in summer warmth at 1.9 °C of warming compared to stabilising at 1.5 °C (Figure 4, second row), although the impact of higher summer temperatures may be offset by wetter soils for most Eurasian Boreal regions. Interestingly, as global temperatures return to 1.5 °C, some Eurasian boreal regions may still stay substantially warmer and, in general, soil moistures (especially during the driest months) will likely stay drier, enhancing fire risk (Figure 5a), compared to 1.5 °C in the NO pathway.

The UKESM results presented here are illustrative, as they are based on a single Earth system model (UKESM1.1) and an ensemble of four members each for the VHO and NO pathways.



VHO peak and return
Mean Surface Temperature (° C)
Max annual Surface Temp. (° C)
Mean Soil Moisture (kg m^-2)
Min annual Soil Moisture (kg m^-2)
Vegetation Carbon (kg m^-2)
Tree Cover (%)
Total Veg. Cover (%)
2060-2069
2090-2099
Change

(a)



(b) 7

Figure 5. Temperature, soil moisture, vegetation carbon, tree cover and total vegetation cover in the VHO and NO pathways: Panel (a) shows these variables for “mid-century” at a peak temperature of 1.9 °C (left-hand column) and for “end-century” once temperatures have returned to 1.5 °C (middle column), in the VHO and the difference between the two time periods (right-hand column = “end century” – “mid-century”), for the first ensemble member of each UKESM scenario run. Panel (b) shows these variables for “end-century” at 1.5 °C of warming in the NO (left-hand column) and the VHO (middle column) UKESM runs (first ensemble member of each), and the difference between the two pathways (as VHO-NO, right-hand column). The maps presented are illustrative as they are based on a single Earth system model (UKESM1.1) and a limited set of ensemble runs for the VHO and NO pathways.

4. Impacts on biodiversity and fauna

The typical response of species to climatic changes over time has been one of range change (Parmesan *et al.*, 2022). While there have been some evolutionary changes (and a few have been observed in response to the amount of warming already observed), this takes a long period of time, even in species with rapid population cycling (e.g. outbreak insects). Species usually will attempt to track the climate change, and these movements can often be noted even in response to climate variability (e.g. the North Atlantic Oscillation, El Nino Southern Oscillation) (Price, unpublished work). For example, in North America in the 1960s–1970s in response to local cooling attributable to sulphate aerosol emissions from coal-fired power plants, many bird species expanded their ranges south and others, like the Eastern Bluebird, suffered large-scale population declines. Then, once the climate began to return to normal, the southerly range expansions retreated and populations began to recover but this occurred over decades (Price, unpublished work). At least among highly mobile species, this would be expected to be the response to overshoot. Thus, even if there were a short period of overshoot, the recovery time could be much longer. For species with lesser ability to move, recovery would take even longer. Finally, with species that essentially are unable to move within this time frame then ranges (and populations) will be squeezed, becoming smaller before slowly beginning to recover. If the range is too small, or too fragmented, then local to global extinctions may occur. This section reviews the potential consequences of overshoot on biodiversity by looking at a well-established database on the projected potential changes owing to shifts in the suitable climate of ~135,000 terrestrial species (fungi, plants, invertebrates, and vertebrates) as a sample of the whole (Warren *et al.*, 2018a).

4.1 Observed changes at ~1 °C of warming

The first identification of a link between observed warming and changes in species events (e.g. phenology and ranges) was made in the IPCC Third Assessment Report (Gitay *et al.*, 2001) and a subsequent meta-analysis that came from it (Root *et al.*, 2003). Since then, each of the IPCC Assessments has specifically looked at this question and the amount of literature and number of species observed changing has drastically increased. By the time of the IPCC AR6, thousands of species have been identified as undergoing changes (either in timing, ranges, or other significant factor) attributable to climate change (Parmesan *et al.*, 2022, Table 2.2). This has led to the assessment that there is now *very high confidence* that poleward and upward movements of species is attributable to climate change, across a large number of species types (taxa) and across the globe. This is important as it supports knowledge from the paleo-ecological literature that one of the main responses of species to climate change is to move to track the climate, remaining in suitable climate spaces. This is only possible if the rate of change matches the ability of the species to move at that rate to track its suitable climate. If the rate is too fast, then local extinctions are likely to occur, becoming overall extinctions if the change is great enough, or a species has a very small range. To date, two terrestrial species and at least one terrestrial subspecies have been identified as becoming extinct owing to climate change, (Parmesan *et al.*, 2022). In one global study of 976 species, climatically driven local extinctions had been observed in 47% of them (Wiens, 2016). Thus, species are already moving, and already facing local extinctions even with ≤1 °C of warming. More recently, this work has been expanded, showing that many of these local extinctions (as well as the global extinctions) were driven by extreme events occurring on top of the embedded warming (Román-Palacios and Wiens, 2020, Parmesan *et al.*, 2022). This would suggest that even a short period at the maximum overshoot temperature could potentially have many of the impacts projected as occurring at 2 °C of warming.

4.2 Projected changes

The changes depicted below are predominantly from the large-scale global study of Warren *et al.* (2018a). A full description and caveats of this work can be found in the CS-N0W report D1.2, Warren *et al.* (2018a) and an overall review of modelling limitations in Parmesan *et al.* (2022).

These analyses are based on the Wallace Initiative database, containing projections of potential climate change impacts on the climatically determined geographic ranges of more than 130,000 individual terrestrial species (fungi, plants, invertebrates, and vertebrates) at warming levels of 1.5 °C to 4 °C above pre-industrial. Analyses with these data have been widely used in the studies published in peer-reviewed journals (e.g. Warren *et al.*, 2013, Smith *et al.*, 2018, Warren *et al.*, 2018a, Warren *et al.*, 2018b, Jenkins *et al.*, 2021, Manes *et al.*, 2021, Saunders *et al.*, 2023) and multiple chapters of IPCC AR6 WGII. The results from the Wallace Initiative database should be viewed as a statistical sample to attempt to discover the underlying relationships, trends, and patterns for broader populations. The methodology follows that used in Warren *et *al.* (2013), Warren *et al.* (2018a) and Warren *et al.* (2018b). The global scale Wallace Initiative (WI) database was created using an established species distribution model, MaxENT, using 21 alternative regional climate change projections for each level of warming to incorporate uncertainty in regional climate projection. MaxENT relies on developing a statistical relationship between current species distributions and current climate, and assuming this relationship holds into the future. These models sourced the occurrence data from the Global Biodiversity Information Facility.

What is projected is the potential loss of a suitable climate for the species. This means that the species is projected to be lost (i.e. become locally extinct) due to climate change alone and is independent landcover and landcover changes that have occurred or may occur in the future. Some species may be more, or less, vulnerable than others to loss of climatic suitability, and this analysis assumes that all species are equally vulnerable. Therefore, local extinctions of some species might be over, or under, estimated relative to others. Our results are likely to be generally conservative, in particular in light of the lack of consideration of extreme events (e.g. drought), the potential disruption of predator-prey, plant-pollinator, mutualistic, or other species-species interactions and the limited evidence that mutualisms may or may not be substituted under climate change. Such disruptions may lead to losses of ecosystem functioning, particularly important in the light of the finding that projected range losses in insects and plants may, in many places, exceed those for birds and mammals that have a greater ability to disperse naturally to track their geographically shifting climate envelope. This means that more species may be lost than we project. Additionally, lack of consideration of potential risks associated with extreme weather events, projected to become more frequent and intense in many regions or fire regimes all may lead to impacts potentially occurring sooner than the model projects. This means that more species may be lost than we project.

The analyses presented here do not explore the potential for some species to move to new geographical locations (adaptation by movement) under climate change. In some cases, this may lead to an overestimation of species loss, but in most cases, this is not likely. While many mammals and birds have an ability to disperse in this way, plants, reptiles, amphibians and most invertebrates have a substantially reduced ability to do so (Warren *et al.*, 2018a). Furthermore, many areas are highly fragmented with settlements, transport networks, and agriculture potentially acting as barriers to movement. The degree to which dispersal may result in the successful shifting of an individual species' range will be affected by their dependency on plants and insects which may have been unable to track the shifting climate and therefore this is excluded from the process of identifying climate refugia that are designed to act as indicators of ecosystem intactness. Dispersal is frequently modelled as an important adaptation for the persistence of individual species. However, at the level of the community, potential changes in competition for limited resources, and/or changes to predator-prey, pollinator and seed dispersal interactions, may counter individual species level benefits. Indeed, this community level transformation may lead to greater impacts than presented here.

For the purposes of this study, we used 2.0 °C warming for the overshoot, rather then the 1.87 °C in the model runs. This is because there was very little difference between 1.87 and 2.0 °C (at most ~3% in the areas projected to see the greatest change) in the results from the biodiversity models and this small difference in temperature is well within the error bounds from the different GCM outputs across the 21 models used in the modelling. Performing the analysis in this way allowed for standardisation as well as using the direct model outputs as opposed to interpolating to the slightly lower temperature. One of the major messages is that these models, like most species distribution models, are based on long-term changes in the mean climates and do not take into account extreme events that increasingly occur with changes in the mean (see above). Therefore, even though the time at maximum overshoot may be short, if it occurs in tandem with an extreme event (e.g. El Nino driven heat wave) then the impact may very well still occur. The absence of extreme events in the models make them generally conservative. Bringing extreme events into large scale species modelling is a research goal of many of the groups who work in this space.

There have been thousands of papers published on the potential impacts of climate change on species, usually concentrating on one, or a small group of species. There have been relatively few papers published on overshoot and biodiversity, and overshoot pathways are so specific that they are not comparable. For this study we are using the results from the largest set of models available (Warren *et al.*, 2018a) as it allows us to compare results with other reports in this series, and has been covered thoroughly in the peer reviewed literature and used in multiple chapters in IPCC AR6.

IPCC AR4 was the first to attempt to carefully quantify climate change mediated extinction risk. IPCC AR6 (Parmesan *et al.*, 2022) went much farther both in carefully using the IPCC risk definition and in quantifying both the area of risk (local or global), the level of risk (high or very high based on projected loss of climatic range) and the number of species involved – concentrating on studies that were either meta-analyses or that examined a very large number of species. The Cross Chapter Paper on Biodiversity Hotspots (Costello *et al.*, 2022) specifically looked at changes within hotspots and this was further summarised in relationship to endemic species which found a higher risk of extinction among endemic species (Manes *et al.*, 2021). Similar results were identified for small islands whose species are range restricted even if not truly endemic (Mycoo *et al.*, 2022). Based on the literature, endemic species and species on small islands (or otherwise restricted in range) might be expected to be most impacted by an overshoot pathway, even if it occurred for a relatively short period of time, as there is reduced resiliency and adaptive capacity in these systems.

In examining extinction risk, AR6 started by looking at high extinction risk and its possible impacts on ecosystem functioning. Figure 6 shows the projected local loss of biodiversity at (a) 1.5 °C (NO pathway) and (b) 2.0 °C (similar to the VHO pathway). Those areas projected to lose more than 25% of their species are seen as being at increasing overall risk owing to loss of ecosystem functioning. This is not only functioning for the ecosystem itself but also in loss of ecosystem services that society depends upon. These maps go beyond the projected climate driven changes but also include current land cover changes that will also have had impacts on biodiversity. Even with no overshoot, many areas in Brazil, Southern Africa, Europe and Australia are projected to lose more than 25% of their spcies. At 2 °C, many of these same areas are projected to lose more than 50% of their species and areas losing more than 25% of their species expand in South America, North America, Europe, Asia and Australia. |These maps were based on models that took into account a period of time at 2.0 °C with no disperal - i.e. differences from what is expected to be seen in a given location relative to the present. However, some taxa are generally able to track climate in ‘real time’ (e.g. many birds, mammals and some insects) while others are relatively ‘fixed’ (e.g. low dispersal rates, even over decades; see Warren *et al.* (2018a)). Maps showing how these change are projected to play out over shorter periods of time, including dispersal, can be seen in Figure 8a and b.

Taken globally, at 2 °C (overshoot), range losses of >50% are projected for 18% of insects but only 6% at 1.5 °C; for plants, with 2 °C warming, range losses >50% projected for 16% of the plants but only 8% at 1.5 °C. Thus, avoiding overshoot potentially prevents two thirds of the risks associated with warming of 2 °C for insects and half the risks associated with warming for plants (Warren *et al.*, 2018a).

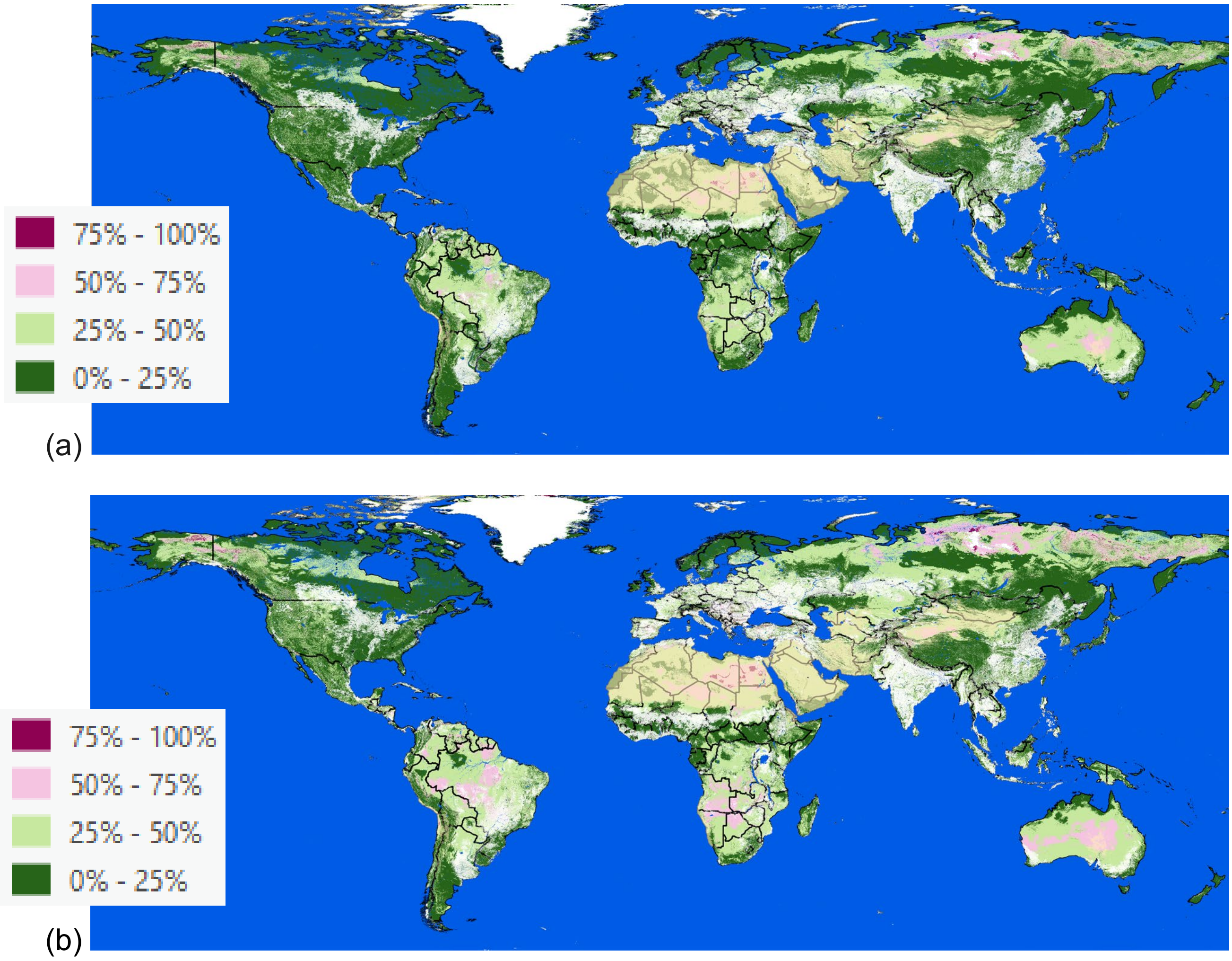
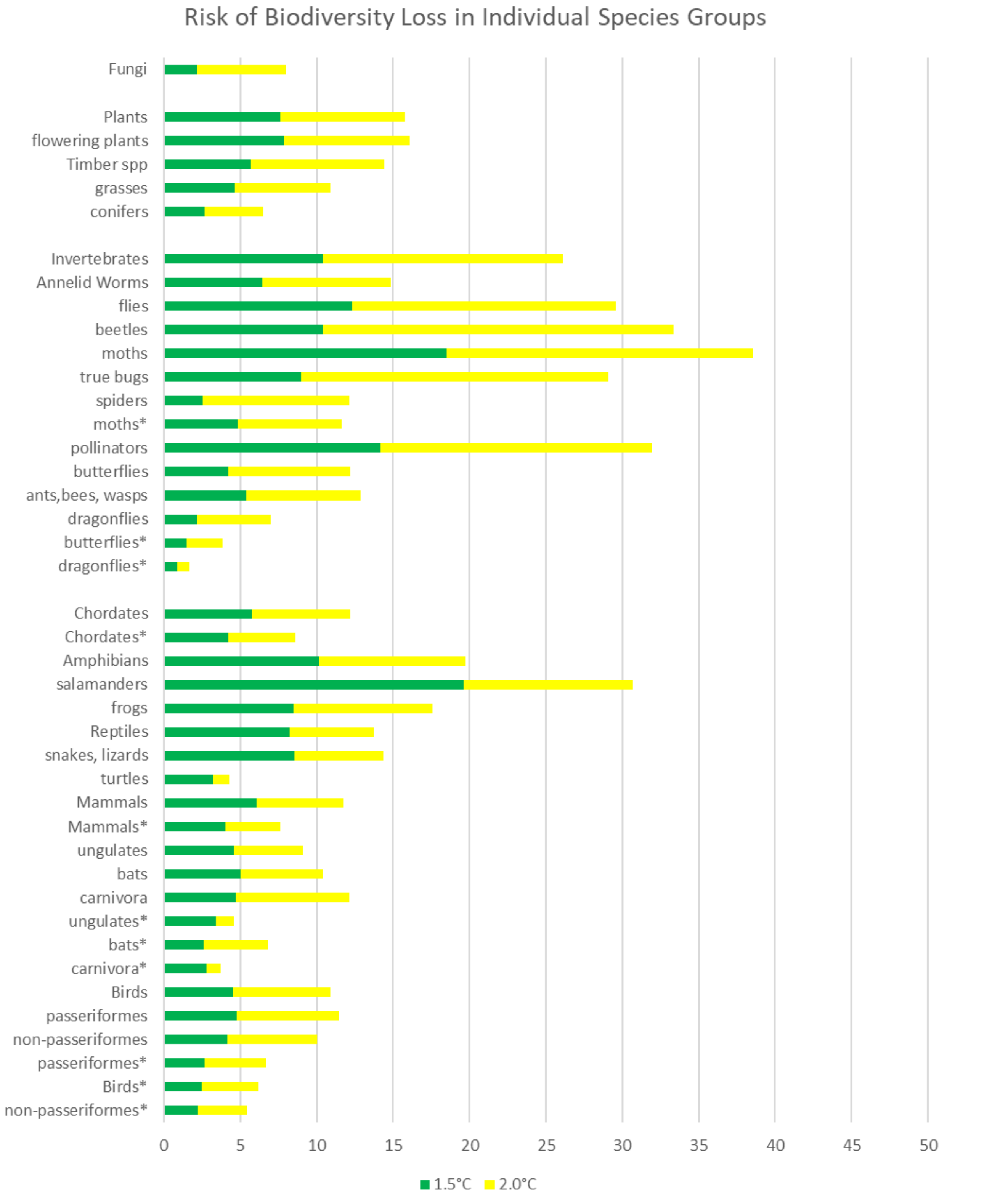


Figure 6. Projected loss of climatic range for biodiversity, as % species loss, for warming to (a) 1.5 °C (i.e. without overshoot) and (b) 2.0 °C.

Maps and caption based on data from Warren et al. (2018a) and modified from Figure 2.6 in IPCC AR6 (Parmesan et al., 2022). Maps depict “Biodiversity loss for different areas at increasing levels of climate change. The higher the percentage of species projected to lose suitable climate in a given area, the higher the risk to ecosystem integrity, functioning and resilience to climate change. Warming levels are based on global surface air temperature (GSAT) above pre-industrial. Colour shading represents proportion of species for which the climate is projected to become sufficiently unsuitable that the species becomes locally ‘endangered’ and at high risk of local extinction within a given pixel across their current distributions at a given GSAT warming level, based on underlying data (Warren et al., 2018a) (modelled n = 119,813 species globally, with no dispersal, averaged over 21 CMIP5 climate models). Areas shaded in deep [pink] and red represent a significant risk of biodiversity loss (areas where climates become sufficiently unsuitable that it renders >50% and >75% of species at high risk of becoming locally extinct, respectively). The maps of species richness remaining have been overlaid with a land cover layer (2015) from the European Space Agency (ESA) Climate Change Initiative. This land cover layer leaves habitats classified by the ESA as natural as transparent. Areas with a land cover identified as agriculture are 5% transparent, such that the potential species richness remaining if the land had not been converted for agriculture shows as pale shading of the legend colours (very pale yellow to very pale red). These paler areas represent biodiversity loss due to habitat destruction, but with a potential to be restored, with yellow shading having the potential for restoration to greater species richness than [pink] or red shading.” (Parmesan et al., 2022).

Previous work on climate change and biodiversity tended to look at one or a few groups of species and presented results of an aggregate across many different groups of species. This aggregation leads to misconceptions as to how different groups of species are projected to be at high risk of extinction (loss of 50% of their climatic range); see Warren *et al.* (2018a) and Parmesan *et al.* (2022) for details. Some of these groups of species have large roles in ecosystems. For example, moths are pollinators, insect pests, and important food resources for birds and thus would potentially have a large knock-on effect to other species. The same is true for pollinators and flowering plants. In IPCC AR6 both projected high and very high extinction risk were examined (Parmesan *et al.*, 2022); very high extinction risk, was not included here as it relates to temperatures above 2.0 °C warming, which are beyond the maximum overshoot that was considered in this study.

Figure 7 allows for easy comparison of the potential additional risk with a temperature rise of 2 °C instead of 1.5 °C. The species groups marked with an asterisk (*) show those where realistic dispersal rates have been applied (Warren *et al.*, 2013). Note that these have used a dispersal period of over 100 years, not over the “relatively short period” of the overshoot in the VHO pathway. For that reason, the benefits of dispersal and hence reduced risk of extinction will not be as pronounced as shown here. Of the groups of species analysed, invertebrates and especially moths, beetles, flies (and, collectively, pollinators) show the greatest number of species at high extinction risk with overshoot. This is followed by salamanders and flowering plants.



% species projected to lose >50% of their climatic range (high risk of extinction)

Figure 7**.** Species groups projected to be at a high risk of extinction. Based on Warren *et al.* (2018a), modified from Figure 2.8b (Parmesan *et al.*, 2022). **"**Species groups listed projected to be at a high risk of extinction, corresponding to the IUCN Red List criteria for a species classified as 'endangered' (v3.1) by losing >50% of its climatically suitable range area. For (a) and (b), values were calculated from the underlying data in (Warren *et al.*, 2018a). Values for each temperature are the mean values across 21 CMIP5 models. The grey band represents the high end of extinction risk from the 10th percentile of the climate models to show the maximum range of values, while the low end (90th percentile, 1.5 °C) is not shown as it is too small to appear on the plots. Taxa marked with * represent potential benefits from adaptation, specifically dispersal at realistic rates (Warren *et al.*, 2018a); those with no * have dispersal rates that are essentially not detected in the spatial resolution of the models (20 km). See Warren *et al.* (2018a) for caveats and more details. Sample size for each group is as follows: (1) fungi (16,187 species); (2) all plants (72,399 species), broken down into sub-groups of plants: flowering plants (52310 species), timber species (1328 species), grasses (3389 species) and pines (340 species); (3) all invertebrates (33,949 species), broken down into sub-groups of invertebrates: annelid worms (155 species), flies (4,809 species), beetles (7,630 species), moths (6,910 species), true bugs (1,728 species), spiders (2212 species), all pollinators (1,755 species), butterflies (1,684 species), ants/bees/wasps (5,914 species), dragonflies (599 species); (4) Chordates (12,642 species), broken down into major groups: (4.i) all amphibians (1,055 species), broken down into sub-groups of amphibians: frogs (887 species) and salamanders (163 species); (4.ii) reptiles (1,850 species), snakes (1,741 species) and turtles (94 species); (4.iii) all mammals (1,769 species), broken down into sub-groups of mammals: ungulates (80 species), bats (500 species), carnivores (107 species), (4.iv) all birds (7,968 species), broken down into sub-groups of birds: passeriform birds (4,744 species), and non-passeriform birds (3,224 species)" (Parmesan *et al.*, 2022).

4.3 Key Risks

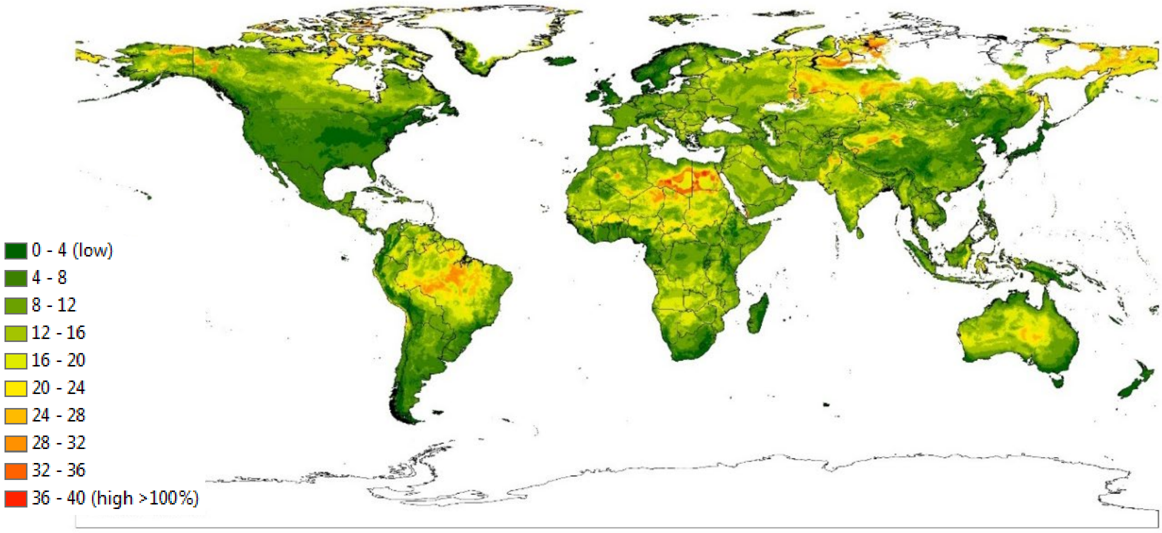
In the analysis of key risks to terrestrial and freshwater ecosystems in IPCC AR6 WG-II (IPCC, 2022a), the risk of biodiversity loss is moderate with no overshoot but at the transition between high and very high risk with an overshoot to 2 °C; that of structural change in ecosystems moderate with no overshoot transitioning to high with overshoot; that of tree mortality transitioning from moderate to high with no overshoot and high with overshoot; that of wildfire increases moderate with no overshoot and transitioning to high with overshoot; and that of carbon loss moderate with no overshoot and transitioning to high with overshoot (Parmesan *et al.*, 2022). While the relatively short period of the overshoot in the VHO pathway (and that this particular overshoot pathway is 1.86 °C and not quite 2 °C) means that some of the longer-term events (e.g. tree mortality, carbon release) are less likely to occur, the reality will depend on the degree that the time at this temperature leads to an increase in disturbance events such as disease outbreaks and wildfire. An increase in disturbance events during the overshoot period would increase the likelihood of the event occurring even with the relatively short period of overshoot. The IPCC AR6 WG-II Summary for Policymakers (IPCC, 2022a) brings together the key risks from the other chapters. In Africa the risks to biodiversity and ecosystems is transitioning to high with no overshoot and to very high with overshoot; the loss and degradation of coral reef ecosystems is already very high even with the NO pathway; sea ice ecosystems owing to loss of Arctic sea ice is high with no overshoot and very high with overshoot (IPCC, 2022a).

4.4 Community Transformation

One of the biggest risks of overshoot on biodiversity is the degree to which ecological communities may potentially transform over time. Many taxa have low dispersal rates (e.g. plants, reptiles, amphibians, many insects) and would not be able to move to track the changing climate. As the climate exceeded the thermal tolerances of these species then the species would be expected to become locally extinct (Wiens, 2016, Warren *et al.*, 2018a, Parmesan *et al.*, 2022). This could occur relatively quickly if lethal thresholds are crossed or it could occur over time, with the length of time, at most, being the lifespan of the species. Other taxa have dispersal rates that would be able to track the climate, or catch up (e.g. birds, mammals, butterflies, dragonflies, some bees). These species, in tracking their climate would move out of those areas exceeding their climate suitability to keep up with the climate envelope, potentially moving into areas where they have not occurred before, becoming climate pioneers. Each individual species has its own exposure to climate change, with the vulnerability increasing with disruption to ecosystem functioning and increasing risk owing to whether adaptation options, such as corridors were available for movement. In the absence of corridors, for those species that cannot fly, the species would be trapped and exposed to the full climate change, potentially facing local extinction (Parmesan *et al.*, 2022).

Thus, the overall picture is one of given areas projected to lose some species, and gain others. This mixing can be expressed in a Community Transformation Index (CTI), based on the proportion of species in a given pixel (20 km x 20 km in this analysis) that are lost, are gained, or undergo no change (Price, unpublished work). This is not really a new finding, and a discussion of the change (but not the consequences) can be found in Price (1995). Maps showing the projected level of CTI in 2100 for global warming of 1.5 °C and 2.0 °C are shown in Figure 8. The degree of CTI with overshoot of 1.5 °C is likely greater than that shown below. This is owing to community composition changes (i.e. different species in the future than are present currently) likely to occur based on differing dispersal rates, the length of time the overshoot occurs, extreme events during this period, and the length of time for the surface temperature to return to 1.5 °C warming. For species with high degrees of dispersal, they may reach their 2.0 °C range while those with lower dispersal rates will not, so there will be a combination of species that 'cross' as they track their suitable climates.

a) 1.5 °C, climate only, no land cover taken into account



b) 2.0 °C, climate only, no land cover taken into account

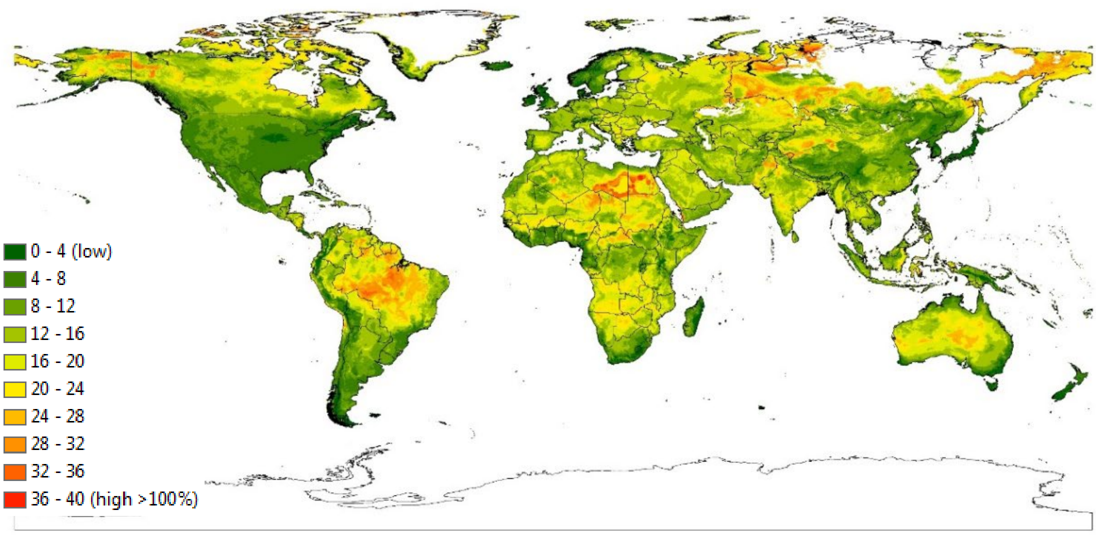


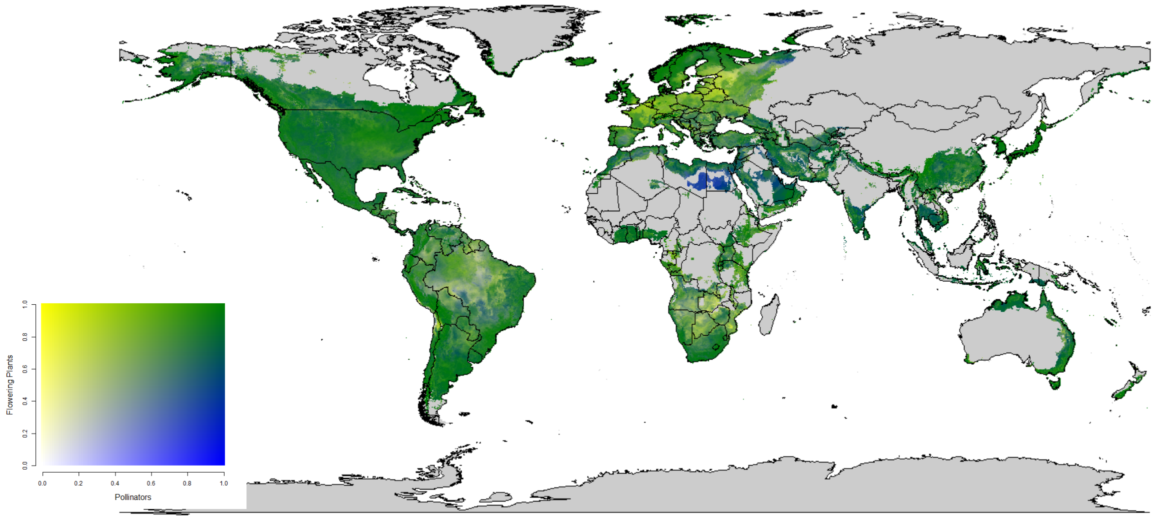
Figure 8. Community Transformation Index for 1.5 °C and 2.0 °C, across taxa considering losses, gains, and no change. Maps are based on climate models for plants, mammals, birds, reptiles, and amphibians across 21 CMIP5 climate model patterns. Areas in green show minimal change through mixing, areas in yellow show moderate transformation while those in orange or red show large amounts of transformation. In most cases, the CTI shows larger impacts occurring sooner than maps of biodiversity change with no dispersal considered. These maps do not include potential land cover transformation (e.g. natural land to agriculture or urban, nor lakes/rivers, bare rock, or permanent snow ice). Many of these land covers will have transformed potential habitats for these species, and act as barriers for movements (dispersal) (Price, unpublished work).

The regions showing the greatest potential risk are in southern Amazonia/Cerrado (South America), Miombo Woodlands (South-Central Africa), Southern Europe, India, parts of Australia and the Kamchatka Peninsula and surrounding areas in Russia. Community Transformation matters because it is unlikely that species will replace like for like in terms of endogenous ecosystem services (e.g. pollination, seed dispersal, pest control) (Gitay *et al.*, 2001, Burkett *et al.*, 2005, Parmesan *et al.*, 2022, Price, unpublished work). In the case of mutualistic species (species that require the presence of one or other species to function) they will not be. This is not a new finding, and the unquantified risk of species mixing was raised in the IPCC Third Assessment Report and follow-up article (Gitay *et al.*, 2001, Burkett *et al.*, 2005).

A visualisation of the potential implications of unequal dispersal rates and community transformation can be seen in Figure 9, which examines the potential differential projected climate impacts on pollinators (some of which can disperse to track the climate) and flowering plants (that generally have dispersal rates too small to track the climate changes. While there are many areas of missing data for pollinators (grey), these maps show that an overshoot is projected to potentially impact the pollinator/flowering plant (including insect pollinated crops) in Amazonia, Southern Africa and much of Europe, once the average global warming above pre-industrial was reached[4]. It is difficult to assign a level of confidence as many of these changes are already occurring, in some cases at rates faster than models' project.

[4] As species respond to climate change in real time, either through shifts or increased risk of disease, pests and fire, the maps are for the time at which the warming temperature is reached.

A) 1.5 °C



B) 2.0 °C

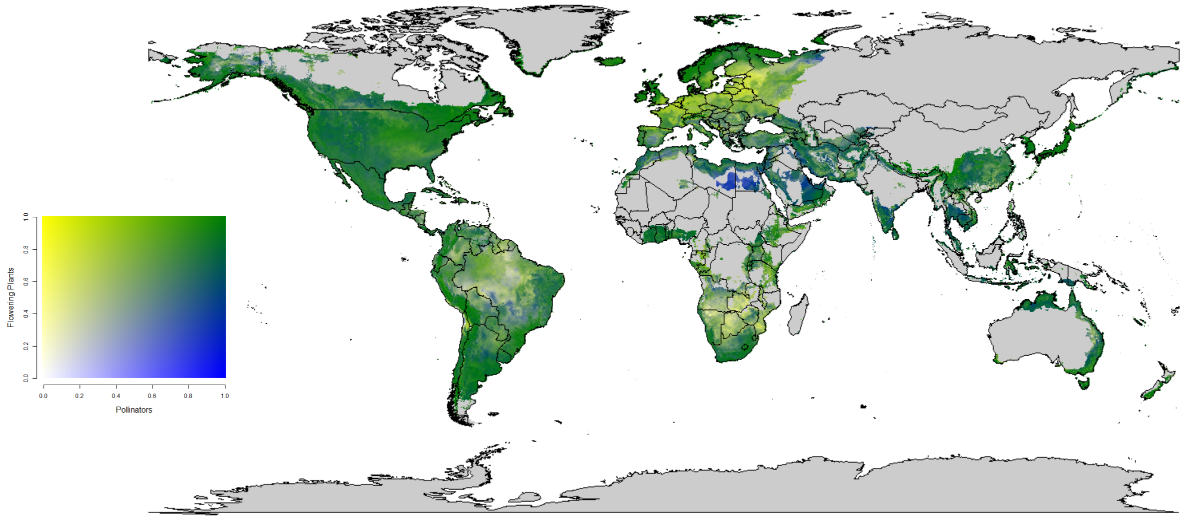


Figure 9. Projected changes in flowering plants and pollinators (species richness remaining) at 1.5 °C and 2.0 °C. Scale is from white (0) to yellow (100% of species remaining) for flowering plants; white (0) to blue (100% of species remaining) for insect pollinators; and white (0) to green (100%) for both. An intact ecosystem for pollinators and flowering plants (baseline) would be green. If the map shows more of a yellow gradient in means that flowering plants are present but there has been a projected loss in climatic space of pollinators. If the map is blue, then there are pollinators but a loss of flowering plants. In both of these cases the overall projected impact of climate change is projected to be larger owing to the loss of the interaction than would be captured by either set of models individually. Based on data from Warren *et al.* (2018a), further elevationally downscaled to 1 km x 1 km. Sample sizes are the same as in Figure 7.

5. Ocean and coastal systems

The ocean plays a fundamentally important role in the Earth's climate system by:

- storing large amounts of heat, e.g. the ocean has absorbed more than 90% of the excess heat in the climate system (IPCC, 2019). By 2100, the ocean will have absorbed two to four times more heat than it has in the last 50 years if global warming is limited to 2 °C (IPCC, 2019);
- transporting heat from warm to cold regions by ocean currents, and releasing heat and moisture;
- regulating the global climate by mediating temperature and determining rainfall, droughts and floods (IPCC (2019); and Figure 10 below - Figure 6.2 in IPCC (2019)); and,
- storing large amount of carbon, e.g. the ocean has taken up 25% of anthropogenically emitted CO_2 from the atmosphere (Friedlingstein *et al.*, 2022).

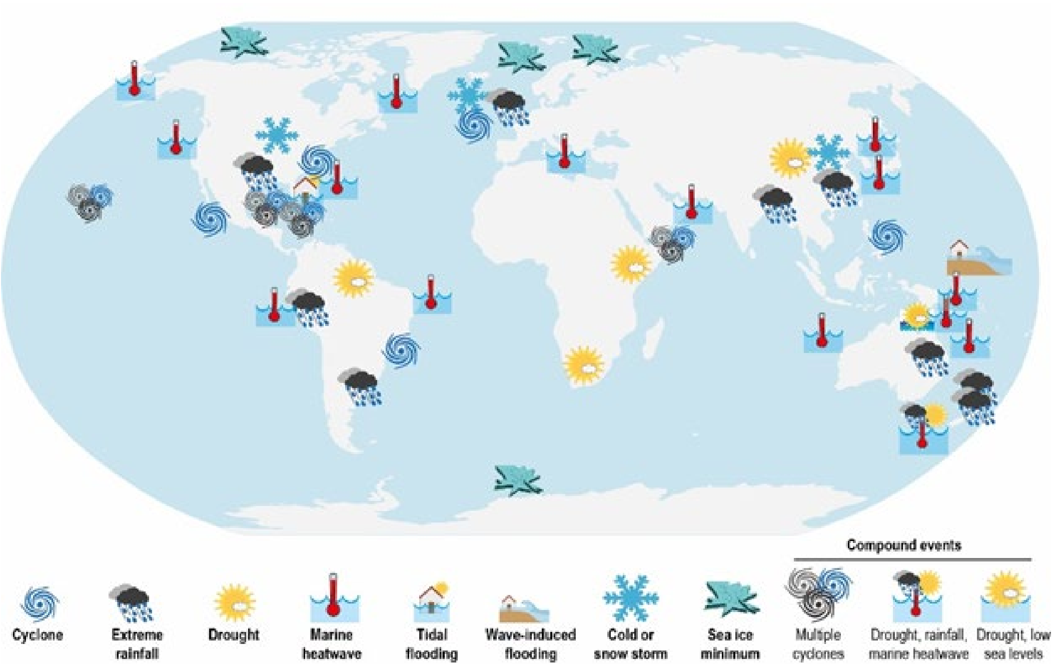


Figure 10. Locations of extreme events with an identified link to ocean changes. From Figure 6.2 of IPCC (2019).

5.1 The Atlantic Meridional Overturning Circulation

The Atlantic Meridional Overturning Circulation (AMOC) is the main overturning current system in the South and North Atlantic oceans, and a part of the global ocean circulation system. The AMOC transports warm upper-ocean water northwards, and cold, deep water southwards. Changes in the AMOC influence global ocean heat content and heat transport, global ocean anthropogenic carbon uptake changes, and dynamical sea level change (IPCC, 2021).

The Atlantic Meridional Overturning Circulation (AMOC) will *very likely* decline over the 21st century for all SSP scenarios (IPCC, 2021). There is medium confidence that the decline will not involve an abrupt collapse before 2100 (IPCC, 2021). None of the CMIP6 models features an abrupt AMOC collapse in the 21st century, but they neglect meltwater release from the Greenland Ice Sheet (IPCC, 2021). In addition, a recent process study reveals that a collapse of AMOC can be induced by even small-amplitude changes in freshwater forcing (Lohmann and Ditlevsen, 2021). As a result, an abrupt collapse of the AMOC will not occur before 2100 (*medium confidence*). Since the publication of the IPCC's Fifth Assessment Report (IPCC, 2013) and the Special Report on the Ocean and Cryosphere in a Changing Climate (SROCC) (IPCC, 2019), confidence in modelled and reconstructed AMOC has decreased due to new observations and model disagreement (IPCC, 2021).

While it is *very likely* that the AMOC will weaken over the 21st century (Figure 11), the SROCC (IPCC, 2019) stated that there is no evidence indicating significantly different amplitudes of AMOC weakening for 1.5 °C versus 2 °C of global warming. In CMIP6 projections, the modelled decline starting in the 1990s continues in all future projections, almost independent of the forcing scenario until about 2060, after which low-emissions scenarios show stabilisation, while high-emissions scenarios continue to exhibit AMOC decline (IPCC, 2021).

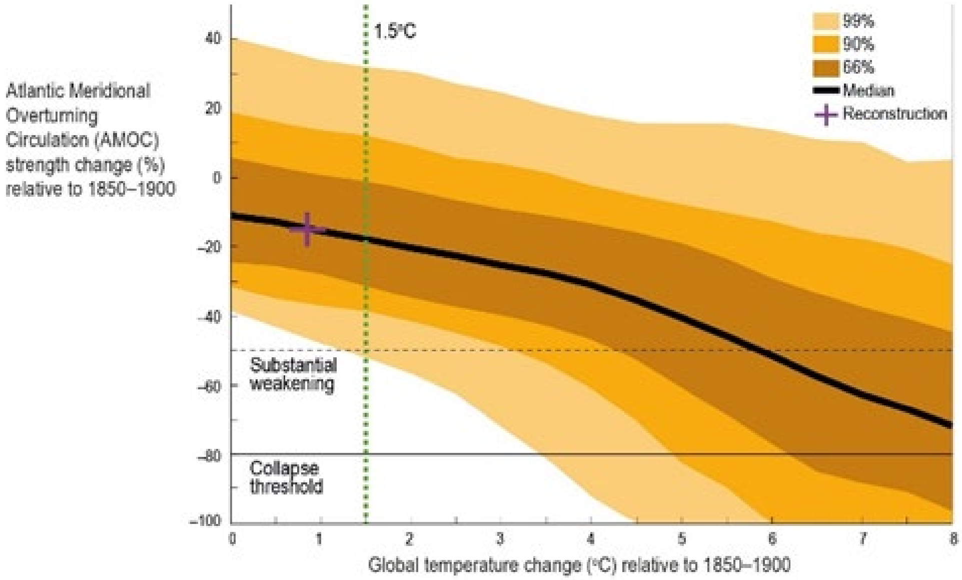


Figure 11. AMOC changes as a function of changes in global mean temperature. From Figure 6.9 of IPCC (2019).

5.1.1 Impacts of AMOC weakening

While the AMOC will not collapse by 2100, weakening of AMOC will affect physical systems, leading to changes in the frequency of extreme events (e.g. drought, flooding) globally. With AMOC slowing down the atmosphere adjusts somewhat by carrying more heat, compensating partly for the decreases in heat carried by AMOC. This will lead to slower warming in parts of Europe. Models indicate that weather patterns around the Atlantic will be affected, with reduced precipitation in the mid-latitudes, changing strong precipitation patterns in the tropics and Europe, and stronger storms in the North Atlantic storm track leading to increased flooding (e.g. in the UK and Europe) and changes in hurricane frequency in North America (IPCC, 2021).

5.1.2 AMOC as one of the tipping elements in Earth Climate System

Early warning indicators have revealed potential destabilisation of AMOC (IPCC, 2021). However, many Earth System Models (ESMs) still lack processes important for resolving potential tipping behaviour as they are biased toward AMOC stability (Liu *et al.*, 2017, IPCC, 2021, Armstrong McKay *et al.*, 2022). The recent review by Armstrong McKay *et al.* (2022) suggests the AMOC be retained as a core global tipping element (medium confidence) with a best estimate threshold of ~4 °C [1.4 to 8 °C] , timescales of ~50 years (15 to 300 years) (medium confidence). Potential causal interactions among tipping elements, e.g. Greenland ice sheet and AMOC, are such that overall tipping of one element increases the likelihood of tipping others, possibly risking a "tipping cascade" of impacts that may further amplify global warming (Armstrong McKay *et al.*, 2022). The terminology used in Armstrong McKay *et al.* (2022) (e.g. "low confidence") follows that of the IPCC Report, see middle column, bottom of page 8 of their paper.

5.1.3 Knowledge Gaps

Key knowledge gaps are:

- There is a lack of scientific literature about AMOC response to overshoot pathways. Only a limited number of publications about changes in AMOC with overshoot or warming of 1.5 °C and 2 °C is available. The limited available studies suggest that there is no evidence indicating significantly different amplitudes of AMOC weakening for 1.5 °C versus 2 °C of global warming (IPCC, 2019).
- Since previous IPCC reports, confidence in modelled and reconstructed AMOC has decreased due to new observations and model disagreement (IPCC, 2021). New observations indicate that there are missing key processes in both models and measurements used for evaluation of AMOC trend and variability.
- There is still a lack of understanding of how ocean circulation, including AMOC, is changing towards 1.5 °C and 2 °C warmer climates, in particular the role of vertical mixing, deep ocean processes, currents, and their impact on weather patterns on a regional scale.
- There is a lack of understanding of the hysteresis of the AMOC.

5.2 Sea Surface Temperature Changes and Marine Heatwaves

IPCC AR6 WGI (IPCC, 2021) concluded that observed warming of the upper ocean with sea surface temperature (SST) increased, with slightly lower rates than global warming. It is virtually certain that SST will continue to increase in the 21st century, at a rate depending on future emissions scenarios. The ocean surface temperature is projected to increase between 1995 to 2014 and 2081 to 2100 on average by 0.86 °C [0.43 to 1.47 °C, likely range] in SSP1-2.6 (IPCC, 2021). At least 83% of the ocean surface will very likely warm over the 21st century in all Shared Socio-economic Pathways (SSP) scenarios (IPCC, 2021).

Marine heatwaves (MHWs) – sustained periods of anomalously high near-surface temperatures that can lead to severe and persistent impacts on marine ecosystems – have become more frequent over the 20th century (high confidence) (IPCC, 2021). Since the 1980s, they have approximately doubled in frequency (high confidence) and have become more intense and longer (medium confidence). The SROCC (IPCC, 2019) suggested that under future anthropogenic warming, MHWs are projected to further increase in duration, intensity, frequency and spatial extent. Projections show that frequencies of MHWs will be 20 times higher at 2° C warming in comparison to pre-industrial levels. Impacts of average and extreme warming include mass mortalities of coastal species and large-scale bleaching of coral reefs as well as shifting fish stocks with reduced fisheries results (IPCC, 2019). For oceans, regional surface temperature means and extremes are projected to be higher at 2 °C compared to 1.5 °C of global warming (IPCC, 2021). The SROCC (IPCC, 2019) highlighted that future change of MHWs will not be globally uniform, with the largest changes in the frequency of marine heatwaves being projected to occur in the western tropical Pacific and the Arctic Ocean (medium confidence).

5.3 Sea level rise

5.3.1 Sea level rise and the overshoot by 2100

Most of the scientific literature about sea level response to overshoot pathways is only just emerging. There is a very limited number of processes-based studies that are relevant to sea level rise with overshoot or warming of 1.5 °C and 2 °C pathways, due to the complexity of simulating the various contributions from sea level components, such as ice mass loss from Antarctic and Greenland ice sheets, glaciers, and thermal expansion of the ocean (IPCC, 2021). In the IPCC approach (e.g. Church *et al.*, 2013), global mean sea level changes over time are represented as the sum of projected sea level components, while each sea level component is simulated with particular types of model; e.g. Atmosphere-Ocean General Circulation Models (AOGSMs) and Earth System Models (ESMs) are used for simulation of thermal expansion; and ice sheet models (Church *et al.*, 2013) utilised to simulate ice mass loss from Greenland and Antarctica ice sheets (Church *et al.*, 2013).

There are insufficient studies focusing on sea level rise in worlds with 1.5 °C and 2 °C of warming, including a small overshoot, leading to the lack of consensus between the reported ranges of global mean sea level rise with warming of 1.5 °C and 2 °C projections (IPCC, 2018). Projections vary in the range 0.20–0.99 m (5–95% confidence) for 1.5 °C of warming. For warming of 2 °C, the range is 0.24–1.17 m for the 5–95% confidence interval. Nevertheless, there is agreement that the median of global mean sea level rise in 2100 would be 0.1 m higher in a 2 °C warmer world compared to a 1.5 °C (IPCC, 2018). There is medium confidence in this assessment because of issues associated with projections of the Antarctic contribution to global mean sea level (IPCC, 2018, 2021).

The range of global mean sea level rise projections with warming of 1.5 ºC and 2 ºC is dependent on global mean air temperature trajectories (see Table 5, taken from Jevrejeva *et al.* (2018)).

Table 5. Projected global mean sea level rise (m) by 2100 with warming of 1.5 °C and 2.0 °C reached by 2030, 2050, 2070, 2090 and kept constant thereafter (from Jevrejeva *et al.* (2018)).

	Global mean sea level rise (m) by 2100		
1.5 ºC			
peak at	**5%**	**50%**	**95%**
2030	0.27	0.52	0.87
2050	0.26	0.51	0.84
2070	0.25	0.47	0.82
2090	0.25	0.46	0.74
2 ºC			
peak at	**5%**	**50%**	**95%**
2030	0.29	0.63	1.12
2050	0.28	0.62	1.04
2070	0.27	0.59	0.98
2090	0.27	0.54	0.92

Over the 21st century, sea level rise rates are projected to exceed the highest rate of rise of the 20th century, even if emissions are limited sufficiently to reach the 1.5 ºC target (Jevrejeva *et al.*, 2018). A smaller sea level rise (e.g. by 10 cm) could mean that up to 10.4 million fewer people would be exposed to the impacts of sea level rise globally in 2100 at 1.5 °C compared to at 2 °C (IPCC, 2019), based on the 2010 global population and assuming no adaptation. In addition, a slower rate of sea level rise enables greater opportunities for adaptation (IPCC, 2019).

5.3.2 Sea level rise and the overshoot beyond 2100

There is high confidence that sea level rise will continue beyond 2100 (IPCC, 2021). Schaeffer *et al.* (2012) found that in an approximately 1.5 ºC overshoot pathway, with temperatures slightly declining towards the end of the 21st century, there could be a small decline in the rate of sea level rise, but sea-levels would nonetheless continue to rise.

5.3.3 Impact of sea level rise on coastal flooding

Several studies have reported an increase in the magnitude and frequency of extreme sea levels, associated with sea level rise under the 1.5 °C and 2 °C warming (Rasmussen *et al.*, 2017, Tebaldi *et al.*, 2021). Tebaldi *et al.* (2021) suggested that by 2100 with warming of 1.5 °C around 50% of 7,283 locations along the global coastline would experience today's 1-in-100-year extreme sea level (combination of waves, storm surge and sea level rise) at least once in a year. The impacts of an overshoot on coastal flooding are not well known.

5.3.4 Gaps/Tipping points/Hysteresis

Despite the global implications of sea level rise, there are no studies about the assessment of the tipping points for sea level rise. Tipping points in future sea level rise will be determined by the interaction between tipping points of both ice sheets (Greenland and Antarctica, see Section 6 Polar Regions) and ocean circulation, considering the complexity of sea level, its components and their interaction (Armstrong McKay *et al.*, 2022). There are no studies focusing on hysteresis in future global sea level rise, although there are studies on the contributing components to sea level rise e.g. hysteresis of the Antarctic ice sheet (Garbe *et al.*, 2020).

5.4 Ocean Acidification

5.4.1 Introduction

The oceans naturally capture CO_2 from the atmosphere and act as a sink for carbon (Friedlingstein *et al.*, 2022). However, the rapid rate of increasing atmospheric CO_2 from anthropogenic activities has increased the rate of uptake of CO_2 into the ocean and caused a shift in the marine carbonate system that, on geological timescales, would be naturally buffered by weathering processes (Hönisch *et al.*, 2012). The marine carbonate system involves the reaction between CO_2 and water to produce bicarbonate and hydrogen ions. The production of hydrogen ions is causing ocean pH to decrease; this phenomenon is known as ocean acidification. Using model statistical calculations to determine the likely pre-industrial ocean chemistry conditions, together with global observations of historic and present day conditions up to year 2000, average global surface pH has declined by 0.10–0.12 units (year 1750 pH 8.18–8.21), or become ~30% more acidic (IPCC, 2021). Within the past two decades pH has continued to decline with an average rate of 0.0016 y^{-1} ([5]), such that in year 2020 the global ocean surface water (average pH = 8.05) was 35–45% more acidic than pre-industrial levels (Findlay *et al.*, 2022). Model projections suggest that under high emissions scenarios the oceans could become 150% more acidic by the end of the century (IPCC, 2021). The production of hydrogen ions also triggers a buffering reaction, whereby calcium carbonate begins to breakdown to its components of carbonate and calcium ions. This component of ocean acidification is referred to as a decrease in saturation state of calcium carbonate minerals such as aragonite (Ω_{Arag}), which are used by many marine calcifying organisms such as calcifying plankton, corals, molluscs and crustaceans. Average global surface ocean Ω_{Arag} was calculated to be about 3.4 in the pre-industrial period, declining to about 2.8 by year 2000 (Raven *et al.*, 2005).

The increase in CO_2, decrease in pH and decrease in saturation state of calcium carbonate minerals has implications for the health of marine organisms through direct impact on their physiology, growth, reproduction, and calcification in calcifying organisms (Findlay and Turley, 2021). Ocean acidification has also been shown to cause changes in biogeochemical cycling, importantly relating to the carbon cycle, for example, the slowdown of carbon uptake (IPCC AR6

[5] EU Copernicus Marine Service Information, https://doi.org/10.48670/moi-00224

WGI SPM (IPCC, 2021)) or reduced carbon export to deep waters (e.g. Langer (2008), Anglada-Ortiz *et al.* (2021)), but also including changes to silica cycling (Petrou *et al.*, 2019), nitrogen cycling (e.g. Blackford and Gilbert, 2007, Rees *et al.*, 2016), and climatically important biogases (Hopkins *et al.*, 2020). Biological thresholds and tipping points related to ocean acidification are not yet well established, although some work has been conducted on a few key species. For instance, Bednaršek *et al.* (2021a) conducted a synthesis of threshold impacts on echinoderms. They found a wide variety of responses with thresholds for effects across different life stages of different species ranging from pH 7.20 to 7.74, with a duration from 7 to 30 days. All the thresholds discussed in the review were characterised with either medium or low confidence (Bednaršek *et al.*, 2021a). Other studies have tried to characterise thresholds for oysters (Barton *et al.*, 2012, Gimenez *et al.*, 2018) and pteropods (Bednaršek *et al.*, 2019). Indeed, both these species (and others, such as the Dungeness crab, Bednaršek *et al.* (2020)) have already been shown to be vulnerable to ocean acidification in some regions of today's ocean (Bednaršek *et al.*, 2012, Barton *et al.*, 2015, Bednaršek *et al.*, 2021b). Bednaršek *et al.* (2019) suggest that the aragonite saturation state range from 1.5 to 0.9 provides a risk range from early warning to lethal impacts. While a threshold of aragonite saturations state of 1.5 has been proposed for oyster larvae (Barton *et al.*, 2012).

Here we primarily focus on the potential thresholds and tipping points associated with the chemical change of ocean acidification, paying particular attention to pH and aragonite saturation state (Ω_{Arag}). It is important to consider though that, for aragonite, while the chemical threshold of moving from saturation (mineral formation) to undersaturation (mineral dissolution) is $\Omega_{Arag} = 1$, the biological processes that respond to Ω_{Arag}, may have thresholds that appear as Ω_{Arag} moves below 1.5 or even higher, for example some warm-water corals (section 5.5).

5.4.2 Relationship to atmospheric CO_2, projections, and tipping points

Ocean acidification has a direct connection with atmospheric CO_2 concentration (*high confidence*), especially across global ocean scales (Caldeira and Wickett, 2003). There are increasing number of observation stations across the ocean with measurement time-series that show ocean pH decreasing alongside increasing oceanic and atmospheric CO_2 (Bates *et al.*, 2014). The chemical shift in the coastal regions is more complicated but here too there are increasing number of observations showing the occurrence of ocean acidification even in these complex environments (McGovern *et al.*, 2023).

Jiang *et al.* (2023) investigate the projected changes in carbonate chemistry in the latest CMIP6 models under a range of scenarios, showing the direct relationship between the change in oceanic pH and the atmospheric CO_2. This relationship is demonstrated here using both historic records (Pearson and Palmer, 2000) as well as future projections (IPCC, 2019) for atmospheric CO_2 and oceanic pH, and shows with *high confidence* that hydrogen ion (H^+) concentration (and pH) is strongly correlated with atmospheric CO_2 concentration (Figure 12).

There are no projections for global ocean acidification in an overshoot pathway to date, with ocean biogeochemistry often not included in these climate models. However, assessing the relationship between atmospheric CO_2 and key ocean acidification parameters, such as pH and aragonite saturation state, provides an insight into the oceanic response to changes in emissions. The rate of change is an important factor in determining the response of the ocean carbonate system. In addition, for aragonite saturation state, the amount of carbonate ions (and indirectly bicarbonate ions) already present in the ocean is also an important contributing factor, and this amount varies throughout the ocean basins. Hönisch *et al.* (2012) demonstrated how varying rates of change can impact the response of the carbonate system using models, to show that the trajectories of mean ocean surface pH and aragonite saturation state become progressively decoupled as the rate of atmospheric pCO_2 change increases.

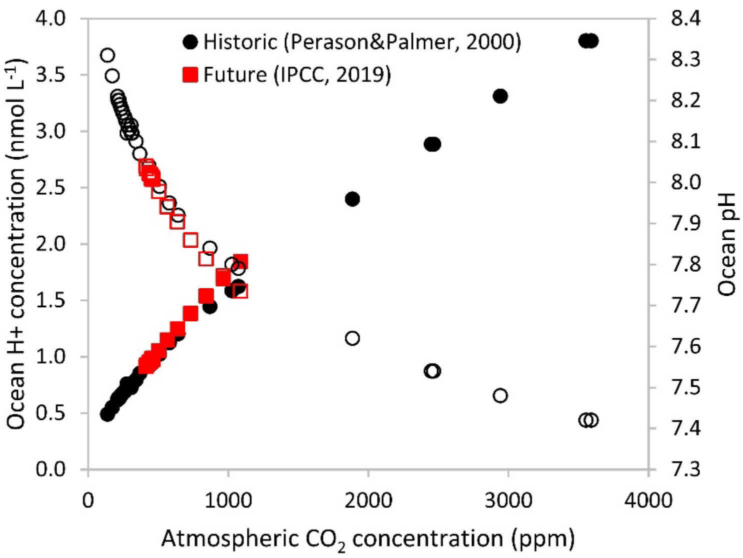


Figure 12. Relationships between surface ocean H^+ concentration and pH with atmospheric CO_2 concentration. Black circles are data are taken from reconstructed pH and CO_2 data over the past 60 million years (Pearson and Palmer, 2000), red squares are data taken from model projections for present to year 2100 (IPCC, 2019). Closed symbols show the H^+ concentration, open symbols show ocean pH.

Here, data from CMIP6 models can be used to highlight the difference in response between emissions scenarios but, importantly, the delayed return of both pH and aragonite saturation state to equilibrium conditions. Under the RCP8.5 scenario of continued emissions, atmospheric CO_2 concentration continues to increase causing both surface ocean pH (Figure 13A) and aragonite saturation state (Figure 13C) to undergo rapid and continued declines. In the middle emissions scenario RCP4.5, there is still continued decline in both pH and aragonite saturation state, however the severity and rate of decline are not as large as in the high emissions scenario (Figure 13A and Figure 13C). In contrast, under RCP2.6 emissions scenario (emissions peaking by 2030 then declining to the end of century), atmospheric CO_2 concentration peaks by about year 2060 then, by year 2100, declines back to levels slightly higher than present day. In this case, pH and aragonite saturation state both decrease slightly, but then remain at these lowered levels even as atmospheric CO_2 concentration comes back down, resulting in a non-linear delay in recovery of oceanic conditions (Figure 13B). This decoupling is due to the slow rates of deep ocean mixing, chemical equilibration with sediments on the seafloor, as well as the geological time-scales over which weathering processes occur (IPCC, 2018).

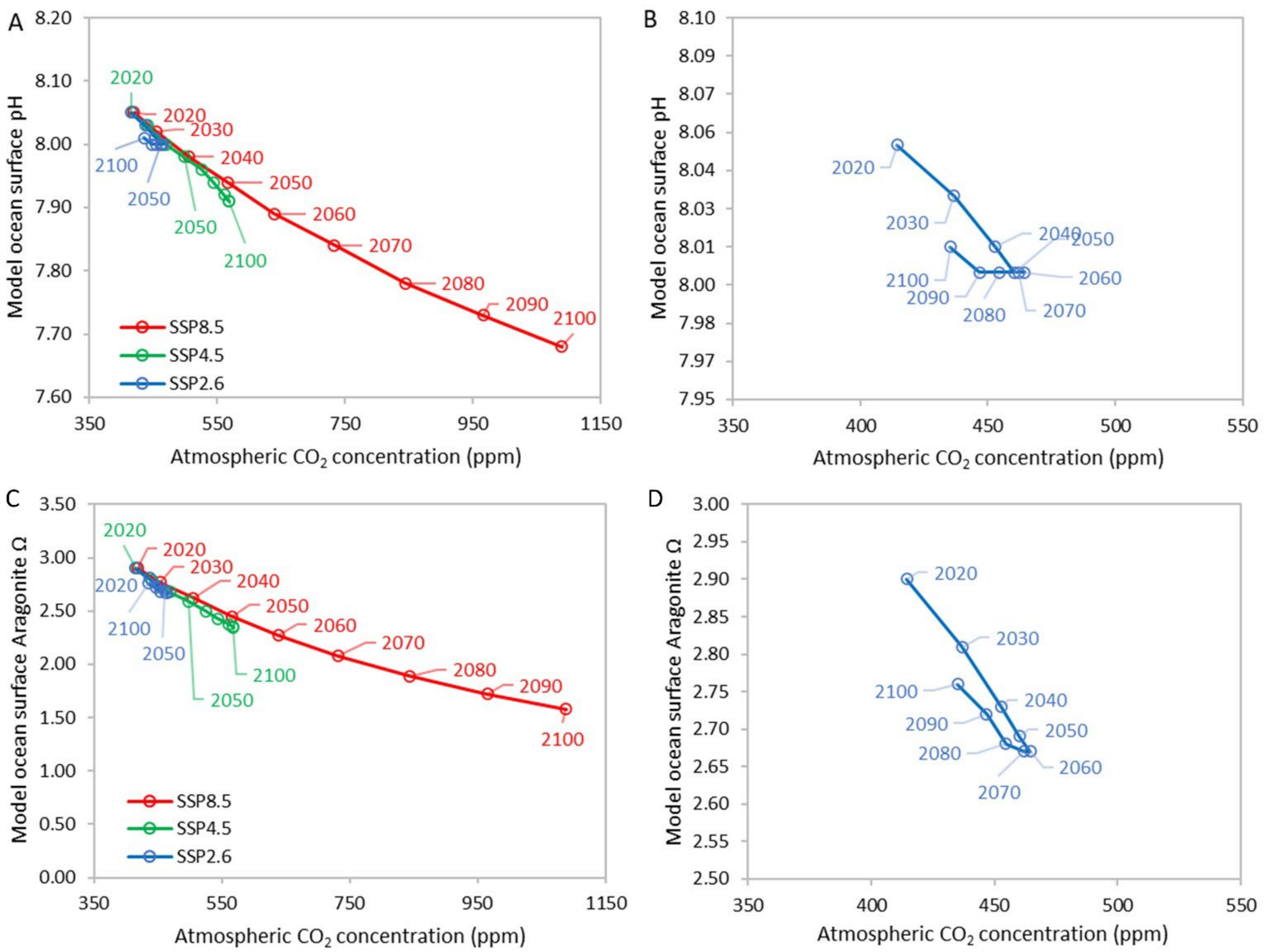


Figure 13. Surface ocean pH and aragonite saturation state as a function of atmospheric CO_2 concentration. A and B show the relationships between surface ocean pH and CO_2, while C and D show the relationships between surface ocean aragonite saturation state and CO_2. Three emissions scenarios are plotted: RCP8.5 (A & C, red), RCP4.5 (A & C, green) and RCP2.6 (blue). Also marked are the year at which the values are reached under each scenario. Data for pH and aragonite saturation state are from Jiang *et al.* (2023) and represent area-averaged inter-model median values. Data for atmospheric CO_2 concentration is from IPCC (2019).

There is *high confidence* that emissions equivalent to 2 °C or greater will result in centennial shifts in the carbonate system. While specific overshoot pathways have yet to be tested, the RCP2.6 scenario demonstrates that even as CO_2 emissions decline back to present-day levels, the ocean will not recover from lowered pH and aragonite saturation states on the same decadal timescales but will take centuries or even millennia to return to present or equilibrium conditions.

5.4.3 Highly vulnerable regions

The ability of the oceans to take up and store CO_2 is more complex in areas that have high river, land and sea-ice influence. In the polar oceans the additional cold water, and overturning circulation that takes carbon away from the surface to the deep waters, combine to make these regions especially vulnerable to ocean acidification (Kloenne *et al.*, 2023). The Arctic Ocean already has a lower amount of carbonate ions due to the large freshwater flows that come into the region from rivers and melting ice. Combined with a warming ocean, sea ice loss and freshening, the Arctic Ocean is already experiencing rapid rates of acidification (Bellerby, 2017) that in some locations are 2–3 times faster than global average rates (Qi *et al.*, 2022). The change in the carbonate system in the Arctic is also resulting in areas becoming seasonally undersaturated with respect to aragonite at present day CO_2 concentrations (Terhaar *et al.*, 2021, Jiang *et al.*, 2023); Figure 14). Future projections for the Arctic suggest that even under the RCP1.9 scenario, large portions of the Arctic Ocean will become undersaturated with respect to aragonite and, as discussed above, will remain at those levels for century to millennia. Model projections from (Terhaar *et al.*, 2021) highlight that the response of aragonite saturation state in the Arctic Ocean is even more delayed against a reduction in atmospheric CO_2 concentrations (Figure 15).

The Southern Ocean is also at risk of increasing events of aragonite undersaturation (Hauri *et al.*, 2016), and similar projections for the various scenarios show that large areas of the Southern Ocean will become seasonally undersaturated with respect to aragonite at emissions scenarios equivalent to 2 °C or warmer (emissions scenario RCP4.5, Figure 14). As demonstrated here, the rate that of change in atmospheric CO_2 concentration has a large impact on the response of these systems and overshoot will therefore lead to a legacy shift in ocean acidification that will take centuries to recover from, especially in these vulnerable regions.

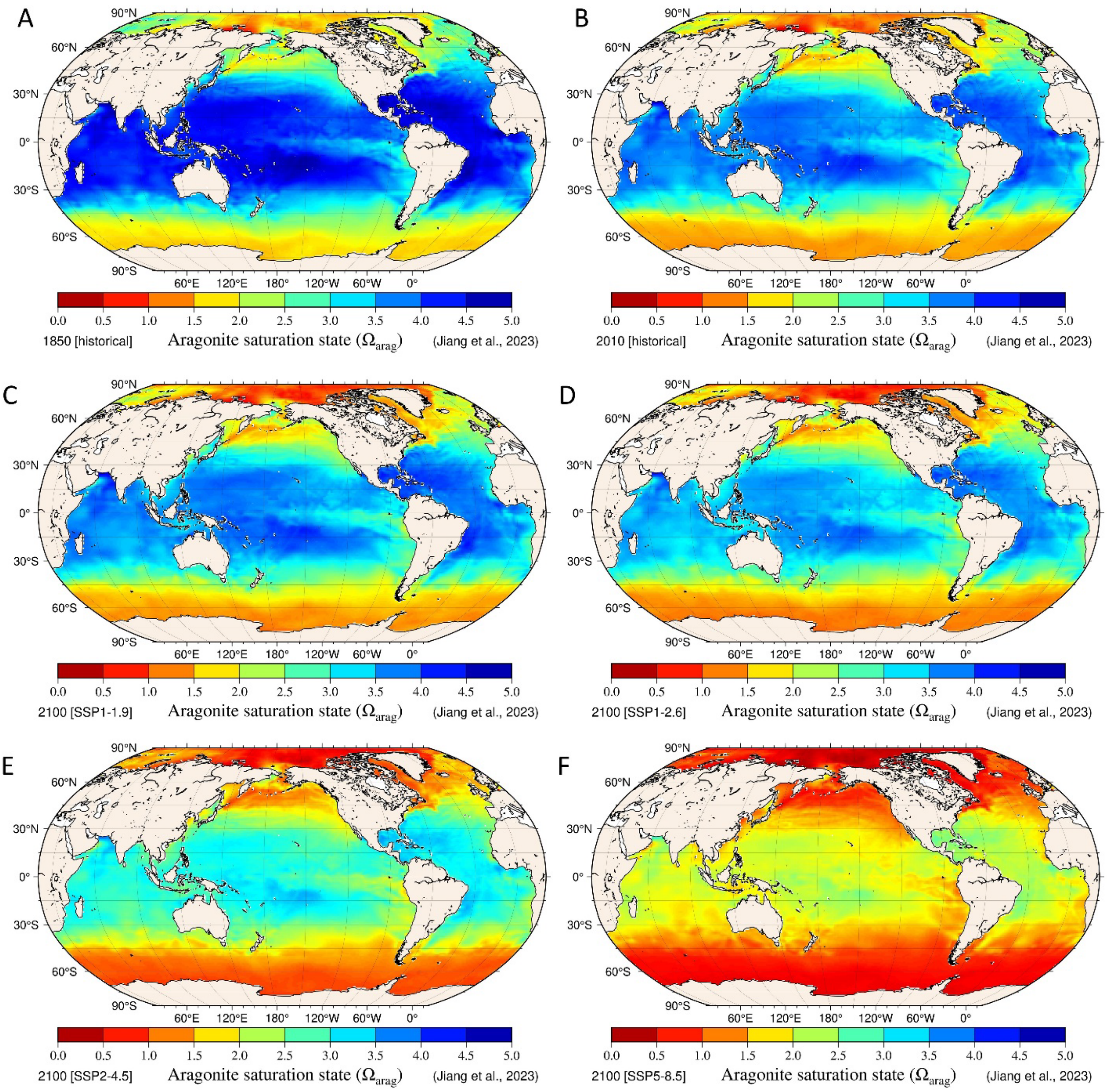


Figure 14. Surface ocean aragonite saturation state (CMIP6 inter-model median) in the decades around A) 1850, B) 2010, C) 2100 (SSP1-1.9), D) 2100 (SSP1-2.6), E) 2100 (SSP2-4.5), and F) 2100 (SSP5-8.5). SSP refers to Shared Socioeconomic Pathways. Produced online at: https://www.ncei.noaa.gov/access/ocean-carbon-acidification-data-system/synthesis/surface-oa-indicators.html from Jiang *et al.* (2023).

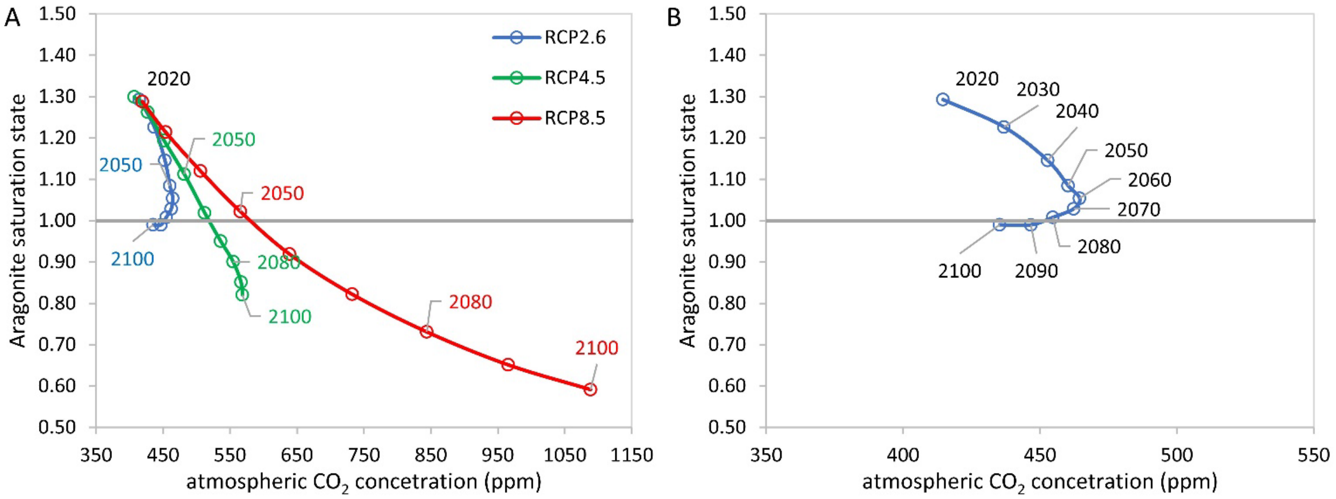


Figure 15. Relationship between the surface ocean aragonite saturation state and atmospheric CO_2 concentration. A) shows three emissions scenarios: RCP8.5 (red), RCP4.5 (green) and RCP2.6 (blue). B) shows just scenario RCP2.6. Also marked are the year at which the values are reached under each scenario. Undersaturation (mineral dissolution) occurs below 1. Data for aragonite saturation state are from Terhaar *et al.* (2021) and data for atmospheric CO_2 concentration is from IPCC (2019).

In addition to the polar oceans, certain regions in the lower latitudes have also been shown to be at risk of rapid acidification, especially in near shore and coastal regions (e.g. McGovern *et al.*, 2023) where there are confounding factors that can exacerbate ocean acidification, including river run-off and upwelling events (Feely *et al.*, 2008). Furthermore, bottom waters both on the shelf and in the deep ocean are also vulnerable to increasing exposure to aragonite undersaturation (Findlay *et al.*, 2022, McGovern *et al.*, 2023). For instance, regional models for the North West European shelf seas project that, under high-emissions scenarios bottom waters will become corrosive to aragonite. Episodic undersaturation events are projected to begin by 2030 in the RCP8.5 scenario, and by 2100, up to 90% of the North West European shelf seas may experience undersaturation for at least one month of each year (Findlay *et al.*, 2022, McGovern *et al.*, 2023). The probability of experiencing such levels of undersaturation in terms of extent and duration are significantly reduced in lower emissions scenarios.

5.5 Coral

5.5.1 Introduction

The warm water coral reef ecosystems are highly diverse, supporting livelihoods and food security of millions of people directly and indirectly. The ecosystem services they provide include provisioning (fishery and building materials), regulating (coastal protection, water quality, biogeochemical cycling), cultural (cultural values, social cohesion, tourism and recreation) and supporting (habitat and biodiversity benefit) services (e.g. Woodhead *et al.*, 2019). The coral reef ecosystems are one of the most vulnerable marine ecosystems to climate change impacts (high confidence, IPCC (2022a), AR6 WGII), while also being impacted by other anthropogenic factors such as overfishing, sedimentation (driven, for example by land use change) and habitat destruction.

5.5.2 Vulnerability of the warm water corals to climate change impacts

When the water temperature exceeds a certain threshold, the coral expels their symbiotic algae (coral bleaching), which may become irreversible; the likelihood of recovery decreases with the severity, duration and frequency of the bleaching events (e.g. Frieler *et al.*, 2013). Ocean acidification (another consequence of enhanced atmospheric CO_2 levels) exacerbates coral bleaching, reducing the growth of coral skeletons (Hoegh-Guldberg *et al.*, 2007). Although the coral bleaching response to high temperatures is localised, the forcing mechanisms (marine heatwaves) triggering this response are often large-scale, leading to a coherent sub-continental scale response (e.g. large scale bleaching of the Great Barrier Reef, e.g. Hughes *et al.* (2018)).

5.5.3 Warm water corals as a tipping element

Warm water coral reef ecosystems constitute a tipping element (high confidence, Armstrong McKay *et al.* (2022)). Warm water corals fall into the category of regional impact tipping elements, characterised by a substantial societal impact (affecting more than 100 million people) but limited feedback on the Earth system via changes in ocean productivity and biogeochemical cycling. Armstrong McKay *et al.* (2022) estimate that the threshold of reaching this tipping point is ~1.5 °C (1 to 2 °C) (high confidence), occurring at timescales of ~10 years (medium confidence). The disappearance of coral reefs would have widespread and severe ecological, social, and economic impacts. A large-scale coral die-off will remove one of the most biodiverse marine ecosystems, impacting wider food webs and marine biogeochemistry, with millions of people, mostly in developing countries, disrupting their main source of food and income (e.g. Armstrong McKay *et al.* (2022)).

5.5.4 Observed impacts of climate change on the warm water corals

The IPCC AR6 WGII (IPCC, 2022a) provides the following summary of already observed climate change impacts on the shallow water corals: "*Heat stress and mass bleaching events caused decreases in live coral cover (virtually certain), loss of sensitive species (extremely likely), vulnerability to disease (extremely likely) and declines in coral recruitment in the tropics (medium confidence)*". The first major mass coral bleaching event in 1998 killed about 8% of the world's coral (Souter *et al.*, 2021). In the absence of large-scale disturbances, the global average coral cover recovered to pre-1998 levels within a decade, however between 2009 and 2018, there was a progressive loss of about 14% of the coral from the world's coral reefs. This was primarily due to recurring large-scale coral bleaching events (marine heatwaves), combined with other anthropogenic pressures such as coastal development and habitat destruction, pollution, unsustainable fishing and tropical storms (Souter *et al.*, 2021). However, the reefs in East Asia's Coral Triangle, which contains almost 30% of the world's coral reefs, had more coral in 2019 than they did three decades ago and were less impacted by thermal disturbances, until the most recent events in 2010 and 2016.

5.5.5 Projected changes

IPCC AR6 WGII (IPCC, 2022a) states that "Warm-water coral reefs face near-term threats to their survival". These corals are in decline due to increasing frequency and duration of marine heatwaves (very high confidence, (IPCC, 2022a) AR6 WGII). Coral reefs are under threat of transitioning to net erosion with >1.5 ºC of global warming (high confidence), with impacts expected to occur fastest in the Atlantic Ocean. IPCC AR6 WGII (IPCC, 2022a) also notes that the effectiveness of conservation efforts to sustain living coral area, coral diversity, and reef growth is limited for the majority of the world's reefs with >1.5ºC of global warming (high confidence).

The IPCC report on Warming of 1.5 °C (IPCC (2018), Summary for Policy Makers) concludes with high confidence that coral reefs are projected to decline by a further 70–90% at 1.5 °C (high confidence) with larger losses (>99%) at 2 ºC (very high confidence). The report also suggests (high confidence) that the transition from high to very high risk for the coral reefs is now located between 1.5 °C and 2 °C of global warming as opposed to at 2.6 °C of global warming in AR5, owing to new and multiple lines of evidence for changing risks for coral reefs.

6. Cryosphere

Six of nine major global tipping elements relate to the Polar Regions (Lenton, 2020), and they are all ultimately based on the fundamental and often profound environmental changes that come about through the phase change of thawing, from solid, reflective and potentially insulating ice and snow into fluid, transparent, heat-conducting and biologically vital water. Despite their potential importance, these tipping elements affect polar systems that are almost universally less well observed than comparable systems at lower latitudes and that are experiencing some of the highest rates of warming on Earth (IPCC, 2019).

This review considers which tipping points may be crossed with warming of between 1.5 and 1.9 °C in coming decades, and which of these are reversible with post 'overshoot' cooling to 1.5 °C by 2100. This implies a focus on tipping thresholds that are already quite close to being reached, and which have either long 'effective timescales' (centuries-millennia) compared to the overshoot time, so they can be avoided, or short timescales (years-decades) so they can be reversed.

Geographically, the focus is on the Arctic and Antarctic (and in some cases, adjacent systems dependent on them), plus 'mountain glaciers'. Specifically, this review identifies from the literature and assesses the following potential tipping behaviour: acceleration of ice loss from the ice sheets of Greenland, West Antarctica and East Antarctica; reduction in area of sea ice in the Arctic; permafrost thawing; slowdown of Atlantic circulation; and melting of mountain glaciers outside Greenland and Antarctica.

6.1 Arctic

6.1.1 Loss of the Greenland Ice Sheet

In recent decades, the Greenland Ice Sheet has experienced strong, accelerating loss due to the acceleration of outlet glaciers and an increase in surface melt, with the latter process increasingly dominant in determining the rate of loss (IPCC, 2019), in particular during increasingly extreme summer warm events (Slater *et al.*, 2021).

Projected losses over the 21st century have been expected to be linearly related to temperature (Figure 16) (Gregory *et al.*, 2020, Edwards *et al.*, 2021). As of IPCC AR6 (IPCC, 2021), negative feedbacks (increased snowfall) resulting from warming were expected to dominate this century over positive feedbacks (increased melt as the ice sheet surface lowers) (Gregory *et al.*, 2020), with irreversible retreat requiring a sustained 2 to 3 °C warming for >2000 years (Gregory *et al.*, 2020). This would imply no twenty-first century tipping point and losses that are reversible on decadal timescales (Gregory *et al.*, 2020, Edwards *et al.*, 2021) for the overshoot pathways developed in this study.

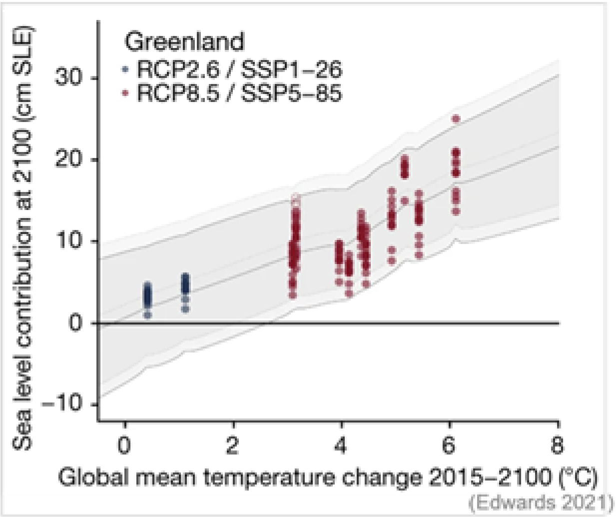


Figure 16. Projected sea-level contributions from the Greenland Ice Sheet as a function of temperature anomaly (Edwards *et al.*, 2021). Reproduced with permission from Springer Nature.

However, a more recent assessment (Armstrong McKay *et al.*, 2022) revises the tipping threshold downwards to 1.5 °C (0.8 to 3 °C), which now falls within the range of overshoot pathway peak temperatures (1.6 to 1.9 °C). This downward revision is ascribed *high confidence* based on multiple consistent, published estimates from different evidence bases (modelling and palaeo-records) (Armstrong McKay *et al.*, 2022). The ice sheet response timescale is so long (10 kyr, with a range of 1–15 kyr), however, that tipping behaviour would be avoidable with post-overshoot cooling to 1.5 °C by 2100, provided that the uncertain Greenland tipping threshold itself does in fact lie in the upper end of the estimated range (i.e. 1.5 to 3 °C). If the threshold instead lies below 1.5 °C (i.e. 0.8 to 1.5 °C), then even the NO pathway would likely lead to committed loss of the Greenland Ice Sheet, and indeed this threshold may have already been passed. Given the above, there is *medium agreement and medium evidence* that a tipping point in Greenland ice loss will be crossed with warming of between 1.5 and 1.9 °C in the coming decades, and that this is avoidable or reversible with post-overshoot cooling to 1.5 °C by 2100.

Greenland tipping could trigger multiple global cascades via the Atlantic Circulation (AMOC) leading to, for example, Amazon dieback and West Antarctic collapse (Wunderling *et al.*, 2021). This is unlikely this century (medium confidence, IPCC (2021); WGI TS.3, TS.9)) and under the overshoot pathways created in this study, however, because the best estimates of warming needed to tip AMOC of 3.5 to 6.0 °C (Wunderling *et al.*, 2021) or ~4 °C (range 1.4 to 8.0 °C) (Armstrong McKay *et al.*, 2022) are greater than VHO pathway warming and because several estimates of the AMOC tipping time (at about 300 years) are also slow compared to the timescales of the VHO overshoot (Ritchie *et al.*, 2021, Wunderling *et al.*, 2021, Kim *et al.*, 2022). A timescale of 50 years or shorter has also been suggested however (Armstrong McKay *et al.*, 2022).

6.1.2 Loss of Arctic Sea ice

Over recent decades, Arctic sea ice has experienced strong accelerating loss with an overall trend linearly related to temperature IPCC (2021) (Figure 17), but within which, most loss occurs during short-lived but increasingly extreme weather events (Walsh *et al.*, 2020). Furthermore, the response of the sea ice system to variable forcing exhibits some evidence of ‘flickering’, potentially indicative of an incipient tip (Overland, 2020).

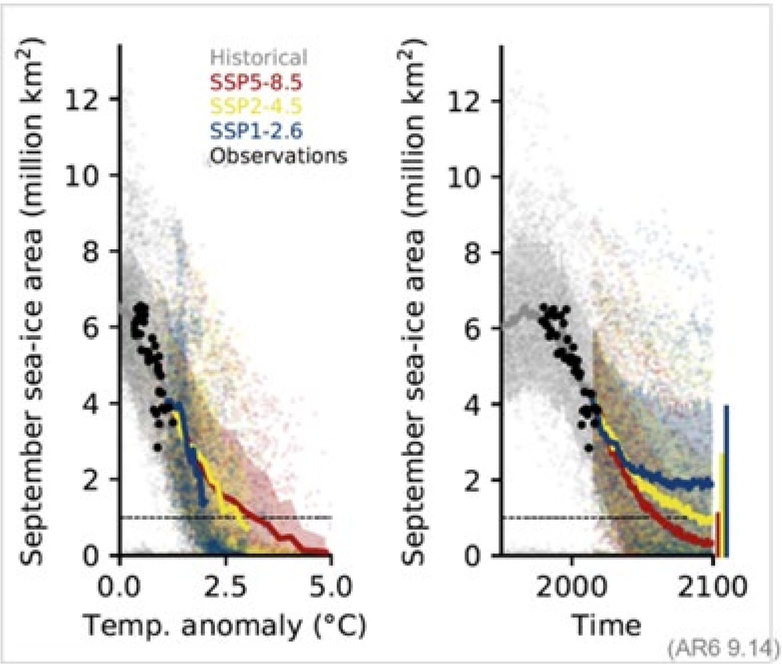


Figure 17. Observed and predicted loss of Arctic Sea ice by SSP scenario, temperature anomaly and date, from IPCC AR6 WGI 9.14 (IPCC, 2021). Arctic ice is considered 'lost' when its September area falls below 1 million km^2.

Perennial sea ice in the Arctic is *likely* to be lost under sustained warming of >1.5 °C, and the first ice-free Arctic summers are predicted by 2050 under all IPCC AR6 scenarios (IPCC, 2021). However, negative feedbacks (winter cooling) are expected to dominate over positive feedbacks (ice-albedo, storm break-up), which implies that the Arctic summer sea ice system as a whole exhibits no hysteresis and no tipping point, with losses reversible 'within years to decades' under a cooling climate (IPCC, 2018, 2021).

A more recent analysis (Armstrong McKay *et al.*, 2022) does, however, identify a regional-scale exception to this picture of relative stability. The Barents Sea ice system exhibits some evidence of a positive feedback through an influx of warm Atlantic waters induced by ice loss (*low confidence*), based on two models published in 2015. This tip could occur with ~1.6 °C (1.5 to 1.7 °C) warming (*medium confidence*), and on a timescale as short as 25 years (*low confidence*), as a regional exception to the broader reversibility of Arctic summer sea ice. For winter Arctic Sea ice, potential ice tipping thresholds continue to lie beyond changes covered by the overshoot pathways created in this study.

Given the lack of a net positive feedback mechanism for the broader Arctic sea-ice system, we assess that this system is not prone to tipping in the VHO pathway *(high agreement, medium evidence).* In contrast, the sea ice system in the Barents Sea may cross a self-sustaining tipping threshold.

Even without sea-ice tipping, Arctic food webs are vulnerable to irreversible tipping triggered by near-term sea ice loss, in a cascade effect. Specifically, the Pacific Arctic marine food web could be 'fundamentally reconfigured' due to sea ice loss over next 20 years (Huntington *et al.*, 2020, Overland, 2020, Walsh *et al.*, 2020), while the distribution of some sea-ice dependent Atlantic marine species has failed to recover following extreme events (Walsh *et al.*, 2020). In addition, 'major reproductive failure' has been reported following an extreme snowfall in a Greenland terrestrial ecosystem, and more such extreme snowfalls are predicted with sea ice loss (Schmidt *et al.*, 2019).

6.1.3 Permafrost thaw

Permafrost underlies around a quarter of Northern Hemisphere land and stores around twice as much carbon as the atmosphere. There is *very high confidence* that permafrost temperatures have increased, and widespread decreases in Arctic permafrost are projected this century (*very high confidence*) (IPCC, 2019). Loss of permafrost carbon due to thaw is irreversible at centennial time scales (*high confidence*) (IPCC (2021), SPM B.5.2), and permafrost loss can invoke local positive thaw feedbacks through changes in surface albedo and insulation (and potentially through heat-generating 'compost' decomposition of organic matter), and permafrost carbon losses would also constitute a positive feedback to atmospheric warming. However, there is only *medium evidence* and *low agreement* that recent permafrost warming is currently causing northern permafrost regions to release additional methane and carbon dioxide, and permafrost sensitivity to atmospheric warming is poorly understood (IPCC, 2019). As a result, feedbacks between atmospheric warming and carbon flux from permafrost to the atmosphere are not yet fully included in climate and Earth system models (including the UKESM), and "there is *low confidence* on the timing, magnitude and linearity of the permafrost-climate feedback" (IPCC, 2021). This precluded an assessment of permafrost tipping for the VHO pathway.

A more recent analysis has, however, proposed a potential tipping point in a particular mode of permafrost loss acting at a 'regional impact' (but not global) scale (Armstrong McKay *et al.*, 2022). This mode of loss is termed Permafrost Abrupt Thaw (PFAT) (as opposed to Permafrost Gradual Thaw which is linear with temperature, or Permafrost Tipping Point which would be a process global in scale). PFAT involves localised tipping mechanisms, including thermokarst lake formation, gulley erosion, vegetation-albedo feedbacks and ground slumping, with localized feedbacks relating to lower surface albedo and lower insulation of the sub-surface. Although these mechanisms act locally and are subject to local conditions, they could occur near synchronously on a subcontinental scale under widespread warming. The Permafrost Abrupt Thaw threshold of 1.5 °C (1 to 2.3 °C) and globally-integrated timescale of 200 years (100–300 years, locally very abrupt at ~10 years) now place this regional impact within the range of the VHO pathway. All pathways could exceed this temperature threshold and, given the response time, there is potential to avoid regional-scale tipping with a rapid subsequent temperature decrease. However, the uncertain but low threshold (1 to 2.3 °C) could imply that the post-overshoot temperature still exceeds the threshold, leading to committed regional permafrost tipping.

There is *low agreement and medium evidence* that a regional (but not global) tipping point in permafrost thaw will be crossed with warming of between 1.5 and 1.9 °C in coming decades, and that this is avoidable or reversible on the regional (but not local) scale with post-overshoot cooling to 1.5 °C by 2100.

6.2 Antarctic

6.2.1 Loss of Antarctic ice sheets

There is *very high confidence* that the West Antarctic ice sheet has experienced strong and accelerating loss due to the speed up of major coastal outlet glaciers in recent decades (IPCC, 2019). This has been driven by the sub-surface, ocean-driven melting and thinning of fringing ice shelves that has altered the delicate force balance controlling ice flow as it reaches the Southern Ocean (IPCC, 2019). On a smaller scale, glaciers on the Antarctic Peninsula have also accelerated sharply due to the abrupt collapse and loss of ice shelves, primarily due to unusually strong summer surface melting of these shelves (IPCC, 2019). The ice-dynamic perturbation resulting from ice shelf thinning or collapse, forced either by ocean or atmospheric warming at the ice shelf interface, can potentially trigger a self-sustaining acceleration of glacier flow and retreat of the grounded ice sheet through the well-established Marine Ice Sheet Instability (MISI) or the theoretical Marine Ice Cliff Instability (MICI) (IPCC, 2019). Most of the West and large parts of the East Antarctic ice sheets are potentially vulnerable to collapse through MISI and/or MICI. Of these, the MICI mechanism of ice shelf collapse has the potential for rapid ice-dynamic tipping (years to decades) that could be triggered if a threshold for summer surface melting is crossed, with positive albedo and firn-densification melt feedbacks (IPCC, 2019).

As of AR6, the dominant community view was for major West Antarctic loss through MISI with 2 to 3 °C warming, and partial East Antarctic loss at 3 °C warming, leading to a sea level contribution of order 0.1 m by 2100 (Figure 18) and ultimately 6–12 m after several millennia (IPCC, 2021). However, the sensitivity of Antarctic glacier/ice shelf response is seen as being characterized by ‘deep uncertainty’, and indeed the threshold for irreversible retreat (under the

MISI mechanism) on key West Antarctic glaciers may already have been crossed (Joughin *et al.*, 2014, Rignot *et al.*, 2014). Ice loss is seen as crucially dependent on the behaviour of individual ice shelves and outlet glacier systems, and potentially subject to the hypothesised, but not yet observed, MICI collapse mechanism (DeConto *et al.*, 2021).

A marked MICI tipping point has been proposed in response to an overshoot pathway of 3 °C warming in the 21st century, mitigated by carbon dioxide reduction (CDR) that is delayed until 2070, prompting surface-melt-driven collapse of the Thwaites Ice Shelf (West Antarctica) and a runaway MICI retreat, and ultimately generating 2–5 m of sea level rise (DeConto *et al.*, 2021) (Figure 19). Some support for this pathway comes from predictions that extreme ice shelf surface melt events will increase (Feron *et al.*, 2021, Turner *et al.*, 2021), that melt could double by 2050 with 1.8 °C warming (though mostly on the Antarctic Peninsula) (Trusel *et al.*, 2015, Pattyn *et al.*, 2018), and that some shelves could collapse by 2070 under sustained warming of 1.5 to 2 °C above present (Pattyn *et al.*, 2018, Rintoul *et al.*, 2018).

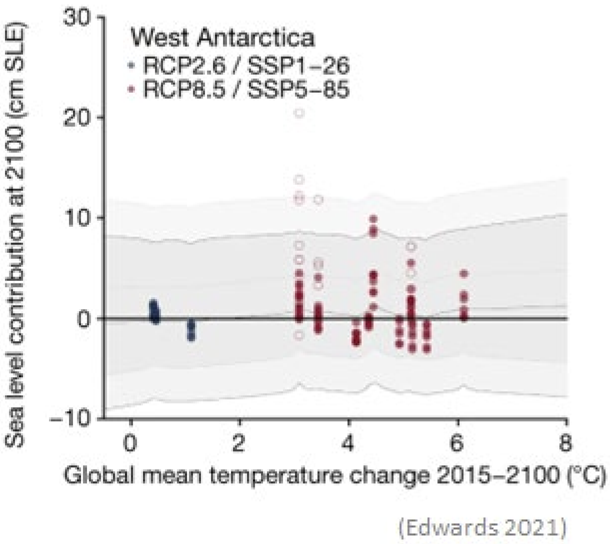


Figure 18. An ensemble of model outputs for 21st century Antarctic sea-level contribution in response to global mean temperature change (from Edwards *et al.* (2021)). Reproduced with permission from Springer Nature.

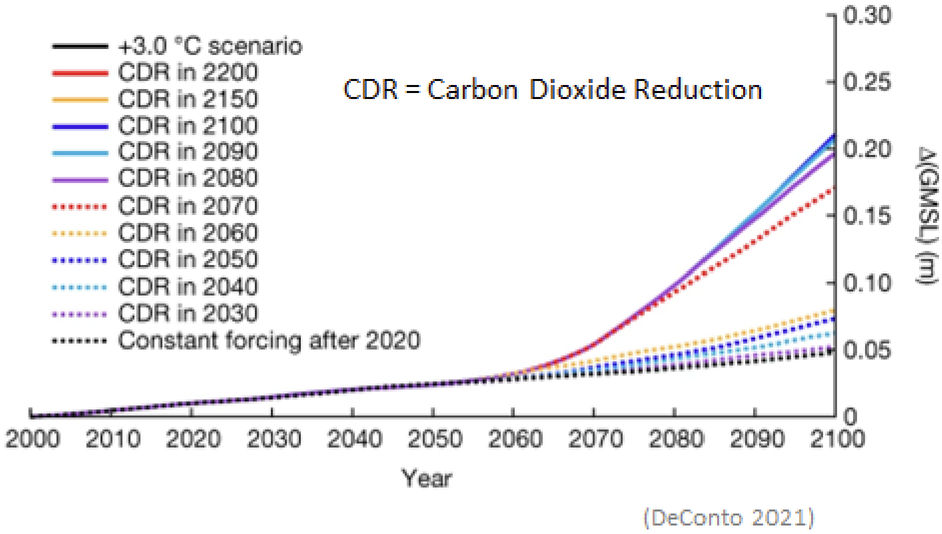


Figure 19. Proposed ice loss rates under an 'overshoot' 3 °C warming pathway mitigated by carbon dioxide reduction (CDR) beginning at some point in the 21st or 22nd century. Markedly higher rates are apparent for CDR beginning in 2070 or later, indicating sensitivity to tipping within this pathway (from DeConto *et al.* (2021)). Reproduced with permission from Springer Nature.

A more recent analysis (Armstrong McKay *et al.*, 2022) revises down the AR6 West Antarctic tipping point to 1.5 °C (1–3 °C), with a timescale ~2 kyr, (or a shorter 500 yr for high forcing and/or MICI), or up to 13 kyr if the threshold is only 'marginally transgressed'. Other studies concur that the response time for key glaciers (centuries to millennia) is much longer than the forcing timescale (Rosier *et al.*, 2021, Reese *et al.*, 2023) and so tipping is potentially reversible with post-overshoot cooling even if the threshold has been or is closed to being crossed under contemporary or near-future forcing.

In conclusion, under sustained current-climate forcing or for all overshoot pathways developed in Annex 1, key West Antarctic glaciers may cross or may already have crossed a tipping point (*low agreement, medium evidence*). The potential loss of these key glaciers would imply ultimate loss of the full West Antarctic Ice Sheet (but not the East Antarctic Ice Sheet), and ultimately 3 m of sea level rise (Feldmann and Levermann, 2015). However, the response timescale is long and removal or capping of forcing in the 21st century could be sufficient to avoid tipping *(medium agreement, medium evidence).* For the VHO pathway, with overshoot warming dropping to 1.5 °C by 2100, clearly the success of such a 21st century cap on forcing in preventing ice sheet collapse depends on where the (uncertain) tipping threshold actually lies: the threshold must lie above a warming of 1.5 °C for these pathways to prevent the tipping point being crossed.

6.3 Mountain Glaciers

The world's mountain glaciers have been losing mass in most regions (*very high confidence*) and at an accelerating rate for several decades, broadly in line with rising temperatures that both increase melt rates and decrease accumulation rates (IPCC, 2019). There is strong agreement that losses will continue over coming decades to centuries, with peak meltwater production around the middle of this century which will then decline due to diminishing ice reserves (rather than reduced forcing).

Mountain glaciers have been assessed with *medium confidence* as having a 'regional impact tipping element' threshold at 2 °C (1.5 to 3 °C), for >50% glacier ice loss globally over ~200 years, though local and regional timescales can be as short as decades (Armstrong McKay *et al.*, 2022). This is in general agreement with the AR6 WGI assessment (made with *low confidence*) that a 2–3 °C warming will generate an equivalent loss, supported by several regional and global model studies (IPCC, 2021).

No global self-reinforcing feedback mechanism exists but glaciers individually are strongly sensitive to a positive albedo feedback related to thinner and therefore short-lived snowpack (as less snow accumulates because more precipitation falls as rain, more sensible heat is delivered by this rain, and glacier albedo is 'reset' (to a high value) less often by fresh snowfall (Johnson and Rupper, 2020)). The strength of this effect is regionally variable (depending on glacier climate regime), being particularly strong (accounting for up to 80% of increased melt resulting from a 1 °C warming) in the summer-accumulation regimes of High Mountain Asia (Johnson and Rupper, 2020). Other positive feedbacks of albedo, heat-conduction and calving exist, associated with the formation of surface melt ponds and proglacial lakes, counteracted to some extent by negative feedbacks associated with the accumulation and thickening of a surface debris layer in areas with debris-covered glaciers, whose prevalence and extent also varies regionally dependent on regional histories of glacial erosion. These mechanisms and further uncertainties associated with the size of the remaining glacier ice reserve are not discussed or quantified by Armstrong McKay *et al.* (2022), however, and it is also not clear whether implied net positive feedbacks are sufficiently strong as to confer irreversibility in the context of the VHO pathway. Post-overshoot cooling would in principle enable glaciers to stabilize or reform on timescales of decades to centuries wherever winter snow packs were able to survive through subsequent summers.

Given the temperature thresholds that overlap the peak temperatures of the three overshoot pathways developed in this study, and the short (decades to two centuries) response timescales described above, we assess the population of mountain glaciers on regional scales as potentially susceptible to tipping in an overshoot of any magnitude (*medium agreement, medium evidence*). Given the lack of information, uncertainties and regional variability in feedback mechanisms, we assess such tipping as being potentially avoidable and probably reversible with subsequent cooling for each overshoot pathway (*low agreement, limited evidence*).

7. Conclusions

Tipping points in the climate and Earth system refer to thresholds that can occur as a consequence of human induced climate change, and that lead to changes that are abrupt, high-impact, and often irreversible. The focus of this annex is on those tipping points or cascade of tipping points, and high impact events that could or will occur in the overshoot pathways under investigation. Specifically, which tipping points may be crossed with warming of around 1.5 to 2.5 °C or which are reversible with 'overshoot' cooling after a few decades?

We have reviewed the literature for the evidence on tipping points, high impact events and hysteresis in the climate and natural systems, since and including the IPCC sixth assessment reports. We also include new results for fire based on the bespoke UKESM scenario runs undertaken as part of this study.

Observations indicate that parts of the West Antarctic ice sheet may have already passed a tipping point. There are early indications about other tipping elements: the Greenland ice sheet, the Amazon rainforest and the Atlantic Meridional Overturning Circulation. There is an ongoing decline of the AMOC, which will not involve an abrupt collapse during the 21^{st} century.

Although the temperature threshold of some tipping points is lower than previously considered, the thresholds of many tipping elements are still above 2.5 °C of warming. Of interest are the tipping elements with temperature thresholds between 1.5–2.0 °C of warming, which include: warm water corals, boreal permafrost, sea ice in the Barents Sea, Labrador-Irminger seas/Subpolar gyre convection, and mountain glaciers. Sensitive regions, such as the Arctic, will pass critical chemical thresholds for ocean acidification, even under 1.5 °C warming.

Overshoots not exceeding 2 °C may still keep warming below the temperature thresholds of many tipping points. Thus, it may be possible to safely overshoot tipping points in slower elements such as ice sheets, but the allowable overshoot times need further research. Globally, the risk of biodiversity loss is generally moderate with no overshoot but at the transition between high and very high with overshoot to 2 °C of warming. However, there are regions (Africa and Arctic Sea ice ecosystems), where the risks are higher (high with no overshoot and very high with overshoot).

This is an active area of research. Further work on tipping points is part of the NERC National Capability project TerraFIRMA (Future Impacts, Risks and Mitigation Actions in a changing Earth system), involving all the NERC Research Centres in partnership with the Met Office. The TerraFIRMA project has a focus on 3 tipping systems: Antarctic ice sheets, Marine productivity and ecosystems and Tropical forests. Working with other NERC National Capability projects (e.g. BIOPOLE: Biogeochemical processes and ecosystem function in a changing polar system; CANARI: Climate change in the Arctic–North Atlantic region and impact on the UK) should enable assessment of the risk of rapid change in phenomena such as; permafrost, Arctic Sea ice, the Atlantic meridional overturning circulation (AMOC) and monsoons.

8. References

Anglada-Ortiz, G., Zamelczyk, K., Meilland, J., Ziveri, P. *et al.* (2021) Planktic Foraminiferal and Pteropod Contributions to Carbon Dynamics in the Arctic Ocean (North Svalbard Margin). *Frontiers in Marine Science,* 8. https://www.frontiersin.org/articles/10.3389/fmars.2021.661158/full

Archibald, S., Lehmann, C. E. R., Belcher, C. M., Bond, W. J. *et al.* (2018) Biological and geophysical feedbacks with fire in the Earth system. *Environmental Research Letters,* 13**,** 033003. https://dx.doi.org/10.1088/1748-9326/aa9ead

Armstrong McKay, D. I., Staal, A., Abrams, J. F., Winkelmann, R. *et al.* (2022) Exceeding 1.5°C global warming could trigger multiple climate tipping points. *Science,* 377**,** eabn7950. https://doi.org/10.1126/science.abn7950

Barton, A., Hales, B., Waldbusser, G. G., Langdon, C. and Feely, R. A. (2012) The Pacific oyster, Crassostrea gigas, shows negative correlation to naturally elevated carbon dioxide levels: Implications for near-term ocean acidification effects. *Limnology and Oceanography,* 57**,** 698-710. https://doi.org/10.4319/lo.2012.57.3.0698

Barton, A., Waldbusser, G. G., Feely, R. A., Weisberg, S. B. *et al.* (2015) Impacts of coastal acidification on the Pacific Northwest shellfish industry and adaptation strategies implemented in response. *Oceanography,* 28**,** 146-159. https://doi.org/10.5670/oceanog.2015.38

Bates, N. R., Astor, Y. M., Church, M. J., Currie, K. *et al.* (2014) A time-series view of changing surface ocean chemistry due to ocean uptake of anthropogenic CO2 and ocean acidification. *Oceanography,* 27**,** 126-141. https://doi.org/10.5670/oceanog.2014.16

Bednaršek, N., Calosi, P., Feely, R. A., Ambrose, R. *et al.* (2021a) Synthesis of Thresholds of Ocean Acidification Impacts on Echinoderms. *Frontiers in Marine Science,* 8. https://www.frontiersin.org/articles/10.3389/fmars.2021.602601

Bednaršek, N., Feely, R. A., Beck, M. W., Alin, S. R. *et al.* (2020) Exoskeleton dissolution with mechanoreceptor damage in larval Dungeness crab related to severity of present-day ocean acidification vertical gradients. *Science of The Total Environment,* 716**,** 136610. https://www.sciencedirect.com/science/article/pii/S0048969720301200

Bednaršek, N., Feely, R. A., Howes, E. L., Hunt, B. P. V. *et al.* (2019) Systematic Review and Meta-Analysis Toward Synthesis of Thresholds of Ocean Acidification Impacts on Calcifying Pteropods and Interactions With Warming. *Frontiers in Marine Science,* 6. https://www.frontiersin.org/articles/10.3389/fmars.2019.00227

Bednaršek, N., Newton, J. A., Beck, M. W., Alin, S. R. *et al.* (2021b) Severe biological effects under present-day estuarine acidification in the seasonally variable Salish Sea. *Science of The Total Environment,* 765**,** 142689. https://www.sciencedirect.com/science/article/pii/S0048969720362185

Bednaršek, N., Tarling, G. A., Bakker, D. C. E., Fielding, S. *et al.* (2012) Extensive dissolution of live pteropods in the Southern Ocean. *Nature Geoscience,* 5**,** 881-885. https://doi.org/10.1038/ngeo1635

Bellerby, R. G. J. (2017) Ocean acidification without borders. *Nature Climate Change,* 7**,** 241-242. https://doi.org/10.1038/nclimate3247

Berg, A., Lintner, B. R., Findell, K. L., Malyshev, S. *et al.* (2014) Impact of Soil Moisture–Atmosphere Interactions on Surface Temperature Distribution. *Journal of Climate,* 27**,** 7976-7993. https://journals.ametsoc.org/view/journals/clim/27/21/jcli-d-13-00591.1.xml

Bistinas, I., Harrison, S. P., Prentice, I. C. and Pereira, J. M. C. (2014) Causal relationships versus emergent patterns in the global controls of fire frequency. *Biogeosciences,* 11**,** 5087-5101. https://bg.copernicus.org/articles/11/5087/2014/

Blackford, J. C. and Gilbert, F. J. (2007) pH variability and CO2 induced acidification in the North Sea. *Journal of Marine Systems,* 64**,** 229-241. https://www.sciencedirect.com/science/article/pii/S0924796306001163

Bowman, D. M., Balch, J. K., Artaxo, P., Bond, W. J. *et al.* (2009) Fire in the Earth system. *Science,* 324**,** 481-4.

Burkett, V. R., Wilcox, D. A., Stottlemyer, R., Barrow, W. *et al.* (2005) Nonlinear dynamics in ecosystem response to climatic change: Case studies and policy implications. *Ecological Complexity,* 2**,** 357-394. https://www.sciencedirect.com/science/article/pii/S1476945X05000334

Burton, C., Kelley, D. I., Burke, E., Mathison, C. *et al.* (submitted) Fire weakens land carbon sinks before 1.5 °C.

Burton, C., Kelley, D. I., Jones, C. D., Betts, R. A. *et al.* (2022) South American fires and their impacts on ecosystems increase with continued emissions. *Climate Resilience and Sustainability,* 1**,** e8. https://doi.org/10.1002/cli2.8

Caldeira, K. and Wickett, M. E. (2003) Anthropogenic carbon and ocean pH. *Nature,* 425**,** 365-365. https://doi.org/10.1038/425365a

Church, J. A., P.U. Clark, Cazenave, A., Gregory, J. M. *et al.* (2013) *Sea Level Change.* Cambridge, United Kingdom and New York, NY, US: C. U. Press. https://www.ipcc.ch/report/ar5/wg1/

Costello, M., Vale, M., Kiessling, W., Maharaj, S. *et al.* (2022) Cross-Chapter Paper 1: Biodiversity Hotspots. In: Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC). 2123-2161. https://www.ipcc.ch/report/ar6/wg2/chapter/ccp1/

DeConto, R. M., Pollard, D., Alley, R. B., Velicogna, I. *et al.* (2021) The Paris Climate Agreement and future sea-level rise from Antarctica. *Nature,* 593**,** 83-89. https://doi.org/10.1038/s41586-021-03427-0

Drüke, M., Sakschewski, B., von Bloh, W., Billing, M. *et al.* (2023) Fire may prevent future Amazon forest recovery after large-scale deforestation. *Communications Earth & Environment,* 4**,** 248. https://doi.org/10.1038/s43247-023-00911-5

Edwards, T. L., Nowicki, S., Marzeion, B., Hock, R. *et al.* (2021) Projected land ice contributions to twenty-first-century sea level rise. *Nature,* 593**,** 74-82. https://doi.org/10.1038/s41586-021-03302-y

Feely, R. A., Sabine, C. L., Hernandez-Ayon, J. M., Ianson, D. and Hales, B. (2008) Evidence for Upwelling of Corrosive "Acidified" Water onto the Continental Shelf. *Science,* 320**,** 1490-1492. https://www.science.org/doi/abs/10.1126/science.1155676

Feldmann, J. and Levermann, A. (2015) Collapse of the West Antarctic Ice Sheet after local destabilization of the Amundsen Basin. *Proceedings of the National Academy of Sciences,* 112**,** 14191-14196. https://doi.org/10.1073/pnas.1512482112

Feron, S., Cordero, R. R., Damiani, A., Malhotra, A. *et al.* (2021) Warming events projected to become more frequent and last longer across Antarctica. *Scientific Reports,* 11**,** 19564. https://doi.org/10.1038/s41598-021-98619-z

Findlay, H. S., Artoli, Y., Birchenough, S. N. R., Hartman, S. *et al.* (2022) Ocean Acidification around the UK and Ireland. *MCCIP Science Review*. https://doi.org/10.48670/moi-00224

Findlay, H. S. and Turley, C. (2021) Chapter 13 - Ocean acidification and climate change. *In* T. M. Letcher (ed.) *Climate Change (Third Edition).* Elsevier, 251-279. https://www.sciencedirect.com/science/article/pii/B978012821575300013X

Forkel, M., Dorigo, W., Lasslop, G., Chuvieco, E. *et al.* (2019) Recent global and regional trends in burned area and their compensating environmental controls. *Environmental Research Communications,* 1**,** 051005. https://dx.doi.org/10.1088/2515-7620/ab25d2

Friedlingstein, P., Jones, M. W., O'Sullivan, M., Andrew, R. M. *et al.* (2022) Global Carbon Budget 2021. *Earth Syst. Sci. Data,* 14**,** 1917-2005. https://essd.copernicus.org/articles/14/1917/2022/

Frieler, K., Meinshausen, M., Golly, A., Mengel, M. *et al.* (2013) Limiting global warming to 2 °C is unlikely to save most coral reefs. *Nature Climate Change,* 3**,** 165-170. https://doi.org/10.1038/nclimate1674

Garbe, J., Albrecht, T., Levermann, A., Donges, J. F. and Winkelmann, R. (2020) The hysteresis of the Antarctic Ice Sheet. *Nature,* 585**,** 538-544. https://doi.org/10.1038/s41586-020-2727-5

Gimenez, I., Waldbusser, G. G. and Hales, B. (2018) Ocean acidification stress index for shellfish (OASIS): Linking Pacific oyster larval survival and exposure to variable carbonate chemistry regimes. *Elementa: Science of the Anthropocene,* 6. https://doi.org/10.1525/elementa.306

Gitay, H., Brown, S., Easterling, W. and Jallow, B. (2001) *Ecosystems and their goods and services.* : C. U. Press. https://www.ipcc.ch/report/ar3/wg2/

Gregory, J. M., George, S. E. and Smith, R. S. (2020) Large and irreversible future decline of the Greenland ice sheet. *The Cryosphere,* 14**,** 4299-4322. https://tc.copernicus.org/articles/14/4299/2020/

Hauri, C., Friedrich, T. and Timmermann, A. (2016) Abrupt onset and prolongation of aragonite undersaturation events in the Southern Ocean. *Nature Climate Change,* 6**,** 172-176. https://doi.org/10.1038/nclimate2844

Hoegh-Guldberg, O., Mumby, P. J., Hooten, A. J., Steneck, R. S. *et al.* (2007) Coral Reefs Under Rapid Climate Change and Ocean Acidification. *Science,* 318**,** 1737-1742. https://www.science.org/doi/abs/10.1126/science.1152509

Hönisch, B., Ridgwell, A., Schmidt, D. N., Thomas, E. *et al.* (2012) The Geological Record of Ocean Acidification. *Science,* 335**,** 1058-1063. https://www.science.org/doi/abs/10.1126/science.1208277

Hopkins, F. E., Suntharalingam, P., Gehlen, M., Andrews, O. *et al.* (2020) The impacts of ocean acidification on marine trace gases and the implications for atmospheric chemistry and climate. *Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences,* 476**,** 20190769. https://royalsocietypublishing.org/doi/abs/10.1098/rspa.2019.0769

Hughes, T. P., Kerry, J. T. and Simpson, T. (2018) Large-scale bleaching of corals on the Great Barrier Reef. *Ecology,* 99**,** 501-501. https://doi.org/10.1002/ecy.2092

Huntington, H. P., Danielson, S. L., Wiese, F. K., Baker, M. *et al.* (2020) Evidence suggests potential transformation of the Pacific Arctic ecosystem is underway. *Nature Climate Change,* 10**,** 342-348. https://doi.org/10.1038/s41558-020-0695-2

IPCC (2013) Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp.. Available from https://www.ipcc.ch/site/assets/uploads/2018/02/WG1AR5_all_final.pdf.

IPCC (2018) *Global Warming of 1.5 °C. An IPCC special report on the impacts of global warming of 1.5 °C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty.* Cambridge, UK. http://www.ipcc.ch/report/sr15/

IPCC (2019) Collins M., M. Sutherland, L. Bouwer, S.-M. Cheong, T. Frölicher, H. Jacot Des Combes, M. Koll Roxy, I. Losada, K. McInnes, B. Ratter, E. Rivera-Arriaga, R.D. Susanto, D.

Swingedouw, and L. Tibig, 2019: Extremes, Abrupt Changes and Managing Risk. In: I*PCC Special Report on the Ocean and Cryosphere in a Changing Climate* [H.-O. Pörtner, D.C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegría, M. Nicolai, A. Okem, J. Petzold, B. Rama, N.M. Weyer (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 589-655. https://doi.org/10.1017/9781009157964.008.

IPCC (2021) *Climate Change 2021: The Physical Science Basis. Working Group I contribution to the IPCC Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2391 pp. doi:10.1017/9781009157896.

IPCC (2022a) Climate Change 2022: Impacts, Adaptation and Vulnerability. The Working Group II contribution to the IPCC Sixth Assessment Report. https://www.ipcc.ch/report/sixth-assessment-report-working-group-ii/

IPCC (2022b) Climate Change 2022: Mitigation of Climate Change . The Working Group III contribution to the IPCC's Sixth Assessment Report. Available from: https://www.ipcc.ch/report/sixth-assessment-report-working-group-3/ (Accessed: December 2022).

Jenkins, R. L. M., Warren, R. F. and Price, J. T. (2021) Addressing risks to biodiversity arising from a changing climate: The need for ecosystem restoration in the Tana River Basin, Kenya. *PLoS ONE,* 16**,** e0254879.

Jevrejeva, S., Jackson, L. P., Grinsted, A., Lincke, D. and Marzeion, B. (2018) Flood damage costs under the sea level rise with warming of 1.5 °C and 2 °C. *Environmental Research Letters,* 13**,** 074014. https://dx.doi.org/10.1088/1748-9326/aacc76

Jiang, L.-Q., Dunne, J., Carter, B. R., Tjiputra, J. F. *et al.* (2023) Global Surface Ocean Acidification Indicators From 1750 to 2100. *Journal of Advances in Modeling Earth Systems,* 15**,** e2022MS003563. https://doi.org/10.1029/2022MS003563

Johnson, E. and Rupper, S. (2020) An Examination of Physical Processes That Trigger the Albedo-Feedback on Glacier Surfaces and Implications for Regional Glacier Mass Balance Across High Mountain Asia. *Frontiers in Earth Science,* 8. https://www.frontiersin.org/articles/10.3389/feart.2020.00129

Jones, M. W., Abatzoglou, J. T., Veraverbeke, S., Andela, N. *et al.* (2022) Global and Regional Trends and Drivers of Fire Under Climate Change. *Reviews of Geophysics,* 60**,** e2020RG000726. https://doi.org/10.1029/2020RG000726

Joughin, I., Smith, B. E. and Medley, B. (2014) Marine Ice Sheet Collapse Potentially Under Way for the Thwaites Glacier Basin, West Antarctica. *Science,* 344**,** 735-738. https://www.science.org/doi/abs/10.1126/science.1249055

Kelley, D. I., Bistinas, I., Whitley, R., Burton, C. *et al.* (2019) How contemporary bioclimatic and human controls change global fire regimes. *Nature Climate Change,* 9**,** 690-696. https://doi.org/10.1038/s41558-019-0540-7

Kelley, D. I., Burton, C., Huntingford, C., Brown, M. A. J. *et al.* (2021) Technical note: Low meteorological influence found in 2019 Amazonia fires. *Biogeosciences,* 18**,** 787-804. https://bg.copernicus.org/articles/18/787/2021/

Kim, S.-K., Kim, H.-J., Dijkstra, H. A. and An, S.-I. (2022) Slow and soft passage through tipping point of the Atlantic Meridional Overturning Circulation in a changing climate. *npj Climate and Atmospheric Science,* 5**,** 13. https://doi.org/10.1038/s41612-022-00236-8

Kloenne, U., Nauels, A., Pearson, P., DeConto, R. M. *et al.* (2023) Only halving emissions by 2030 can minimize risks of crossing cryosphere thresholds. *Nature Climate Change,* 13**,** 9-11. https://doi.org/10.1038/s41558-022-01566-4

Kriegler, E., Hall, J. W., Held, H., Dawson, R. and Schellnhuber, H. J. (2009) Imprecise probability assessment of tipping points in the climate system. *Proceedings of the National Academy of Sciences,* 106**,** 5041-5046. https://www.pnas.org/content/pnas/106/13/5041.full.pdf

Langer, M. R. (2008) Assessing the Contribution of Foraminiferan Protists to Global Ocean Carbonate Production1. *Journal of Eukaryotic Microbiology,* 55**,** 163-169. https://doi.org/10.1111/j.1550-7408.2008.00321.x

Lasslop, G., Brovkin, V., Reick, C. H., Bathiany, S. and Kloster, S. (2016) Multiple stable states of tree cover in a global land surface model due to a fire-vegetation feedback. *Geophysical Research Letters,* 43**,** 6324-6331. https://doi.org/10.1002/2016GL069365

Lenihan, J. M., Daly, C., Bachelet, D. and Neilson, R. P. (1998) Simulating broad-scale fire severity in a dynamic global vegetation model. *Northwest Science,* 72**,** 91-101.

Lenton, T. M. (2020) Tipping positive change. *Philosophical Transactions of the Royal Society B: Biological Sciences,* 375**,** 20190123. https://royalsocietypublishing.org/doi/abs/10.1098/rstb.2019.0123

Lenton, T. M., Rockström, J., Gaffney, O., Rahmstorf, S. *et al.* (2019) Climate tipping points - too risky to bet against. *Nature,* 575**,** 592-595.

Liu, W., Xie, S.-P., Liu, Z. and Zhu, J. (2017) Overlooked possibility of a collapsed Atlantic Meridional Overturning Circulation in warming climate. *Science Advances,* 3**,** e1601666. https://www.science.org/doi/abs/10.1126/sciadv.1601666

Lohmann, J. and Ditlevsen, P. D. (2021) Risk of tipping the overturning circulation due to increasing rates of ice melt. *Proceedings of the National Academy of Sciences,* 118**,** e2017989118. https://www.pnas.org/doi/abs/10.1073/pnas.2017989118

Manes, S., Costello, M. J., Beckett, H., Debnath, A. *et al.* (2021) Endemism increases species' climate change risk in areas of global biodiversity importance. *Biological Conservation,* 257**,** 109070. https://www.sciencedirect.com/science/article/pii/S0006320721001221

McGovern, E., Schilder, J., Artioli, Y., Birchenough, S. *et al.* (2023) *Ocean Acidification.* London. https://oap.ospar.org/en/ospar-assessments/quality-status-reports/qsr-2023/other-assessments/ocean-acidification

Mycoo, M., Wairiu, M., Campbell, D., Duvat, V. *et al.* (2022) *Small Islands.* Cambridge, UK and New York, NY, USA: C. U. Press. https://www.ipcc.ch/report/ar6/wg2/chapter/chapter-15/

Overland, J. E. (2020) Less climatic resilience in the Arctic. *Weather and Climate Extremes,* 30. https://repository.library.noaa.gov/view/noaa/29145

Parmesan, C., Morecroft, M., Trisurat, Y., Adrian, R. *et al.* (2022) *Terrestrial and Freshwater Ecosystems and Their Services.* Cambridge, UK and New York, NY, USA: C. U. Press. https://www.ipcc.ch/report/ar6/wg2/chapter/chapter-2/

Pattyn, F., Ritz, C., Hanna, E., Asay-Davis, X. *et al.* (2018) The Greenland and Antarctic ice sheets under 1.5 °C global warming. *Nature Climate Change,* 8**,** 1053-1061. https://doi.org/10.1038/s41558-018-0305-8

Pearson, P. N. and Palmer, M. R. (2000) Atmospheric carbon dioxide concentrations over the past 60 million years. *Nature,* 406**,** 695-699. https://doi.org/10.1038/35021000

Petrou, K., Baker, K. G., Nielsen, D. A., Hancock, A. M. *et al.* (2019) Acidification diminishes diatom silica production in the Southern Ocean. *Nature Climate Change,* 9**,** 781-786. https://doi.org/10.1038/s41558-019-0557-y

Price, J. T. (1995) Potential impacts of global climate change on the summer distributions of some North American grassland birds. Wayne State University.

Price, J. T. (unpublished work).

Qi, D., Wu, Y., Chen, L., Cai, W.-J. *et al.* (2022) Rapid Acidification of the Arctic Chukchi Sea Waters Driven by Anthropogenic Forcing and Biological Carbon Recycling. *Geophysical Research Letters,* 49**,** e2021GL097246. https://doi.org/10.1029/2021GL097246

Rasmussen, D. J., Bittermann, K., Buchanan, M. K., Kulp, S. *et al.* (2017) Coastal flood implications of 1.5 °C, 2.0 °C, and 2.5 °C temperature stabilization targets in the 21st and 22nd century. *Environmental Research Letters,* 13. http://doi.org/10.1088/1748-9326/aaac87

Raven, J., Caldeira, K., Elderfield, H., Hoegh-Guldberg, O. *et al.* (2005) Ocean acidification due to increasing atmospheric carbon dioxide, Royal Society Report, Policy Document 12/05, 68pp, ISBN 0 85403 617 2 (Available from https://royalsociety.org/~/media/royal_society_content/policy/publications/2005/9634.pdf).

Rees, A. P., Brown, I. J., Jayakumar, A. and Ward, B. B. (2016) The inhibition of N2O production by ocean acidification in cold temperate and polar waters. *Deep Sea Research Part II: Topical Studies in Oceanography,* 127**,** 93-101. https://www.sciencedirect.com/science/article/pii/S0967064515004373

Reese, R., Garbe, J., Hill, E. A., Urruty, B. *et al.* (2023) The stability of present-day Antarctic grounding lines – Part 2: Onset of irreversible retreat of Amundsen Sea glaciers under current climate on centennial timescales cannot be excluded. *The Cryosphere,* 17**,** 3761-3783. https://tc.copernicus.org/articles/17/3761/2023/

Rignot, E., Mouginot, J., Morlighem, M., Seroussi, H. and Scheuchl, B. (2014) Widespread, rapid grounding line retreat of Pine Island, Thwaites, Smith, and Kohler glaciers, West Antarctica, from 1992 to 2011. *Geophysical Research Letters,* 41**,** 3502-3509. https://doi.org/10.1002/2014GL060140

Rintoul, S. R., Chown, S. L., DeConto, R. M., England, M. H. *et al.* (2018) Choosing the future of Antarctica. *Nature,* 558**,** 233-241. https://doi.org/10.1038/s41586-018-0173-4

Ripple, W. J., Wolf, C., Lenton, T. M., Gregg, J. W. *et al.* (2023) Many risky feedback loops amplify the need for climate action. *One Earth,* 6**,** 86-91. https://www.sciencedirect.com/science/article/pii/S2590332223000040

Ritchie, P. D. L., Clarke, J. J., Cox, P. M. and Huntingford, C. (2021) Overshooting tipping point thresholds in a changing climate. *Nature,* 592**,** 517-523. https://doi.org/10.1038/s41586-021-03263-2

Román-Palacios, C. and Wiens, J. J. (2020) Recent responses to climate change reveal the drivers of species extinction and survival. *Proceedings of the National Academy of Sciences,* 117**,** 4211-4217. https://doi.org/10.1073/pnas.1913007117

Root, T. L., Price, J. T., Hall, K. R., Schneider, S. H. *et al.* (2003) Fingerprints of global warming on wild animals and plants. *Nature,* 421**,** 57-60. https://doi.org/10.1038/nature01333

Rosier, S. H. R., Reese, R., Donges, J. F., De Rydt, J. *et al.* (2021) The tipping points and early warning indicators for Pine Island Glacier, West Antarctica. *The Cryosphere,* 15**,** 1501-1516. https://tc.copernicus.org/articles/15/1501/2021/

Saunders, S. P., Grand, J., Bateman, B. L., Meek, M. *et al.* (2023) Integrating climate-change refugia into 30 by 30 conservation planning in North America. *Frontiers in Ecology and the Environment,* 21**,** 77-84. https://doi.org/10.1002/fee.2592

Schaeffer, M., Hare, W., Rahmstorf, S. and Vermeer, M. (2012) Long-term sea-level rise implied by 1.5 °C and 2 °C warming levels. *Nature Climate Change,* 2**,** 867-870. https://doi.org/10.1038/nclimate1584

Schmidt, N. M., Reneerkens, J., Christensen, J. H., Olesen, M. and Roslin, T. (2019) An ecosystem-wide reproductive failure with more snow in the Arctic. *PLOS Biology,* 17**,** e3000392. https://doi.org/10.1371/journal.pbio.3000392

Schuur, E. A. G., Abbott, B. W., Commane, R., Ernakovich, J. *et al.* (2022) Permafrost and Climate Change: Carbon Cycle Feedbacks From the Warming Arctic. *Annual Review of Environment and Resources,* 47**,** 343-371. https://doi.org/10.1146/annurev-environ-012220-011847

Silva, P. S., Rodrigues, J. A., Santos, F. L. M., Pereira, A. A. *et al.* (2020) Drivers Of Burned Area Patterns In Cerrado: The Case Of Matopiba Region *2020 IEEE Latin American GRSS & ISPRS Remote Sensing Conference (LAGIRS)*, 542-547.

Slater, T., Shepherd, A., McMillan, M., Leeson, A. *et al.* (2021) Increased variability in Greenland Ice Sheet runoff from satellite observations. *Nature Communications,* 12**,** 6069. https://doi.org/10.1038/s41467-021-26229-4

Smith, P., Price, J., Molotoks, A., Warren, R. and Malhi, Y. (2018) Impacts on terrestrial biodiversity of moving from a 2°C to a 1.5°C target. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences,* 376**,** 20160456. https://doi.org/10.1098/rsta.2016.0456

Souter, D., Planes, S., Wicquart, J., Logan, M. *et al.* (2021) *Status of coral reefs of the world: 2020 report*. https://gcrmn.net/wp-content/uploads/2023/01/Status-of-Coral-Reefs-of-the-World-2020-Full-Report.pdf

Tebaldi, C., Ranasinghe, R., Vousdoukas, M., Rasmussen, D. J. *et al.* (2021) Extreme sea levels at different global warming levels. *Nature Climate Change,* 11**,** 746-751. https://doi.org/10.1038/s41558-021-01127-1

Terhaar, J., Frölicher, T. L. and Joos, F. (2021) Southern Ocean anthropogenic carbon sink constrained by sea surface salinity. *Science Advances,* 7**,** eabd5964. https://doi.org/10.1126/sciadv.abd5964

Thompson, V., Kennedy-Asser, A. T., Vosper, E., Lo, Y. T. E. *et al.* (2022) The 2021 western North America heat wave among the most extreme events ever recorded globally. *Science Advances,* 8**,** eabm6860. https://doi.org/10.1126/sciadv.abm6860

Thonicke, K., Spessa, A., Prentice, I. C., Harrison, S. P. *et al.* (2010) The influence of vegetation, fire spread and fire behaviour on biomass burning and trace gas emissions: results from a process-based model. *Biogeosciences,* 7**,** 1991-2011. https://bg.copernicus.org/articles/7/1991/2010/

Trusel, L. D., Frey, K. E., Das, S. B., Karnauskas, K. B. *et al.* (2015) Divergent trajectories of Antarctic surface melt under two twenty-first-century climate scenarios. *Nature Geoscience,* 8**,** 927-932. https://doi.org/10.1038/ngeo2563

Turner, J., Lu, H., King, J., Marshall, G. J. *et al.* (2021) Extreme Temperatures in the Antarctic. *Journal of Climate,* 34**,** 2653-2668. https://journals.ametsoc.org/view/journals/clim/34/7/JCLI-D-20-0538.1.xml

UNEP (2022) Spreading like Wildfire – The Rising Threat of Extraordinary Landscape Fires. Rapid Response Assessment. United Nations Environment Programme (Edited by A. Sullivan, E. Baker and T. Kurvits), Nairobi, Kenya. Available from https://www.unep.org/resources/report/spreading-wildfire-rising-threat-extraordinary-landscape-fires (Accessed March 2023).

van Nes, E. H., Staal, A., Hantson, S., Holmgren, M. *et al.* (2018) Fire forbids fifty-fifty forest. *PLOS ONE,* 13**,** e0191027. https://doi.org/10.1371/journal.pone.0191027

Walsh, J. E., Ballinger, T. J., Euskirchen, E. S., Hanna, E. *et al.* (2020) Extreme weather and climate events in northern areas: A review. *Earth-Science Reviews,* 209**,** 103324. https://www.sciencedirect.com/science/article/pii/S0012825220303706

Wang, S., Foster, A., Lenz, E. A., Kessler, J. D. *et al.* (2023) Mechanisms and Impacts of Earth System Tipping Elements. *Reviews of Geophysics,* 61**,** e2021RG000757. https://doi.org/10.1029/2021RG000757

Warren, R., Price, J., Graham, E., Forstenhaeusler, N. and VanDerWal, J. (2018a) The projected effect on insects, vertebrates, and plants of limiting global warming to 1.5 °C rather than 2 °C. *Science,* 360**,** 791-795. https://www.science.org/doi/abs/10.1126/science.aar3646

Warren, R., Price, J., VanDerWal, J., Cornelius, S. and Sohl, H. (2018b) The implications of the United Nations Paris Agreement on climate change for globally significant biodiversity areas. *Climatic Change,* 147**,** 395-409. https://doi.org/10.1007/s10584-018-2158-6

Warren, R., VanDerWal, J., Price, J., Welbergen, J. A. *et al.* (2013) Quantifying the benefit of early climate change mitigation in avoiding biodiversity loss. *Nature Climate Change,* 3**,** 678-682. https://doi.org/10.1038/nclimate1887

Wiens, J. J. (2016) Climate-Related Local Extinctions Are Already Widespread among Plant and Animal Species. *PLOS Biology,* 14**,** e2001104. https://doi.org/10.1371/journal.pbio.2001104

Woodhead, A. J., Hicks, C. C., Norström, A. V., Williams, G. J. and Graham, N. A. J. (2019) Coral reef ecosystem services in the Anthropocene. *Functional Ecology,* 33**,** 1023-1034. https://doi.org/10.1111/1365-2435.13331

Wunderling, N., Donges, J. F., Kurths, J. and Winkelmann, R. (2021) Interacting tipping elements increase risk of climate domino effects under global warming. *Earth Syst. Dynam.,* 12**,** 601-619. https://esd.copernicus.org/articles/12/601/2021/

Quality assurance

Each part of the work was reviewed by a member of the CS-N0W consortium. The climate and ecosystem impacts were reviewed by Garry Hayman (UK Centre for Ecology and Hydrology). Ocean impacts were reviewed by Jason Holt (National Oceanographic Centre) and the Cryosphere impacts by Svetlana Jevrejeva (National Oceanography Centre). Biodiversity impacts were reviewed by Rachel Warren (University of East Anglia). Most of the insights were additionally reviewed in internal workshops with UK Government stakeholders. The whole report was also reviewed Ryan Hogarth (Ricardo), Gwyn Rees (UK Centre for Ecology and Hydrology) and Paul Dodds (University College London).

Glossary

Selected from IPCC (2021) and citations therein unless otherwise stated.

Abrupt change: A change in the system that is substantially faster than the typical rate of the changes in its history. See also **Abrupt climate change** and **Tipping point**.

Abrupt climate change: 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. See also **Abrupt change** and **Tipping point.**

Albedo: The proportion of sunlight (solar radiation) reflected by a surface or object, often expressed as a percentage. Clouds, snow and ice usually have high albedo; soil surfaces cover the albedo range from high to low; vegetation in the dry season and/or in arid zones can have high albedo, whereas photosynthetically active vegetation and the ocean have low albedo. The Earth's planetary albedo changes mainly through changes in cloudiness and of snow, ice, leaf area and land cover.

Aridity: The state of a long-term climatic feature characterized by low average precipitation or available water in a region. Aridity generally arises from widespread persistent atmospheric subsidence or anticyclonic conditions, and from more localized subsidence in the lee side of mountains. See also **Drought**.

Biodiversity: Biodiversity or biological diversity means the variability among living organisms from all sources including, among other things, terrestrial, marine and other aquatic ecosystems, and the ecological complexes of which they are part; this includes diversity within species, between species, and of ecosystems. See also **Ecosystem**.

Climate variability: Deviations of climate variables from a given mean state (including the occurrence of extremes, etc.) at all spatial and temporal scales beyond that of individual weather events. Variability may be intrinsic, due to fluctuations of processes internal to the climate system (internal variability), or extrinsic, due to variations in natural or anthropogenic external forcing (forced variability).

Coral bleaching: Loss of coral pigmentation through the loss of intracellular symbiotic algae (known as zooxanthellae) and/or loss of their pigments.

Coral reef: An underwater **ecosystem** characterized by structure building stony corals. Warm-water coral reefs occur in shallow seas, mostly in the tropics, with the corals (animals) containing algae (plants) that depend on light and relatively stable temperature conditions. Cold-water coral reefs occur throughout the world, mostly at water depths of 50–500 m. In both kinds of reef, living corals frequently grow on older, dead material, predominantly made of calcium carbonate ($CaCO_3$). Both warm- and cold-water coral reefs support high **biodiversity** of fish and other groups and are considered to be especially vulnerable to climate change.

Cryosphere: The components of the Earth system at and below the land and ocean surface that are frozen, including snow cover, glaciers, ice sheets, ice shelves, icebergs, sea ice, lake ice, river ice, permafrost and seasonally frozen ground.

Drought: An exceptional period of water shortage for existing ecosystems and the human population (due to low rainfall, high temperature, and/or wind).

Earth system model (ESM): A coupled atmosphere–ocean general circulation model (AOGCM) in which a representation of the carbon cycle is included, allowing for interactive calculation of atmospheric carbon dioxide (CO2) or compatible emissions. Additional components (e.g. atmospheric chemistry, ice sheets, dynamic vegetation, nitrogen cycle, but also urban or crop models) may be included.

Ecosystem: A functional unit consisting of living organisms, their non-living environment and the interactions within and between them. The components included in a given ecosystem and its spatial boundaries depend on the purpose for which the ecosystem is defined: in some cases, they are relatively sharp, while in others they are diffuse. Ecosystem boundaries can change over time. Ecosystems are nested within other ecosystems, and their scale can range from very small to the entire biosphere. In the current era, most ecosystems either contain people as key organisms or are influenced by the effects of human activities in their environment.

Ensemble: A collection of comparable datasets that reflect variations within the bounds of one or more sources of uncertainty and that, when averaged, can provide a more robust estimate of underlying behaviour.

Gyre: Basin-scale ocean horizontal circulation pattern with slow flow circulating around the ocean basin, closed by a strong and narrow (100 to 200 km wide) boundary current on the western side. The subtropical gyres in each ocean are associated with high pressure in the centre of the gyres; the subpolar gyres are associated with low pressure.

Heatwave: A period of abnormally hot weather, often defined with reference to a relative temperature threshold, lasting from two days to months. Heatwaves and warm spells have various and, in some cases, overlapping definitions. See also **Marine heatwave**.

Irreversibility: 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. See also **Tipping point**.

Human system: Any system in which human organizations and institutions play a major role. Often, but not always, the term is synonymous with society or social system. Systems such as agricultural systems, urban systems, political systems, technological systems and economic systems are all human systems in the sense applied in this Report.

Marine heatwave: A period during which water temperature is abnormally warm for the time of the year relative to historical temperatures, with that extreme warmth persisting for days to months. The phenomenon can manifest in any place in the ocean and at scales of up to thousands of kilometres. See also **Heatwave**.

Marine ice cliff instability (MICI): A hypothetical mechanism of an ice cliff failure. In case a marine-terminated ice sheet loses its buttressing ice shelf, an ice cliff can be exposed. If the exposed ice cliff is tall enough (about 800 m of the total height, or about 100 m of the above-water part), the stresses at the cliff face exceed the strength of the ice, and the cliff fails structurally in repeated calving events. See also **Marine ice sheet instability (MISI)**.

Marine ice sheet instability (MISI): A mechanism of irreversible (on the decadal to centennial time scale) retreat of a grounding line for the marine-terminating glaciers, in case the glacier bed slopes towards the ice sheet interior. See also **Marine ice cliff instability (MICI)**.

Meridional overturning circulation (MOC): Meridional (north–south) overturning circulation in the ocean quantified by zonal (east–west) sums of mass transports in depth or density layers. In the North Atlantic, away from the subpolar regions, the MOC (which is in principle an observable quantity) is often identified with the thermohaline circulation (THC), which is a conceptual and incomplete interpretation. The MOC is also driven by wind, and can also include shallower overturning cells such as occur in the upper ocean in the tropics and subtropics, in which warm (light) waters moving poleward are transformed to slightly denser waters and subducted equatorward at deeper levels. The **Atlantic Meridional Overturning Circulation (AMOC)** is the main current system in the South and North Atlantic Oceans. AMOC transports warm upper-ocean water northwards and cold, deep water southwards, as part of the global ocean circulation system. Changes in the strength of AMOC can affect other components of the climate system.

Natural systems: The dynamic physical, physicochemical and biological components of the Earth system that would operate independently of human activities.

Natural variability: See **Climate variability**.

Ocean acidification (OA): A reduction in the pH of the ocean, accompanied by other chemical changes (primarily in the levels of carbonate and bicarbonate ions), over an extended period, typically decades or longer, which is caused primarily by uptake of carbon dioxide (CO_2) from the atmosphere, but can also be caused by other chemical additions or subtractions from the ocean.

Ocean deoxygenation: The loss of oxygen in the ocean. It results from ocean warming, which reduces oxygen solubility and increases oxygen consumption and stratification, thereby reducing the mixing of oxygen into the ocean interior. Deoxygenation can also be exacerbated by the addition of excess nutrients in the coastal zone.

Permafrost: Ground (soil or rock, and included ice and organic material) that remains at or below 0°C for at least two consecutive years. Note that permafrost is defined via temperature rather than ice content and, in some instances, may be ice-free.

Near-surface permafrost: within about 3–4 m of the ground surface. The depth is not precise, but describes what commonly is highly relevant for people and ecosystems. Deeper permafrost is often progressively less ice-rich and responds more slowly to warming than near-surface permafrost. The presence or absence of near-surface permafrost is not the only significant metric of permafrost change, and deeper permafrost may persist when near-surface permafrost is absent.

Permafrost degradation: Decrease in the thickness and/or areal extent of permafrost.

Permafrost thaw: Progressive loss of ground ice in permafrost, usually due to input of heat. Thaw can occur over decades to centuries over the entire depth of permafrost ground, with impacts occurring while thaw progresses. During thaw, temperature fluctuations are subdued because energy is transferred by phase change between ice and water. After the transition from permafrost to non-permafrost, ground can be described as thawed.

Risk: The potential for adverse consequences for human or ecological systems, recognizing the diversity of values and objectives associated with such systems. In the context of climate change, risks can arise from potential impacts of climate change as well as human responses to climate change. Relevant adverse consequences include those on lives, livelihoods, health and well-being, economic, social and cultural assets and investments, infrastructure, services (including ecosystem services), ecosystems and species.

Sea level change (sea level rise/sea level fall): Change to the height of sea level, both globally and locally (relative sea level change) at seasonal, annual, or longer time scales due to (i) a change in ocean volume as a result of a change in the mass of water in the ocean (e.g. due to melt of glaciers and ice sheets), (ii) changes in ocean volume as a result of changes in ocean water density (e.g. expansion under warmer conditions), (iii) changes in the shape of the ocean basins and changes in the Earth's gravitational and rotational fields, and (iv) local subsidence or uplift of the land. Global mean sea level (GMSL) change resulting from change in the mass of the ocean is called barystatic. The amount of barystatic sea level change due to the addition or removal of a mass of water is called its sea level equivalent (SLE). Sea level changes, both globally and locally, resulting from changes in water density are called steric. Density changes induced by temperature changes only are called thermosteric, while density changes induced by salinity changes are called halosteric. Barystatic and steric sea level changes do not include the effect of changes in the shape of ocean basins induced by the change in the ocean mass and its distribution.

Tipping element: A component of the Earth system that is susceptible to a tipping point.

Tipping point: A critical threshold beyond which a system reorganizes, often abruptly and/or irreversibly. See also **Tipping element**, **Irreversibility** and **Abrupt change**.

Uncertainty: A state of incomplete knowledge that can result from a lack of information or from disagreement about what is known or even knowable. It may have many types of sources, from imprecision in the data to ambiguously defined concepts or terminology, incomplete understanding of critical processes, or uncertain projections of human behaviour. Uncertainty can therefore be represented by quantitative measures (e.g. a probability density function) or by qualitative statements (e.g. reflecting the judgement of a team of experts).

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