SECTION 2

EARTH SYSTEM TIPPING POINTS AND RISKS

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2.1 Introduction to Earth system tipping points risks

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Key Messages

Earth system tipping points pose profound risks

- Tipping points threaten the stability of the Earth system, which our society and economy fundamentally rely on. Societal development, wellbeing, prosperity, and economic health are threatened by tipping points.
- Earth system tipping points create different types of risk to other climate impacts, often characterized by irreversibility, deep uncertainty, and potential for cascading failures across natural and human systems.
- **This is a national security issue as food, water and heat stresses will impact populations.**

New risk assessment and management approaches are needed for tipping points

- Traditional risk assessment fails: conventional impact-probability matrices capturing individual climate impacts are inappropriate for tipping point risk analysis, owing to uncertainty, nonlinear dynamics, and the systemic scale and scope of interactions between impacts and their cascading effects.
- New risk assessment frameworks are required: assessing tipping point risks can benefit from specialized approaches including risk registers that translate Earth system changes into policy-relevant “risk currencies” while capturing cascading effects and system interactions.

This Chapter introduces the concept of tipping points in the Earth system, their significance in climate change science, and a framework for assessing their risks and impacts. This framework provides the foundation for the assessment of Earth system tipping points presented in the remainder of this report. **Chapter 2.2** examines the biophysical science basis of individual ESTPs, providing an update on the status and likelihood of ESTPs and their interactions. **Chapter 2.3** explores overshoot scenarios and the risks of temperature overshoot for tipping points. **Chapter 2.4** translates these scientific insights into a practical risk register that quantifies impacts across our identified risk currencies, providing policymakers with actionable information for decision-making.

2.1.1 Why Tipping Points?

Tipping points represent critical thresholds in Earth's climate system where small changes can lead to significant, often irreversible consequences. Multiple tipping elements in the Earth system (Armstrong McKay et al., 2022) are already showing signs of destabilization under current warming levels. Current global warming already lies within the lower end of uncertainty ranges for several tipping points, including major ice sheets, permafrost systems, coral reefs, and various circulation patterns (Armstrong McKay et al., 2022). Several tipping points may be triggered within the range of 1.5-2°C global warming, with further increases in the likelihood of many more tipping points occurring at the 2-3°C of warming expected under current policy trajectories (Armstrong McKay et al., 2022). This creates an urgent need for systemic risk assessment that can inform policy decisions across scales from local adaptation planning to global climate governance. Understanding these tipping points is crucial for appropriate risk assessment and effective climate change mitigation and adaptation strategies.

In the Global Tipping Points Report 2023 (Lenton et al, 2023) we provided an assessment of Earth system tipping points, their risks and their implications for human societies. That report established the scientific foundation by identifying various Earth system tipping points, assessing their likelihood and timescales, and exploring potential impacts. The 2023 report demonstrated that several tipping points could be triggered in the 2030s at current rates of warming, with potentially catastrophic consequences for billions of people.

The 2023 report also highlighted critical knowledge gaps, particularly around tipping point interactions, cascading risks, and the translation of Earth system changes into policy-relevant risk assessments. While it found that empirical evidence of tipping cascades was scarce, it identified the potential for catastrophic risks from interconnected failures across natural and human systems.

Here we build on the previous assessment in several key ways. We incorporate the latest scientific evidence published since 2023 to update our assessments of individual tipping point likelihood, timing, and severity (Chapter 2.2). Building on the limited evidence of tipping cascades identified in 2023, we provide a more detailed assessment of how tipping points interact with each other and how risks cascade through interconnected natural and human systems. We then examine the critical question of temperature overshoot scenarios - whether temporarily exceeding temperature thresholds before returning below them could still trigger irreversible tipping points, and what this means for climate policy (Chapter 2.3). Finally, to make our scientific insights actionable, we translate our assessments into a detailed risk register that quantifies impacts across multiple risk domains, providing practical information for policymakers and risk managers (Chapter 2.4).

To do so, we apply and adapt established risk assessment approaches to ESTPs, translating Earth system science into policy-relevant "risk currencies" including food security, energy security, and geopolitical stability (Roberts et al, 2021).

New geography of climate change

The concept of tipping points fundamentally alters our understanding of climate change and its geographical implications. It introduces the possibility of abrupt, nonlinear and irreversible changes in regional and global climate patterns, challenging smooth projections. The impacts of tipping points are not uniformly distributed across the globe. For example, collapse of the Atlantic Meridional Overturning Circulation (AMOC) would affect the North Atlantic region most strongly. Tipping points highlight the interconnectedness of Earth's systems across different geographical scales, from local ecosystems to global atmospheric and oceanic circulation patterns.

This understanding requires a reevaluation of climate risks across different geographical regions and interconnected social and economic systems, potentially altering priorities for adaptation and mitigation strategies (as addressed in Section 1 of this report). The new geography of climate change must account for both gradual and reversible changes and the potential for sudden and irreversible shifts, necessitating a more dynamic approach to climate modeling and policy-making.

Thresholds, timescales and tipping mechanisms

Tipping points are associated with specific thresholds in key system parameters, such as the volume of ice on Greenland or the strength of the AMOC, and associated thresholds in forcing factors, such as temperature or freshwater input (**Chapter 2.2** provides a detailed analysis of these thresholds for individual tipping points). Once a tipping point is crossed the resulting transition can occur over various timescales, from abrupt changes occurring over decades to slower transitions spanning centuries. However, there is a common feature that on approaching a tipping point, linearity of response (where response scales linearly with small changes in forcing) breaks down.

For instance, a specific level of global warming might trigger the start of a melt of the Greenland or Antarctic ice sheet that may be irreversible - this represents 'bifurcation' tipping, where a system becomes unstable as key conditions slowly change, leading to a sudden transition to a new state once a critical threshold is crossed. This type of tipping is often associated with the classic notion of "tipping points" and can result in abrupt, irreversible changes. The speed at which systems approach and cross tipping points, and the rate at which these systems "tip" can vary widely, because of the physical processes involved.

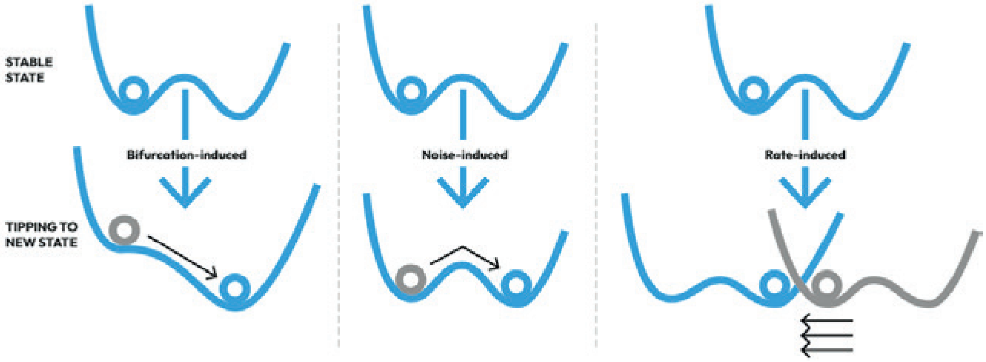


Figure 2.1.1: *Three types of tipping mechanisms in Earth systems. Bifurcation tipping occurs when a system becomes unstable as conditions slowly change, leading to a sudden transition once a critical threshold is crossed. Noise-induced tipping results from random fluctuations or extreme events pushing a system past its tipping point despite otherwise stable average conditions. Rate-induced tipping happens when the rate of change exceeds the system's ability to adapt, even before reaching absolute thresholds.*

This variation partly reflects different tipping mechanisms (Figure 2.1.1) - some systems are sensitive not just to how much forcing occurs, but how quickly it happens. 'Rate-induced' tipping happens when the rate of change in a system parameter exceeds the system's ability to adapt, even if the absolute change hasn't reached a critical threshold. This type of tipping highlights the importance of not just the magnitude of change, but also its speed. In Earth systems, rapid changes in factors like greenhouse gas concentrations or land use could potentially trigger rate-induced tipping events. The AMOC, for example, appears to be sensitive not just to how much warming occurs, but how quickly it happens - suggesting it could shut down from rapid warming even before critical temperature limits are crossed.

A third mechanism, 'noise-induced' tipping, can occur when random fluctuations or perturbations push a system past a tipping point even when average conditions might otherwise be stable. In the climate system, natural variability or extreme weather events can act as this "noise." For example, marine heatwaves can push already-stressed coral reefs past their recovery capacity, triggering widespread bleaching and ecosystem collapse even if average conditions might otherwise be tolerable (see **4.3 Coral Case Study**).

Understanding these different types of tipping is crucial for accurately assessing and predicting potential changes in different components of the Earth system (Figure 2.1.2). Bifurcation tipping may be more predictable given sufficient data on system thresholds, while rate-induced and noise-induced tipping present additional challenges for forecasting and risk assessment. Each type of tipping requires different approaches for detection, modeling, and prevention or mitigation strategies.

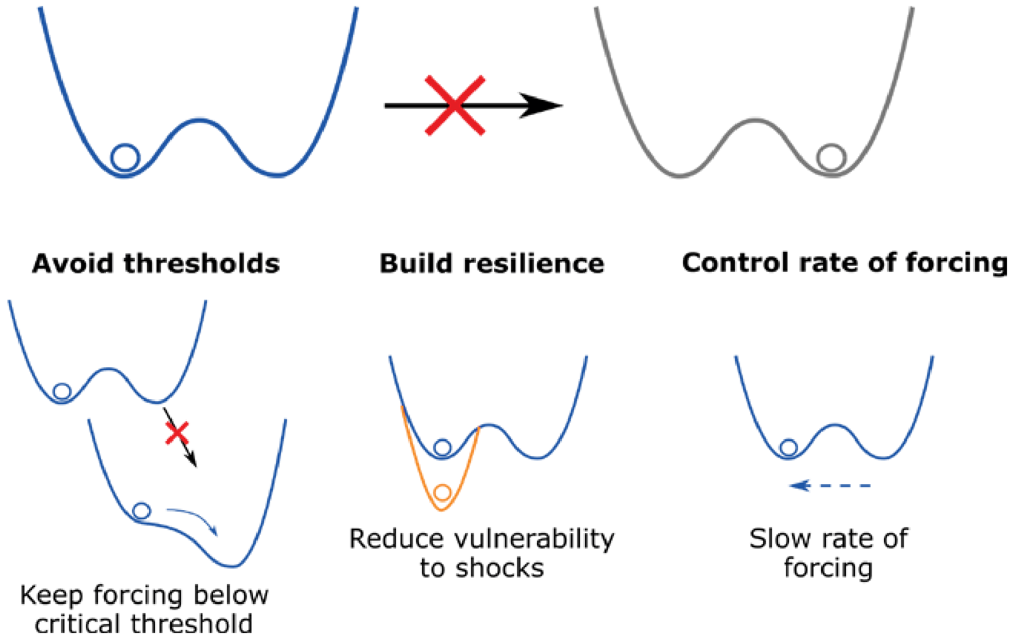


Figure 2.1.2: Prevention strategies for different tipping mechanisms. Bifurcation tipping can be prevented by avoiding critical thresholds through limiting the magnitude of forcing (e.g., keeping warming below specific temperature limits). Noise-induced tipping can be mitigated by strengthening system resilience and reducing background stresses that make systems vulnerable to extreme events and natural variability. Rate-induced tipping requires controlling the rate of change, such as limiting how quickly warming occurs.

Extremely fast changes could occur after passing tipping points for processes such as the collapse of monsoons. These present a challenge in that the speed of changes may exceed possible mitigation and adaptation. For more slowly evolving systems, such as deep ocean circulation, the effect of crossing a tipping point may unfold much more slowly (but still inexorably) over decades or centuries. In such cases, there remains the possibility that the consequences of crossing a tipping point can be avoided, if there is a return below the tipping point immediately after "overshooting" it. This reversibility is fleeting, however: if the tipping element completes its tipping then the known constraints on irreversibility for that tipping point apply and the opportunity is lost. This is explored in **Chapter 2.3**.

Bifurcation tipping may be prevented by keeping forcing below critical thresholds, while rate-induced tipping may be prevented by controlling rates of change, such as limiting how quickly warming occurs. Noise-induced tipping can be mitigated by strengthening system resilience and reducing background stresses that make systems vulnerable to extreme events. The governance of tipping point risks and strategies for prevention, adaptation and mitigation are covered in **Section 1** of this report.

It is therefore important to understand the processes involved in any tipping point. If the change in forcing is sufficiently slow and the system's behavior follows regular, consistent patterns, we may be able to detect statistical changes that serve as early warning signals of approaching tipping points (covered in Chapter 1.6 of the 2023 Global Tipping Points Report).

2.1.2 Risk framework for Earth system tipping points

Our framework builds on established approaches for environmental risk assessment that integrate climate science with impact assessment (Jones, 2001) and more recent developments in climatic impact-driver frameworks that systematically link physical climate changes to sectoral impacts (Ruane et al., 2022). The IPCC definition of climate change risk can be adopted to assess risks from Earth system tipping points (ESTPs). Risks therein are defined as the "potential for adverse consequences for human or ecological systems, recognizing the diversity of values and objectives associated with such systems" (IPCC 2021). The complex nature of risk was central in the IPCC AR6, which pointed out the immense relevance of including feedbacks, cascades, nonlinear behavior and the potential for surprise (e.g. low likelihood high impact outcomes) in the risk assessment.

The IPCC Special Report on 1.5° Global Warming introduced compound risk as "the interaction of hazards, which can be characterized by single extreme events or multiple coincident or sequential events that interact with exposed systems or sectors" (IPCC 2018). However, this definition did not acknowledge the complex interaction between hazards, exposure and vulnerability shaping risks. Other studies have defined cascading risks as an "event or trend triggering others; interactions can be one way (e.g., domino or contagion effects) but can also have feedbacks; cascading risk is often associated with the vulnerability component of risk, such as critical infrastructure" (Simpson et al. 2021). This includes risks from cascading shocks, such as those causing irreversible changes in climate or impacts on a human timescale, tipping points, and indirect impacts.

However, the definition of risk is only one component of a functioning risk management framework. Key risk management principles are identified as (King et al, 2015):

- **Assess risks in relation to objectives, or interests**
  Start from an understanding of what it is that we wish to avoid, then assess its likelihood.
- **Identify the biggest risks**
  Focus on finding out more about worst-case scenarios in relation to long-term changes, as well as short-term events.
- **Consider the full range of probabilities**
  Bearing in mind that a very low probability may correspond to a very high risk, if the impact is catastrophic.
- **Use the best available information**
  Whether this is proven science or expert judgment. A best estimate is usually better than no estimate at all.
- **Take a holistic view**
  Assess systemic risks as well as direct risks. Assess risks across the full range of space and time affected by the relevant decisions.

Regrettably, these risk management principles have not typically been adhered to by policymakers when considering climate change and tipping points. For example, high-profile climate change assessments – including through the TCFD (Task Force on Climate related Financial Disclosures) - significantly underestimate risk, as they exclude many of the most severe risks we could face. Widely used economic assessments of climate impacts show relatively benign economic impacts which are inconsistent with science as they exclude tipping points, nature risks, and risk cascades such as displacement and conflict, thereby significantly understating risks. Policymakers who use these model outputs to guide decisions may therefore be implicitly accepting far higher levels of risk than they think. Although there is no precise globally-agreed risk appetite, it is reasonable to assume that most decision-makers want to minimise the risk of significant societal disruption, including from ESTPs.

A well recognised risk management principle is the precautionary principle, which is not consistently applied to climate change. The precautionary principle emphasises caution if it is possible that a given course of action may cause significant harm, particularly where there is high uncertainty. One of the most important expressions of the precautionary principle internationally is the Rio Declaration from the 1992 United Nations Conference on Environment and Development (United Nations, 1992). It is in common use as a concept by national governments including the EU (European Commission, 2000) and UK (DEFRA, 2023).

It is illustrative to compare societal approaches to climate change to that used in other areas of human endeavour with mature risk management approaches, which in many cases are regulated. For example, insurance companies hold capital to meet the liabilities they expect to meet in the future, as well as to cover adverse events so they can avoid becoming insolvent. In Europe the amount of capital insurers are required to hold is set at a level designed to withstand an extreme loss scenario that would occur only once in 200 years. Put another way, the amount of capital held is calculated to give a 0.5% chance that an insurance company would fail in any one year. Nuclear facilities have an even higher threshold for failure, designed to cope with hazards on a 1 in 10,000 basis. The contrast with the probabilities of success we have accepted with carbon budgets is stark.

A final consideration from a risk management perspective is the impact of partial tipping. Tipping points do not have to finish tipping to significantly impact weather patterns, with consequent impacts on key socio-economic systems including food, water, energy and transport.

For assessing Earth system tipping points (ESTPs), we adopt and build on the IPCC's understanding of risk complexity, particularly the AR6 framework's recognition that climate responses can themselves become sources of risk and that feedback loops and cascading impacts are central to comprehensive risk assessment. However, tipping points require additional considerations due to their potential for abrupt, irreversible changes and their capacity to trigger cascading failures across interconnected systems - exactly the kind of high-impact events that can have system-wide consequences. The framework addresses a critical gap in current climate-society-economy models, which often inadequately represent the feedback mechanisms and system interactions that are crucial for understanding tipping point risks. By incorporating systemic risk considerations and translating impacts into policy-relevant currencies, our approach ensures that scientific insights about tipping points can inform practical decision-making across different scales and sectors.

Our ESTP risk framework incorporates three main components (Figure 2.1.3). This approach addresses critical gaps identified in integrated models of natural and human Earth systems, particularly the need to better represent cascading effects and telecoupling processes that can amplify tipping point impacts across scales and sectors (Franzke et al., 2022):

1. **ESTP hazards and direct risks:** Individual ESTPs are assessed for their likelihood of occurrence (very unlikely to certain) and potential severity of impact (low to catastrophic) using established scientific evidence. This includes evaluating threshold temperatures, triggering mechanisms (bifurcation, rate-induced, or noise-induced tipping), and timescales of system transitions. We assess our confidence in these evaluations using a standardized scale (very low to very high confidence) that reflects the current state of scientific understanding and observational evidence. **Chapter 2.2** provides detailed assessments of the physical science of individual tipping points, while temperature overshoot scenarios and their implications for triggering irreversible changes are examined in **Chapter 2.3**.
2. **Systemic risk analysis:** Systemic risks arise when individual tipping points interact through cascading failures that spread across interconnected natural and human systems. We examine three types of cascading processes: tipping cascades (where one tipping point triggers another), impact cascades (chains of socioeconomic impacts), and emergent feedbacks (self-reinforcing cycles that amplify effects). The categories are not mutually exclusive: for example, cascades can also be connected through feedbacks. These interconnected processes can lead to severe outcomes, such as system collapse, over various time horizons (Sillmann et al. 2022). Current climate-society-economy models often inadequately represent these feedback mechanisms (e.g. Schaumann & Alastrué de Asenjo 2025), creating critical gaps in risk assessment. Globalization amplifies systemic risk, making it a worldwide concern that affects populations across the globe.
3. **Risk currencies: In Chapter 2.4**, risks arising from Earth system changes are interpreted in terms of policy-relevant “risk currencies” that decision-makers intuitively understand, including food security, energy security, water security, human security, economic stability, and geopolitical stability. This translation process captures both direct impacts from individual tipping points and systemic effects from cascading interactions.

We use these three components to construct a risk register that provides quantitative assessments across multiple domains, enabling policymakers to compare risks, set priorities, and develop targeted response strategies. **Chapter 2.4** presents the detailed risk register with regional and sectoral impact assessments across nine key risk currencies.

By adopting this framework, we seek to bridge the gap between scientific understanding of tipping points and the practical needs of risk management and policy formulation. It allows for a more nuanced treatment of uncertainty and systemic risk while still providing actionable insights for decision-makers.

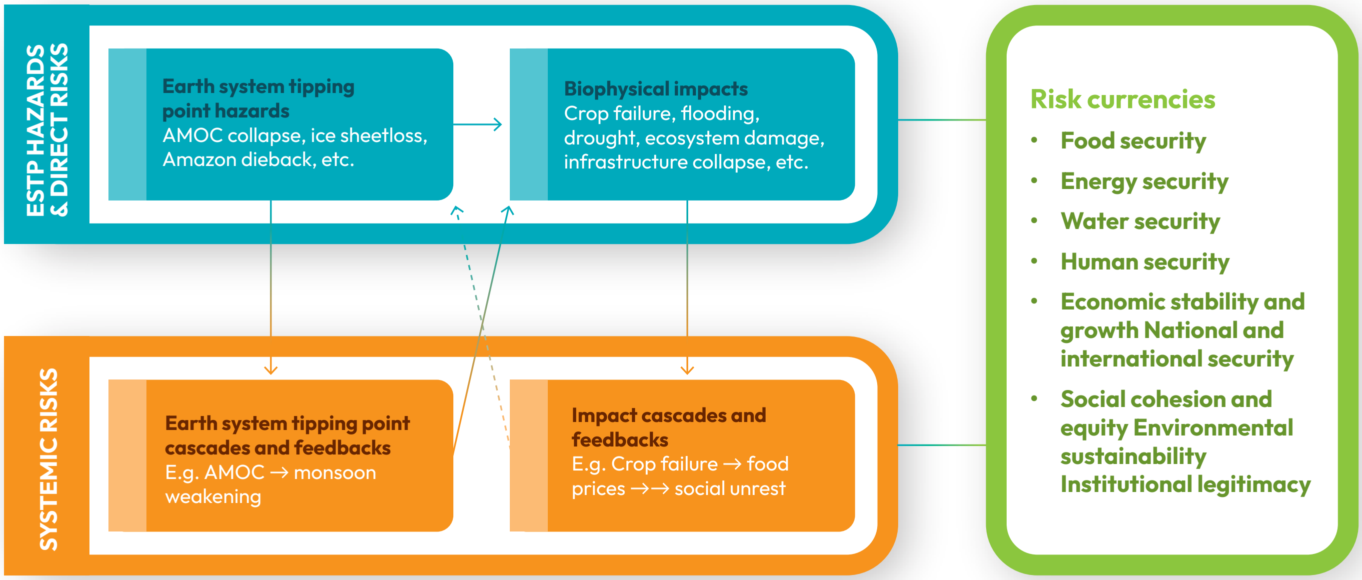


Figure 2.1.3: Direct risks (blue) show the linear pathway from tipping points through biophysical impacts to risk currency domains (green). Systemic risks (red) involve cascades and feedbacks related to Earth systems and impacts. Dashed lines indicate social-ecological feedbacks not fully assessed in this report.

Earth system tipping point hazards and direct risks

ESTPs hazards refer to the immediate and primary consequences of a tipping point being crossed. These might include rapid sea level rise from ice sheet collapse or sudden shifts in regional climate patterns. Direct risks, in contrast, encompass the direct effects that emerge as a result of these ESTPs hazards. For instance, the ESTP hazard of increased drought frequency might lead to direct risks, such as agricultural failures. When assessing ESTP hazards and direct risks, we categorize these in terms of their likelihood of occurrence (very unlikely / unlikely / likely / very likely / certain), and severity (low / moderate / major / critical), while also stating our confidence in those assessments (very low, low, medium, high and very high). Chapter 2.2 employs a standardized confidence framework using a +/- system to evaluate the scientific evidence for each tipping system. This framework assesses whether multiple independent lines of evidence support the presence of self-perpetuating feedback loops that can drive state shifts beyond critical thresholds, with high confidence (+++) indicating consistent support across paleoclimate records, models, and observations, while lower confidence levels (+, ++) reflect greater uncertainties in timing, magnitude, or feedback strength.

Systemic and cascading risks

Systemic risk occurs when the functioning of an entire system could be compromised due to the interactions among its components (Sillmann et al., 2022; Arnscheidt et al, 2025; Renn et al, 2017). The complex, interconnected nature of these risks can be visualized through network approaches that show how multiple risk factors interact and reinforce each other. In the context of Earth system tipping points, systemic risk encompasses the potential for ESTP impacts to propagate through interconnected natural and human systems, threatening the stability and functioning of broader Earth-human systems. Critically, responses to risks can themselves become risk factors, creating additional layers of complexity. When governments, institutions, or communities respond to ESTP impacts, their actions could inadvertently generate new vulnerabilities that propagate through interconnected systems (see Section 1 for a detailed exploration of governance). For example, emergency resource restrictions implemented in response to climate impacts might force communities into unsustainable practices that create longer-term risks.

Systemic risks are assessed in the following domains:

Earth system: Earth system tipping point causes changes to other Earth system components.

Societal: Direct impacts of Earth system tipping point on people causes other impacts on people

Social-ecological: Direct impacts of Earth system tipping point on people leads to acceleration or mitigation of other Earth system tipping points

Cascading risk is a specific type of systemic risk characterized by chains of impacts where one event triggers the next in a broadly domino-like fashion (Figure 2.1.4), although sometimes with feedback between the 'dominoes' to accelerate tipping (Simpson et al. 2021). The interconnected nature of cascading risks has been recognized across multiple disciplines as a fundamental challenge for risk assessment (Helbing, 2013), particularly in environmental systems where multiple interacting hazards can compound impacts in nonlinear ways (Pescaroli & Alexander, 2018; Zscheischler et al., 2018). Cascading regime shifts can occur both within ecological systems and across social-ecological scales (Rocha et al., 2018), making them especially relevant for understanding tipping point interactions. For example, the melting of the Greenland Ice Sheet could lead to increased heat absorption by the darker ocean surface, accelerating regional warming. This, in turn, could trigger further tipping points such as permafrost thaw or changes in atmospheric circulation patterns. Each step in this cascade can exacerbate the original impact and potentially push other systems closer to their own tipping points (Wunderling et al, 2024).

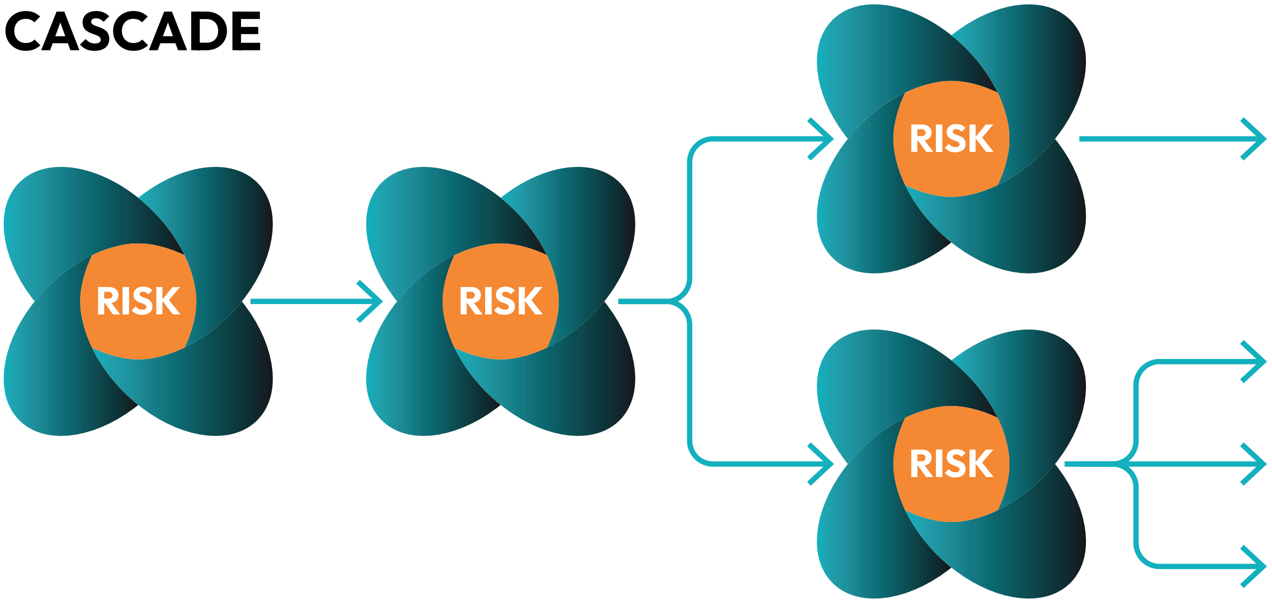


Figure 2.1.4: Cascading risk pathways showing how initial triggers can propagate through interconnected systems.
Source: Adapted from Simpson et al. (2021).

The 2023 Global Tipping Points report found that empirical evidence of tipping cascades is currently scarce, with most research focused on climate change, coastal flooding and marine species tipping cascades. Significantly less is known about cascades from biophysical to socio-economic systems compared to cascades between biophysical systems. However, extrapolating from known feedbacks in complex human-natural systems suggests that tipping points in social and natural systems could plausibly form tipping cascades, with catastrophic risks for human wellbeing. This previous analysis underscores both the potential severity of cascading risks and the critical need for improved assessment frameworks. Here we differentiate between the following types of cascading risk

- **Tipping cascades:** chains of Earth system and/or societal tipping points where triggering of each tipping point causes the next to tip. For example, AMOC collapse could reduce northward heat transport and shift the Intertropical Convergence Zone southward, weakening the West African and Indian Summer Monsoons, which reduces regional precipitation and triggers vegetation loss that further destabilizes the monsoon systems through reduced evapotranspiration.
- **Impact cascades:** chains of impacts where each impact causes the next impact. These impacts may ultimately be the consequence of a tipping point, but the impacts themselves do not display tipping characteristics. For instance, regional drought leads to crop failure, which causes food price spikes, triggering social unrest and political instability.
- **Emergent feedbacks:** circular chains of Earth system or societal tipping points or impacts that could amplify impacts. For example, forest fires release CO2 causing further warming, which increases fire risk, creating a self-reinforcing cycle.

For each ESTP we assess these different systemic risks, as well as the interplay between these. The interplay between systemic risks can create complex domino effects, feedback loops and amplification processes. For instance, a tipping point in the Amazon rainforest leading to its dieback could trigger a cascade of impacts on regional water cycles, biodiversity, and carbon storage. These cascading effects could then translate into systemic risks for global climate regulation, international trade in agricultural commodities, and geopolitical stability in the region (see **4.1 Amazon Case Study**).

Risk currency

“Risk currency” is a term used to describe the fundamental concerns that drive policy decision-making across all levels of governance: risks of primary importance which are understood intuitively by people and decision-making cultures and systems (Roberts et al 2021). These currencies include the objectives and interests pursued by states and other system-scale actors: food security, energy security, water security, human security, economic stability and growth, national and international security, social cohesion and equity, environmental sustainability, and institutional legitimacy (**Chapter 2.4**). Policymakers think in terms of protecting lives, maintaining economic competitiveness, ensuring energy and food security, preventing social unrest, safeguarding critical infrastructure, and preserving the effectiveness of governance systems. They are concerned with measurable impacts on GDP, employment rates, public health metrics, migration pressures, and the functioning of essential services. In this context, information about the climatic changes and biophysical impacts of tipping points might not be by themselves enough to engage decision-makers, as these do not directly relate to risk currencies. Risk currency thus refers to the translation of Earth system impacts (direct, systemic, cascading) into metrics and language that resonate with policy and decision-makers. The translation of Earth system changes into these risk currencies requires a systematic approach that captures both direct impacts and their strategic implications (Figure 2.1.5).

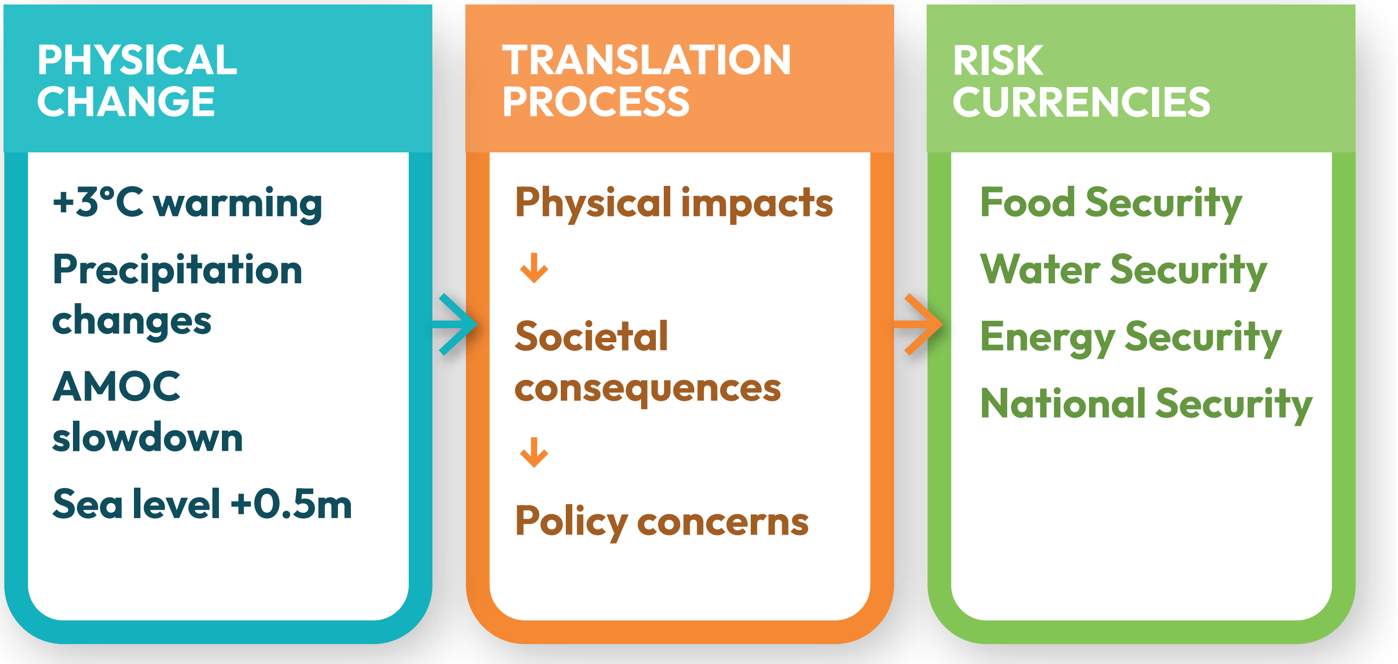


Figure 2.1.5: Risk currency translation framework, showing how Earth system tipping point impacts are converted into policy-relevant security concerns across different domains.

Understanding tipping point risks in terms of these policy-relevant currencies is crucial for several reasons. First, it translates complex Earth system science into the language of policy impact assessment that decision-makers use daily. Second, it demonstrates why tipping points cannot be treated as simply environmental issues but must be recognized as fundamental threats to societal stability (Monnin & Hiebert, 2023). Climate change has a clear systemic dimension: its consequences are not only widespread across all sectors and regions, but potential concentrations, spillovers and interlinkages risk amplifying its impacts further (Monnin & Hiebert, 2023). Third, it provides a framework for prioritizing policy responses based on which risk currencies are most threatened and which populations are most vulnerable (Milkoreit et al., 2024). Finally, it reveals why traditional risk assessment approaches, designed for single-currency risks, are inadequate for the multi-currency, systemic nature of tipping point impacts (European Commission JRC, 2025). Due to their long timescales, multi-hazard, cross-boundary and systemic risk nature, risk and impact assessments of crossing tipping points go beyond conventional disaster and climate risk analysis, and adaptation solutions will be needed (UNDRR, 2022).

The AMOC collapse example illustrates this translation process clearly (Figure 2.1.6). Physical changes in ocean circulation translate into concrete impacts on food security, energy demands, economic costs, and geopolitical stability - each representing different currencies that policymakers can understand and act upon (see **4.2 Atlantic Ocean circulation case study**).

The currency of risk in this framework converts changes in Earth system parameters - such as temperature increases, precipitation pattern shifts, or extreme weather event frequency - into terms directly relevant to societal concerns. For instance, alterations in regional climate patterns are expressed in terms of their implications for food security, considering impacts on crop yields, agricultural productivity, and global food supply chains. Similarly, changes in hydrological cycles are framed in the context of water security, highlighting potential challenges in water availability for human consumption, agriculture, and industry.

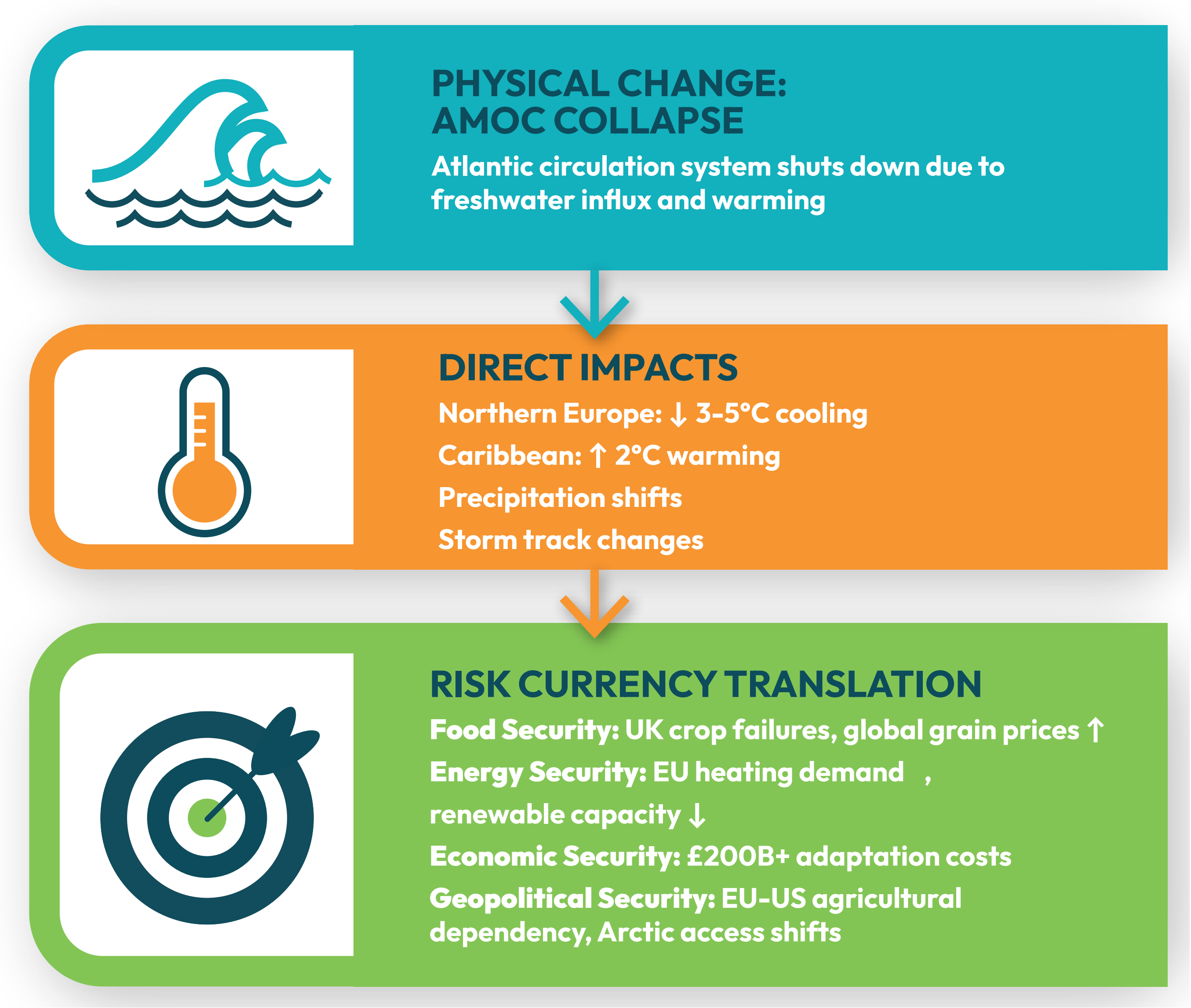


Figure 2.1.6: AMOC collapse risk currency example, demonstrating how physical ocean circulation changes translate into specific policy-relevant impacts across food security, energy security, economic security, and geopolitical domains.

This approach extends to other critical areas of concern for decision-makers. Climate-induced alterations in ecosystems and resource availability are presented in terms of their potential impacts on national security, including the risk of resource conflicts or climate-driven migration. Energy security is another crucial 'currency', with the framework articulating how climate tipping points might affect energy production, distribution, and consumption patterns.

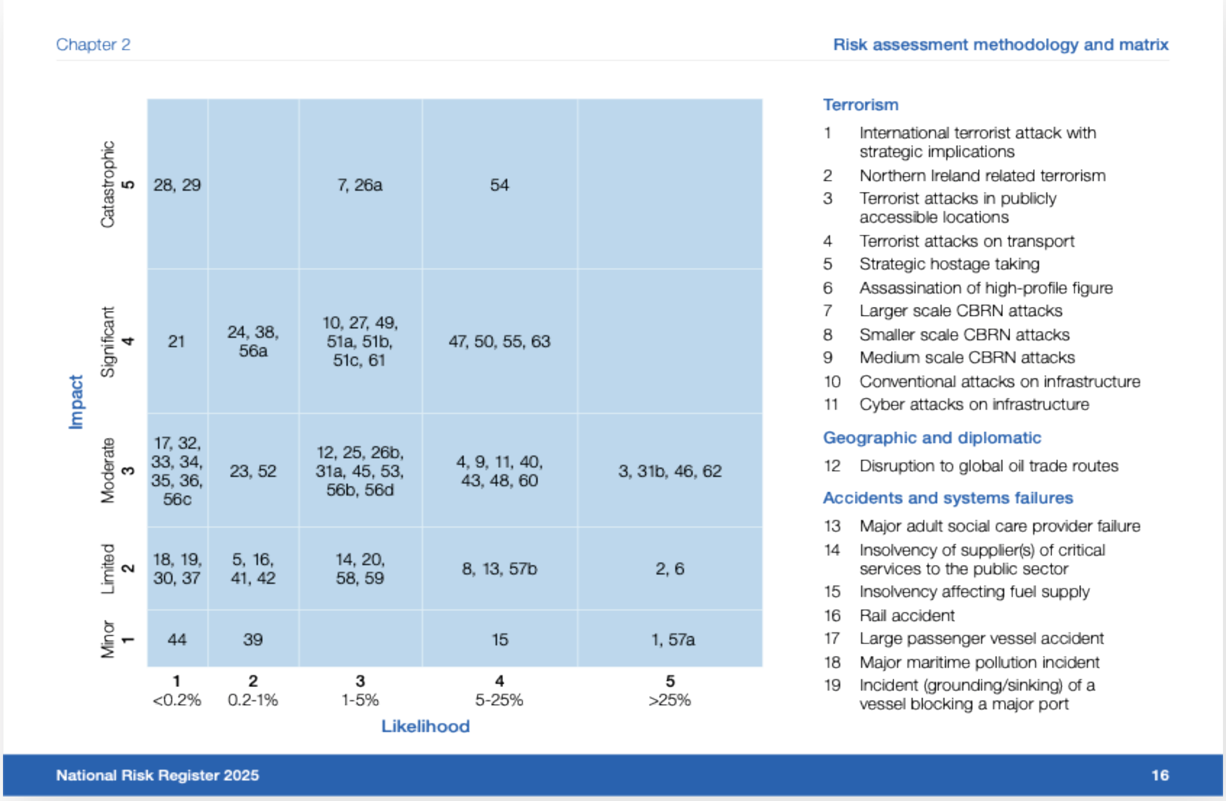
Risk register

Earth system tipping points represent some of the most significant and poorly understood risks in climate science, yet they remain inadequately integrated into policy and risk management frameworks (Armstrong McKay et al., 2022; Lenton et al., 2019). Unlike conventional risks that follow predictable patterns, tipping points involve the change in behaviour of a system beyond a threshold, where small changes in forcing can trigger large, often irreversible changes that fundamentally alter Earth system functioning (Lenton et al., 2008). These systems are characterized by deep uncertainty, meaning precise probabilities cannot be determined with current knowledge, even as scientific understanding advances (Kriegler et al., 2009). Assessing such deep uncertainty requires specialized approaches that move beyond traditional probabilistic risk assessment toward frameworks designed specifically for high impact-low likelihood events where precise probabilities cannot be determined (Wood et al., 2023). This uncertainty is compounded by the cascade potential inherent in these systems, as individual tipping points can interact through complex feedback mechanisms to trigger others, creating the possibility of cascading failures across the Earth system (Wunderling et al., 2021; Wunderling et al., 2024; Klose et al, 2021; Wunderling et al, 2023; Spaiser et al (2024).

The temporal dimension of tipping point risks presents additional challenges for traditional risk management. Many changes associated with tipping points are irreversible on policy-relevant timescales of decades to centuries, meaning that once triggered, these changes cannot be undone through conventional mitigation strategies (Steffen et al., 2018). Furthermore, even regionally-focused tipping points can have global implications, with worldwide consequences for human societies, economies, and ecosystems far from the original source of change (Wang et al., 2023).

Governments use risk registers to provide practical examples of how complex, interconnected risks are assessed and communicated to policymakers and the public, such as the UK's National Risk Register (HM Government, 2025; Figure 2.1.7). A risk register is a tool used to identify, assess, and support the management of risks within a given context. It provides a structured way to record potential threats. The main purpose of a risk register is to support better decision-making via the qualitative or quantitative assessment of the severity and likelihood of an impactful event. By providing a clear overview of current and emerging risks, a risk register can help those with responsibility for risk management to prioritise actions, allocate resources, and remain accountable. As such, risk registers are also a key part of transparency and governance. Overall, a risk register should enable proactive, rather than reactive, management, reducing the chance of being caught off guard and improving the likelihood of achieving objectives.

Risk registers are typically presented as a table, spreadsheet, or a matrix that focuses on quantities relevant to assessment and management. For example, a risk register used by a government to identify major threats at the scale of a society is typically constructed using a matrix plotting the potential impact of a risk against a calculation of the likelihood.



Chapter 2

Risk assessment methodology and matrix

Impact	1 <0.2%	2 0.2-1%	3 1-5%	4 5-25%	5 >25%
Catastrophic 5	28, 29		7, 26a	54	
Significant 4	21	24, 38, 56a	10, 27, 49, 51a, 51b, 51c, 61	47, 50, 55, 63	
Moderate 3	17, 32, 33, 34, 35, 36, 56c	23, 52	12, 25, 26b, 31a, 45, 53, 56b, 56d	4, 9, 11, 40, 43, 48, 60	3, 31b, 46, 62
Limited 2	18, 19, 30, 37	5, 16, 41, 42	14, 20, 58, 59	8, 13, 57b	2, 6
Minor 1	44	39		15	1, 57a

Likelihood

Terrorism

1 International terrorist attack with strategic implications
2 Northern Ireland related terrorism
3 Terrorist attacks in publicly accessible locations
4 Terrorist attacks on transport
5 Strategic hostage taking
6 Assassination of high-profile figure
7 Larger scale CBRN attacks
8 Smaller scale CBRN attacks
9 Medium scale CBRN attacks
10 Conventional attacks on infrastructure
11 Cyber attacks on infrastructure

Geographic and diplomatic

12 Disruption to global oil trade routes

Accidents and systems failures

13 Major adult social care provider failure
14 Insolvency of supplier(s) of critical services to the public sector
15 Insolvency affecting fuel supply
16 Rail accident
17 Large passenger vessel accident
18 Major maritime pollution incident
19 Incident (grounding/sinking) of a vessel blocking a major port

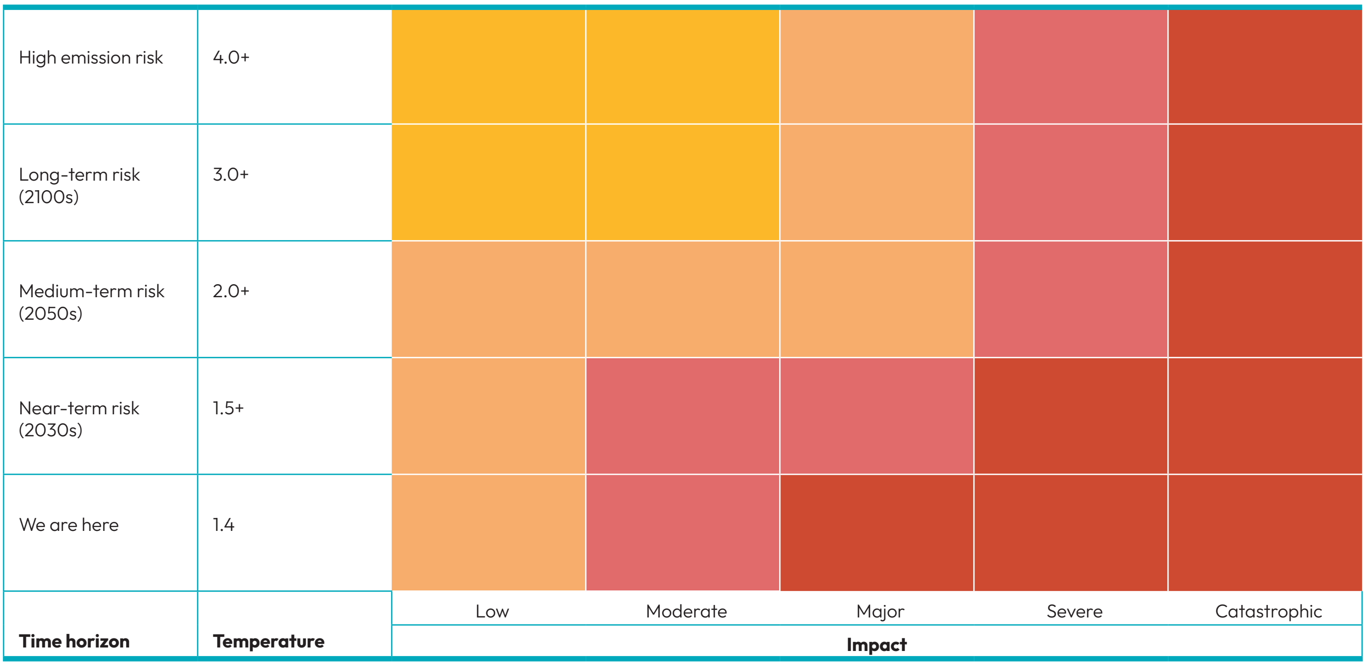
National Risk Register 2025 16

Figure 2.1.7: Example from the UK Government's National Risk Register showing systematic risk assessment methodology, including likelihood-impact matrices and consideration of cascading effects that inform our adapted framework for Earth system tipping points. Source: HM Government (2025) National Risk Register 2025, Cabinet Office.

These registers demonstrate systematic approaches to categorizing risks by likelihood and impact, while also considering cascading effects and dependencies between different risk types. Our ESTP framework builds on these established risk assessment methodologies, adapting them specifically for the unique challenges posed by Earth system tipping points.

Traditional risk register approaches face significant limitations when applied to tipping point systems characterised by deep uncertainty, as precise probability estimates are often misleading or impossible to determine reliably. To illustrate how these approaches could be better adapted for tipping points, we have developed a mock Earth system tipping points risk register (Figure 2.1.8) that uses temperature thresholds as a proxy for the timing of when different tipping points may be triggered, rather than using conventional likelihood categories.

This approach recognizes that while we cannot assign precise probabilities to tipping events, we can identify the temperature ranges at which different systems become vulnerable based on current scientific understanding. While this temperature-based risk register provides a systematic approach for communicating ESTP risks to policymakers, Chapter 2.4 explores this approach alongside alternative methods including impact-focused assessments that emphasize consequence severity rather than probabilistic estimates. These methods provide more robust foundations for policy decision-making under conditions of deep uncertainty, where the focus shifts from predicting when tipping points will occur to understanding what happens if and when they do.



High emission risk	4.0+	🟨	🟨	🟧	🟥	🟫
Long-term risk (2100s)	3.0+	🟨	🟨	🟧	🟥	🟫
Medium-term risk (2050s)	2.0+	🟧	🟧	🟧	🟥	🟫
Near-term risk (2030s)	1.5+	🟧	🟥	🟥	🟫	🟫
We are here	1.4	🟧	🟥	🟫	🟫	🟫
		Low	Moderate	Major	Severe	Catastrophic
Time horizon	**Temperature**	**Impact**				

Figure 2.1.8: Prototype Earth system tipping points risk register using temperature thresholds as a proxy for timing. Unlike traditional risk registers that rely on probability estimates, this template acknowledges deep uncertainty by categorizing tipping point risks according to the temperature ranges at which different Earth systems become vulnerable to irreversible change. This framework provides a structure for communicating risks to policymakers when precise likelihood estimates are unreliable or impossible to determine.

Looking ahead

The following chapters apply this framework. **Chapter 2.2** provides detailed scientific assessment of individual tipping points, their thresholds, timescales, and interactions with each other. **Chapter 2.3** examines the critical question of temperature overshoot scenarios and their implications for tipping point risks. **Chapter 2.4** implements our risk register approach through regional and sectoral impact assessment, translating Earth system science into actionable risk information across nine policy-relevant risk currencies.

2.2 Status of Earth system tipping points: What's new?

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Acknowledged: Daniel Mayor, Arie Staal, Els Weinans

Key messages

Cryosphere

- We have high confidence that ice sheets - from Greenland to West Antarctica - have tipping points leading to irreversible collapse, locking in long-term multi-metre sea level rise, and have been at risk since at least 1°C of global warming.
- While Arctic summer sea ice is unlikely to reach tipping points, we cannot rule out a tipping point for Antarctic sea ice which could already be underway, although this is highly uncertain.
- We have medium confidence in potential regional tipping in permafrost and glaciers, which would respectively amplify emissions and commit some regions to total deglaciation.

Biosphere

- The Amazon rainforest has faced two years of intense El Niño-induced drought, and the combined effects of deforestation and climate change put it at risk below 2°C of global warming.
- Warm-water coral reefs have experienced the worst bleaching event on record over 2023-25, and the central estimate of their thermal tipping point of 1.2°C global warming has been crossed.
- We now recognise river deltas and peat bogs as potential tipping systems, identify the potential for localised mangrove tipping with high confidence, and the potential for local-scale temperate forests tipping with low confidence.

Ocean/Atmosphere circulations

- Recent modelling supports convection in the Atlantic Meridional Overturning Circulation (AMOC) and subpolar gyre being capable of tipping, which cannot be ruled out at current warming levels, but limited models and observations means how likely they are to tip on current trajectory remains uncertain.
- In the Southern Ocean, dense shelf Water formation may be declining and could reach a tipping point, but understanding of its interactions with ice remains limited.
- Evidence has strengthened for no tipping dynamics in the 'jet stream', while recent modelling supports monsoons having tipping dynamics, but evidence remains limited.

Interactions

- Out of 20 climate tipping system interactions assessed, most are destabilising, but a few (e.g. AMOC on Amazon, West Antarctic Ice Sheet on AMOC) may have a stabilising effect.
- A vicious cycle may form where permafrost thaw could lead to amplified Arctic sea ice retreat, which may lead to enhanced inland permafrost degradation and so on.
- The AMOC is the key global mediator of tipping point interactions, featuring in 45 per cent of all assessed tipping point interactions.

2.2.1 Executive summary

Many parts of the Earth system can reach a point beyond which change in response to pressure can become self-sustaining, resulting in an often irreversible and abrupt shift to a very different state - what we refer to as a 'tipping point'. In this chapter we briefly summarise each proposed tipping system covered by the last Global Tipping Points Report, and reassess each based on relevant new scientific research published since the last report.

In the **cryosphere** - Earth's frozen reaches - we (the Global Tipping Points community) maintain high confidence in ice sheet tipping points, two of which have been at risk since around 1°C of warming, with potentially substantial consequences for future sea level rise. We also maintain medium confidence in local to regional tipping in permafrost and glaciers, with implications for amplified emissions and regional deglaciation. While Arctic summer sea ice decline is unlikely to reach a tipping point, we cannot rule out tipping for it in the winter, or around Antarctica, where sea ice has recently dropped for the first time.

In the **biosphere** - the living world - we are more confident in the potential for tipping in the Amazon at various scales, and note that combined with ongoing deforestation as little as 1.5°C of warming could trigger widespread dieback. Both the Amazon and coral reefs have suffered during the 2024-25 El Niño event, seeing the worst coral bleaching event on record and signs of die-off in many regions. We also have higher confidence in localised mangrove tipping, and now include peat bogs and river deltas as potential freshwater tipping systems.

In the **circulations of the ocean and atmosphere**, recent research strengthens the case for North Atlantic convection being capable of tipping, potentially at current warming levels, but large uncertainties remain on if and when they may tip in practice. Convection around Antarctica may also be weakening towards a tipping point, driven by warming and meltwater, but we are not sure how this in turn interacts with ice melt. We now include the East Asian summer monsoon as a potential tipping system, but remain confident that despite changes in response to warming the northern polar 'jet stream' as well as the El Niño Southern Oscillation (ENSO) and large-scale tropical circulations are unlikely to have a tipping point.

Tipping points do not exist in isolation - they **interact** in ways that can change the likelihood of their tipping. We have extended our previous analysis to cover more than twenty climate tipping system interactions, adding in for example interactions with subglacial basins in East Antarctica or interactions with the permafrost. Our newest science updates maintain the finding that the majority are destabilising. For example, a vicious cycle may form where permafrost thaw releases greenhouse gases, driving further warming and more Arctic sea ice retreat, which by making the Arctic darker amplifies warming, amplifying inland permafrost degradation, and so on. The AMOC emerges as a key global mediator of tipping point interactions, featuring in nearly half of all assessed tipping point interactions, including a few that may potentially have a stabilising effect, such as AMOC collapse's impact on the southern Amazon rainforest, and West Antarctic Ice Sheet impact on the AMOC.

2.2.2 Summary table

Table 2.2.1: Tipping assessment for each system considered, highlighting changes since GTPR23. Key: +++ (high confidence yes), ++ (medium yes), + (low yes), ? (uncertain), – – – (high no), – – (medium no), – (low no).

Domain	Tipping system (& tipping dynamics)	GTPR25 tipping system assessment (bolded if changed vs. GTPR23)
Cryosphere	**Ice Sheets (collapse)**	Greenland: +++ **[threshold updated]** West Antarctica: +++ Marine basins East Antarctica: +++ Non-marine East Antarctica: ++
	Sea Ice (loss)	Arctic summer: - - - **Arctic winter: ?** [was: - -] Barents Sea: - Antarctic / Southern Ocean: ?
	Glaciers (retreat) See 4.4 Mountain glaciers case study	++ (regional) - - (global)
	Permafrost (thaw)	++ (regional, land) - - (global, land / subsea)
Biosphere	**Tropical Forests (dieback)** See 4.1 The Amazon rainforest case study	Amazon: +++ (local) **[threshold updated]** ++ (regional) + (continental) Congo: + (local), **? (regional)** [regional added] SE Asia: ? (local), - - (regional)
	Boreal Forests (dieback / expansion)	Dieback: ++ (regional) + (continental) Northern Expansion: + (regional)
	Temperate Forests (dieback)	**+ (local)** [local added] ? (regional)
	Savannas & Grasslands (regime shifts)	++ (local to landscape) ? (regional)
	Drylands (regime shifts)	++ (local to landscape) + (regional)
	Freshwater (regime shifts)	Eutrophication-driven lake anoxia: +++ (widespread localised) Lake DOM loading ('browning'): ++ (widespread localised in boreal) Lake (dis)appearance: – (widespread localised in tundra) Lake N to P-limitation switch: – (localised in high N-deposition regions) Lake salinisation: – (localised in arid regions) Lake invasive species: – (widespread localised) **River deltas: + (localised)** [system added] **Peat bogs: ++ (localised)** [system added]
	Coastal ecosystems (regime shift)	**Mangroves: +++ (local)** [local added] ++ (regional) Seagrass meadows: ++ (regional) Kelp forests: +++ (local)
	See 4.3 Warm-water coral reefs case study	+++ (localised) +++ (regionally clustered)

Table 2.2.1: Tipping assessment for each system considered, highlighting changes since GTPR23. Key: +++ (high confidence yes), ++ (medium yes), + (low yes), ? (uncertain), – – – (high no), – – (medium no), – (low no).

Domain	**Tipping system (& tipping dynamics)**	**GTPR25 tipping system assessment (bolded if changed vs. GTPR23)**
	Marine (benthic & pelagic) ecosystems (regime shifts)	Cod fisheries: +++ (regional) Large fish fisheries: + (regional) Small fish fisheries: – (regional) Marine communities: + (local) Biological (lipid) pump: ? (regional) Biological (gravitational) pump: – – (regional) Marine hypoxia: + (local), ? (regional to global)
Ocean & atmosphere circulations	**Ocean overturning (collapse)** See 4.2 Atlantic Ocean circulation case study	Atlantic Meridional Overturning Circulation (AMOC): ++ Deep convection in North Atlantic Subpolar Gyre (SPG): ++ Southern Ocean: ++
	Monsoons (abrupt collapse / intensification)	West African: + Indian Summer: ? South American: ? **East Asian Summer: ?** [system added]
	Tropical clouds & circulation (reorganisation)	– –
	ENSO (extreme / permanent)	– –
	Mid-latitude jet (wavier)	–

2.2.3 Introduction

The Earth system describes the interconnected complex system at the surface of the planet that sustains life, including the cryosphere (ice-related systems, including ice sheets, sea ice, glaciers and permafrost), biosphere (all living things), atmosphere, hydrosphere (water-based systems, including oceans, rivers and lakes), and the lithosphere (the Earth's solid surface) (Kump, Kasting, & Crane, 1999; Lenton, 2016).

Evidence has accumulated from models, palaeorecords, and observations that change in many parts of the Earth system can under certain circumstances become self-sustaining once forced beyond a threshold, leading to a state change driven by positive (i.e. amplifying) feedback loops, and/or the weakening of negative/balancing feedback loops (Lenton et al., 2008; Armstrong McKay et al., 2022; Wang et al., 2023; GTPR23). We refer to this situation as a 'tipping point', and the systems that this dynamic occurs in as 'tipping systems' (see Introduction of the report).

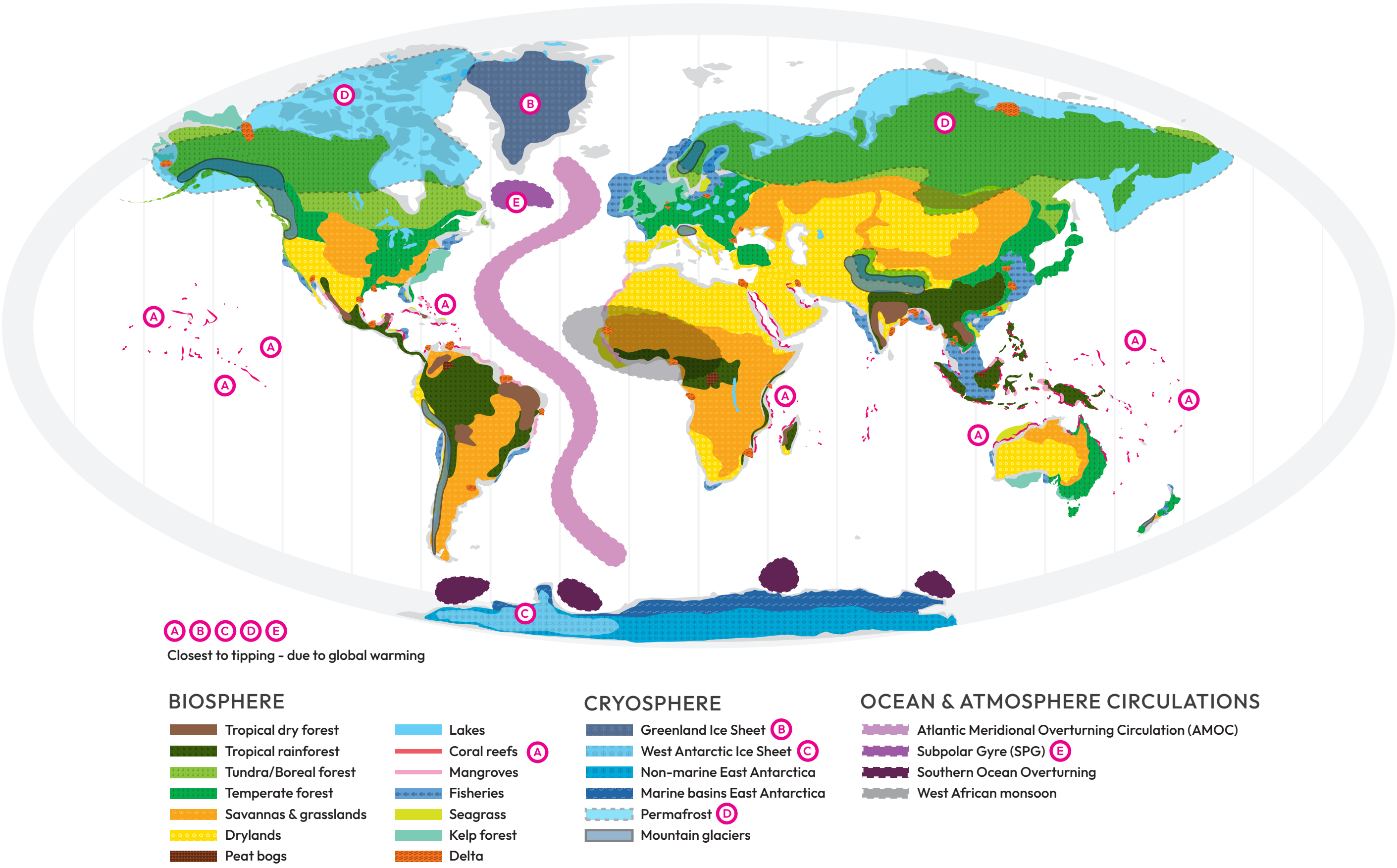

Figure 2.2.1: Map of potential tipping systems across the biosphere, cryosphere, and circulations in oceans and atmosphere.

In the first Global Tipping Points Report (GTPR23), over 120 Earth and environmental scientists assessed the biophysical evidence for tipping dynamics across the Earth system. We assessed the scientific literature for each proposed tipping system, and using collective expert judgement then judged if sufficient evidence exists for tipping dynamics in that system along with an associated confidence level (following the IPCC system; Mastrandrea et al. (2010)), and identified knowledge gaps to be targeted with further research. Based on this, we found evidence for potential tipping in many parts of the Earth system, across the cryosphere, biosphere, and ocean/atmosphere circulations, several of which may already be close to tipping thresholds due to a variety of anthropogenic pressures (Figure 2.2.1).

Since the last Global Tipping Points Report was published, new research has deepened our understanding of many of these systems. In this chapter, we briefly describe each system and our previous assessment of its tipping dynamics, before summarising insights from new research on it, and presenting any changes to the assessments made in GTPR23 (summarised in Table 2.2.1).

2.2.4 Methodology

There are many sources of information that Earth system science draws from. Broadly classified, there are direct observations (in-situ measurements and remote sensing), proxy records on historic or palaeo timescales (indirect reconstructions, e.g. inferring past temperatures via certain isotope concentrations) and models of differing complexity. The latter range from conceptual (e.g. box models) over component models (e.g. ice sheet models representing the relevant physical processes) to fully coupled Earth system models (e.g. the models participating in the Coupled Model Intercomparison Project, CMIP). All these lines of evidence come with their respective strengths and drawbacks, and can help construct a consistent understanding of a system (Boers, Ghil & Stocker, 2022).

In line with the tipping point definition above and as described in Loriani et al. (2025), our assessment reviews evidence for the presence of feedback loops that can drive self-perpetuating change beyond a threshold, leading to a state shift in that system. The confidence in our assessment increases with both robustness and agreement of evidence, following the IPCC system (Mastrandrea et al., 2010). Table 2.2.2 summarises the criteria for different confidence levels.

Critically, this confidence rating concerns merely whether a system can tip under plausible future conditions (within coming centuries to millennia), not that it will tip in future, or could tip under any circumstances. Although these questions are tightly related, estimating whether a system is likely to tip requires quantification of the critical threshold and an assessment of whether that threshold will be transgressed, including a discussion of overshoots and timescales. All of these aspects are surrounded by considerable uncertainties for different systems.

Table 2.2.2: Summary of confidence level criteria for ESTP assessments in this chapter.

Confidence	Criteria (from Loriani et al. [2025])
High (+++)	Multiple, independent lines of evidence consistently indicate the presence of feedback loops that can drive self-perpetuating change beyond a threshold on plausible future trajectories, leading to a state shift in that system. Strong palaeo analogues, consistent tipping behaviour in models across the hierarchy. If applicable, proxy and direct observations are compatible with the expected tipping dynamics.
Medium (++):	Multiple, independent lines of evidence indicate the presence of such feedback loops. However there are uncertainties in timing, magnitude or feedback strength. e.g. there are tipping dynamics in some models, and palaeo records hint at dynamics compatible with tipping. Support from observations is limited or contested.
Low (+):	Singular lines of evidence indicate the presence of such feedback loops. Tipping dynamics only emerge in specific models or under constrained assumptions. e.g. tipping is in principle conceivable via conceptual models, but there are no clear or only weak palaeo analogues. Limited demonstration of tipping dynamics in numerical models.
Not a tipping system	There is evidence indicating the lack of feedback loops that can drive self-perpetuating change beyond a threshold (with low/medium/high confidence).
Unclear	There is conflicting or limited evidence about the existence of such feedback loops.

2.2.5 Potential tipping points in the cryosphere

The cryosphere includes all of the ice-bound parts of the Earth, including ice sheets (separated into the Greenland and Antarctic ice sheets, the latter also subdivided into West Antarctic and East Antarctic ice sheets), mountain glaciers, sea ice, and permafrost.

In this section, we describe each of these systems, their evidence for tipping dynamics, and relevant new research in turn. Based on this, we have reassessed the status of several systems, including the threshold range for the Greenland Ice Sheet, updating Arctic winter sea ice from not a tipping system (low confidence) to uncertain, and discussing the potential implications of recent drop in Antarctic sea ice (Figure 2.2.2).

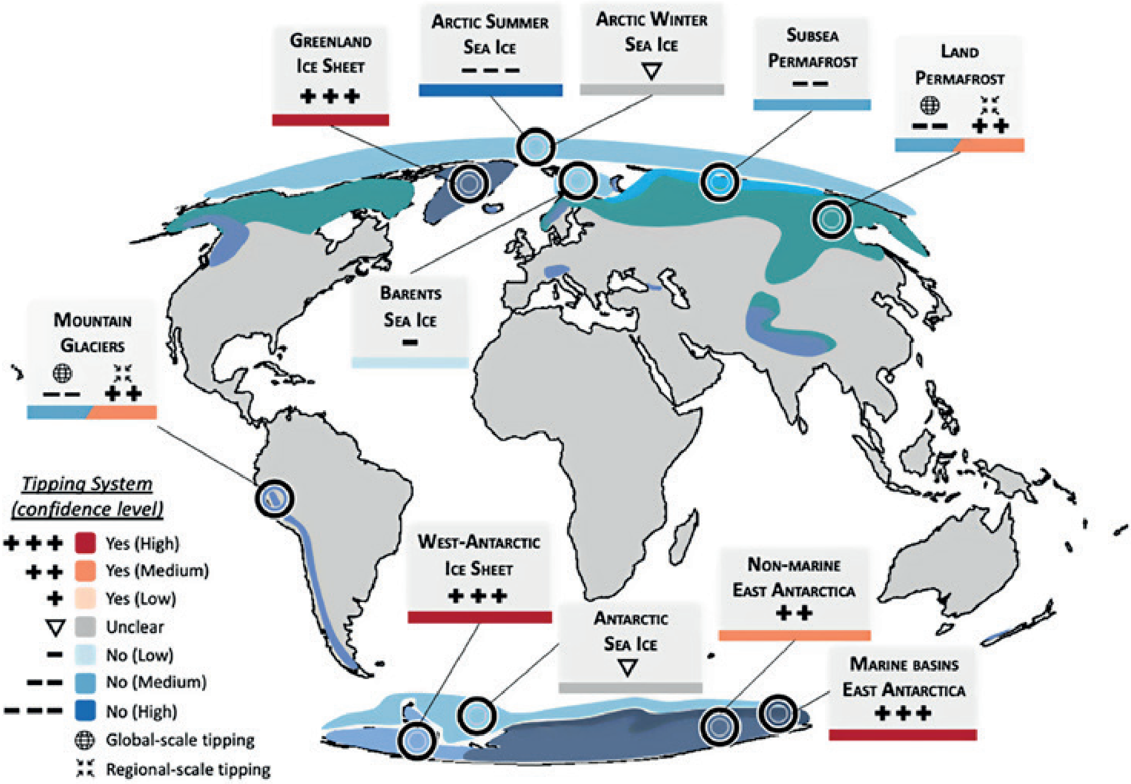

Figure 2.2.2: Map of cryosphere systems considered in this chapter (shading). The markers indicate which of the systems are in this report considered a tipping system (+++ high confidence, ++ medium confidence and + low confidence) and which are not (– – – high confidence, – – medium confidence and – low confidence), ▽ indicates systems for which a clear assessment is not possible based on the current level of understanding.

Greenland Ice Sheet

What it is

The Greenland Ice Sheet (GrIS) consists of the ice sheet covering the island of Greenland, and contains the equivalent of circa 7 metres of sea level equivalent (SLE) (Aschwanden et al., 2019). Palaeoclimate evidence suggests that while it survived many recent interglacials (i.e. warm interludes between cold 'Ice Age' glacials, of which the current Holocene is the latest), it partly collapsed during the last interglacial 130,000 to 115,000 years ago (a.k.a. the 'Eemian', or 'MIS5e'), and may have collapsed during the 'MIS11' interglacial ~420,000 to 395,000 years ago when sea levels were likely 6 to 13 m higher than present (Alley et al., 2010; Schaefer et al., 2016; Rachmayani et al., 2017; Robinson et al., 2017; Christ et al., 2021). While MIS11 may have reached a warmer peak than MIS5e (with up to ~2°C in the former and up to ~1.5°C in the latter relative to pre-industrial, albeit with high uncertainty and differing orbital configurations and regional patterns (Rachmayani et al., 2017; Fox-Kemper et al., 2021)), the larger estimated ice loss during the older interglacial is likely due to a longer duration of warmer climate (Robinson et al., 2017). This sensitivity to only marginally higher warming than preindustrial indicates the presence of a tipping dynamic. Some models also support this, indicating that this is largely driven by melt-elevation feedback, in which ice mass loss leads to the ice sheet surface dropping to warmer altitudes, accelerating ice loss. Below a critical elevation, this process leads to inevitable collapse even if global warming were to halt or reverse (Boers & Rypdal, 2021). If triggered, GrIS collapse would play out over millennia (1-10ky; A. McKay et al. (2022)), but would lock in a multi-metre sea level rise that would prove catastrophic to coastal areas. Early warning signals of tipping points in the Greenland Ice Sheet have been identified in empirical data (Boers & Rypdal, 2021), and ~30 cm sea level rise from Greenland may already be locked in, regardless of emissions scenario (Box et al., 2022).

What's new

In GTPR23, GrIS was assessed as a tipping system with high confidence, with high confidence too in it involving abrupt / large rate change and irreversibility over decadal/centennial timescales, and a threshold range of 0.8-3°C of global warming (Winkelmann, Steinert & Armstrong Mckay et al., 2023).

Since GTPR23, there have been several new publications relevant to this system. Recent observations have shown ongoing mass loss from the GrIS, with 196 ± 37 km3/yr of volume lost between 2010 and 2022 (Ravinder et al., 2024) and widespread accelerated calving across the GrIS from 1985 (Greene et al., 2024), as well as increased crevassing associated with an acceleration of ice flow at the marine-terminating sectors of the GrIS (Chudley et al., 2025). There has also been an increase in extreme melting event frequency and intensity across the GrIS since 1950 (Bonsoms et al., 2024).

The irreversibility of ice loss from the GrIS in a fully coupled Earth system model of intermediate complexity is highlighted in Höning et al. (2024), which finds that once the southern GrIS has melted with a mass loss of greater than 0.4 m SLE, total regrowth would require atmospheric greenhouse gas concentrations below pre-industrial and timescales in the order of 10,000s years. While carbon dioxide removal technologies would be required to bring global warming levels down to below +1.0°C, such technologies at scale are hypothetical and strong ambitions to curb emissions are the most important way to prevent the GrIS from crossing a tipping threshold. Another recent study (Petrini et al., 2024) suggests that a global mean warming of 3.2-3.4°C above pre-industrial levels could result in a near full melt of the GrIS. Again this would unfold over 1,000s-10,000s of years. The higher the temperature forcing, the shorter the timescale of collapse. This analysis also suggests that the topography of the central west of Greenland may play a role in stabilising the GrIS (Petrini et al., 2024).

Based on this new research, the GTP community maintains its assessment of GrIS being a tipping system with high confidence, with an updated threshold range of 0.8-3.4°C.

Antarctic Ice Sheet

What it is

The Antarctic Ice Sheet (AIS) can be divided into the mostly marine-based West Antarctic Ice Sheet (WAIS), the marine-based sectors of East Antarctica, and the non-marine regions of the East Antarctic Ice Sheet (EAIS), on account of the differing dynamics and temperature thresholds associated with their tipping. The response of the Antarctic Ice Sheet—the largest source of long-term sea-level rise—to global warming remains poorly constrained, and large uncertainty regarding its future contribution to global sea-level rise remains (Seroussi et al., 2024; Levermann et al., 2020). The AIS responds extremely slowly to changes in its surrounding climate, so that the full consequences of past and ongoing warming may take centuries or longer to fully unfold (Clark et al., 2016; Klose et al., 2024). Nevertheless, Antarctica is already today losing mass and contributing to sea-level rise (IMBIE team, 2018), with losses projected to accelerate even if global temperatures were stabilised at today's levels (Reese et al., 2023).

The WAIS is separated from the EAIS by the Transantarctic Mountains and holds enough ice to raise sea levels by ~5 m. Unlike the EAIS, which largely rests on bedrock above the sea level, the majority of the WAIS rests on a bed well below sea level, making it especially vulnerable to ocean warming (either directly or by changes in ocean circulation). In contrast to the GrIS, much of the coast of Antarctica is fringed by floating ice shelves, which create a vulnerable point of contact with the ocean. These connections to the ocean, as well as the fact that most of its ice is resting below the sea level, make the WAIS much more vulnerable to climate warming than the EAIS. A collapse of the WAIS would lock in long-term sea-level rise on the order of 3-5 meters, depending on collapse extent (Garbe et al., 2020). At current temperatures, a partial WAIS collapse may already be unavoidable in the long term (Reese et al., 2023). Evidence exists for the collapse of the WAIS during past warm periods, such as the last interglacial (DeConto and Pollard, 2016; Sutter et al., 2016; Turney et al., 2020; Thomas et al., 2020; Weber et al., 2021) and the Pliocene when temperatures were ~2-3°C warmer than pre-industrial (Naish et al., 2009; Grant et al., 2019; DeConto et al., 2021). Several potential mechanisms for WAIS tipping have been proposed. One likely candidate for WAIS loss is Marine Ice Sheet Instability (MISI), when the grounding line sits on a slope that deepens into the ice sheet interior. When the ice retreats inland the greater ice thickness means that more ice flows into the ocean This causes additional thinning and retreat, resulting in a self-accelerating loss until the ice reaches a stable point (often a higher bedrock elevation) (Weertman, 1974; Schoof, 2007; Mengel and Levermann, 2014; Feldmann and Levermann, 2015; Garbe et al., 2020). Another proposed feedback mechanism is Marine Ice Cliff Instability (MICI), whereby ice shelf collapse creates inherently unstable tall marine-terminating ice cliffs, which in turn rapidly collapse and cause a self-reinforcing feedback of ice recession, which only terminates when ice cliff is buttressed or the water shallows (DeConto et al., 2021). However, this feedback has not been observed in Antarctica (yet) and there is much less scientific consensus on this instability than MISI.

Marine-based ice-sheet sectors (like much of the WAIS) also exist in East Antarctica, including in the Wilkes, Aurora, and Recovery subglacial basins. They are potentially vulnerable to the same tipping dynamics as WAIS, including the MISI and the MICI (Morlighem et al., 2020; Stokes et al., 2022). However, unlike the WAIS, palaeorecords of previous interglacials as well as models still carry large uncertainty with regard to their vulnerability. However, most studies suggest that the critical temperature threshold of EAIS marine-based sectors is above that of the WAIS or the GrIS.

Beyond its marine basins, the majority of the EAIS lies above sea level, containing an ice amount equivalent to ~34 meters of global sea level rise (Pritchard et al., 2025). As they have no connection to the ocean, these parts of the ice sheet are not vulnerable to the instabilities of marine-based ice. However, although less vulnerable than the GrIS due to its thermal isolation and its location over the pole, the EAIS is susceptible to the melt-elevation feedback, which might cause self-sustained and irreversible ice loss in the long term (perhaps multiple millenia) if temperatures exceed 6°C of global warming (Garbe et al., 2020). Under current projected warming scenarios, only modest ice loss is expected from this part of the ice sheet, and models suggest an excess of 10°C warming might be needed to lead to complete ice sheet loss (Garbe et al., 2020). Crucially, if the ice sheet were to be lost, there would likely be strong hysteresis, requiring far greater cooling for the ice sheet to be restored.

What's new

WAIS was previously identified as a tipping system with high confidence, with a high likelihood of abrupt / large rate change and irreversibility on a decadal/centennial timescale, with an associated temperature threshold of 1-3°C. Marine-based East Antarctica was identified as a tipping system with high confidence, with a high confidence in abrupt / large rate change and irreversibility on a decadal/centennial timescale, with an associated temperature threshold of 2-6°C. Non-marine based East Antarctica was identified as a medium confidence tipping system, with a high confidence in abrupt / large rate change and medium confidence in irreversibility on a decadal/centennial timescale, with an associated temperature threshold of 6-10°C (Winkelmann, Steinert & Armstrong Mckay et al., 2023). Since GTPR23, there have been numerous publications which are relevant to the science of ice sheet tipping points for the WAIS, marine-based and non-marine based EAIS, and across the whole Antarctica. We shortly highlight these new studies below for the AIS as a whole, and for West and East Antarctica separately.

Across the whole of Antarctica

On potential thresholds, an ice sheet model forced by different climate model simulations of the warm mid-Pliocene (3-3.3 million years ago) compared with warming stabilised at current levels indicates that WAIS collapse occurs with a modest 0.5-1°C of ocean warming above pre-industrial, while the East Antarctic Wilkes Subglacial Basin retreats at a higher level of around 3°C oceanic warming (depending on precipitation changes) (Blasco et al. 2024). Using an ice-sheet model, Coulon et al. (2024) identify a threshold of +7.5°C warming above pre-industrial to amplify melt–elevation feedback across the Antarctic, leading to a complete collapse of the WAIS and retreat of the marine EAIS. Recent simulations in a coupled climate-ice-sheet model also support strong hysteresis of the Antarctic Ice Sheet driven by melt-albedo feedback with associated critical thresholds of atmospheric CO_2 levels for Antarctic Ice Sheet loss (Leloup et al., 2025). Lastly, considering evidence from previous warm periods, ice sheet mass balance observations, and models, Stokes et al. (2025) recently argued that the current warming level is high enough to see substantial loss of ice sheets, and that a long-term limit of 1°C, or lower, above pre-industrial levels is necessary to avert substantial ice sheet loss.

On potential tipping dynamics, further modelling studies have supported the committed nature of sea level rise from Antarctic Ice Sheet loss (Alevropoulos-Borrill et al., 2024), including some degree of committed sea level rise from having potentially passed a tipping point in the Amundsen Sea sector of West Antarctica (Bett et al., 2024) (although a modelling study by Hill et al. (2023) found that a tipping point has not yet been crossed). The sensitivity of ice sheets to intrusion from warmer sea water is identified as an underestimated cause of tipping points in one model (Bradley & Hewitt, 2024). Ice sheet modelling shows that basal water conditions can bring forward tipping points by up to 40 years (Zhao et al., 2025). Atmospheric extreme events - often associated with atmospheric rivers, which are responsible for 50–70 per cent of extreme snowfall events in Antarctica, as well as being involved in the Larsen A and B ice shelf collapses during surface melting events - are not resolved by current-generation models, and could potentially result in faster melting than expected (Kolbe et al., 2025; Wille et al., 2025).

West Antarctica

There is further evidence that the WAIS is committed to long-term collapse at current or near current temperature levels (Van den Akker et al. 2025; Chandler et al., 2025), with each additional fraction of warming increasing the likelihood that collapse could be initiated much sooner. Recent studies show that the WAIS is particularly vulnerable to ocean warming and grounding line retreat (Hill et al., 2024; Rignot et al. 2024). In the ISMIP6 ensemble of 16 ice flow models up to 2300, Seroussi et al. (2024) found a retreat of the WAIS leading to a rapid increase in sea level rise after 2100, reaching up to 4.4 m SLE by 2300 under high-emission scenarios. Offshore sediment cores also indicate that West Antarctica remained ice-free during the initial formation of the Antarctic Ice Sheet following the Eocene-Oligocene Transition around 34 million years ago, implying lower temperatures are required for WAIS formation as well as loss (Klages et al., 2024).

Recently, a study using three ice sheet models showed that the WAIS might be less vulnerable to MICI than previously thought (Morlighem et al., 2024). Additionally, ice core data suggests that the West Antarctic Ronne Ice Shelf survived the Last Interglacial (approximately 125,000 years ago) when regional Antarctic temperatures were higher than today (Wolff et al, 2025), thus suggesting the WAIS may be less sensitive to MICI than previously suggested. Conversely, a study currently under review uses empirical data to suggest that MICI may be sensitive to parameters other than cliff height, such as ice thickness gradients, and if these parameters were better resolved in models more future cliff-calving may be projected (Needell, Walker and Bassis, under review). Additionally, other mechanisms could still lead to a tipping point, and there is still uncertainty around the timing of this (Fricker et al., 2025).

East Antarctica

Hydrological feedbacks, associated with meltwater flowing beneath the ice sheet, which could accelerate ice loss in East Antarctica, are identified in a recent coupled ice sheet-subglacial hydrology model (Pelle et al., 2024). This suggests that models without these feedbacks could underestimate future sea level rise. EAIS vulnerability is shown through the recent sudden disintegration of the Conger-Glenzer Ice Shelf, which is mapped with remote sensing data in Walker et al. (2024).

Summary

Based on this new research, the GTP community maintains its assessment of the WAIS being a tipping system with high confidence (with high agreement across robust evidence). We also assess that the current lower-end threshold estimate for WAIS of 1ºC may be too high to be considered a safe long-term limit (Arthern & Williams 2017; Seroussi et al., 2017; Garbe et al., 2020; Golledge et al., 2021; Reese et al., 2023; Van den Akker et al., 2025; Stokes et al., 2025), and while the exact lower limit is hard to determine, a precautionary limit of 0.5ºC would be appropriate. We also maintain our tipping system assessments for marine-based EAIS as high confidence, and non-marine based EAIS with medium confidence.

Sea ice

What it is

When seawater cools below the freezing point in each hemisphere's autumn to spring, it begins to form a layer of floating sea ice. Large areas of highly reflective (i.e. high albedo) white sea ice helps amplify regional cooling, and conversely reduced sea ice extent with global warming is one of the drivers of the 'Arctic amplification' of warming. This feedback was originally thought to lead to a tipping point beyond which sea ice loss becomes self-sustaining (e.g. Lenton et al., 2008), but more recent work instead expects quasi-linear sea ice loss with warming as a result of counteracting negative feedbacks serving to dampen ice loss (e.g., Gregory et al., 2002; Winton, 2006; Winton, 2008; Notz, 2009; Tietsche et al., 2011; Mahlstein and Knutti, 2012: Wagner and Eisenman, 2015). However, there remains some possibility of sea ice tipping in certain regions and circumstances, such as around Antarctica (Winkelmann, Steinert & Armstrong Mckay et al., 2023).

What's new

In GTPR23, Arctic summer sea ice was assessed as not a tipping system with high confidence, Arctic winter sea ice as not a tipping system with medium confidence, and Barents sea as not a tipping system with low confidence. In contrast, Antarctic sea ice was assessed as unclear, with more evidence required to make an assessment (Winkelmann, Steinert & Armstrong Mckay et al., 2023).

Since GTPR23, several new publications have advanced understanding of sea ice tipping dynamics. Heuzé & Jahn (2024) showed through model simulations that the Arctic Ocean could experience its first entirely ice-free summer day before 2030 under scenarios of continued warming, emphasising that while ice loss is accelerating, it remains largely linear and influenced by acute warming events rather than tipping points. Selivanova et al. (2024) confirmed significant ongoing reductions in Arctic summer sea ice extent and thickness, projecting nearly ice-free summer conditions by the 2040s, indicating a regime shift to a thinner, more transient summer ice cover, but without identifying irreversible thresholds. However, species and ecosystems dependent on sea ice are less recoverable.

In the Barents Sea, Onarheim et al. (2024) documented recent localised thickening due to temporary cooler conditions, emphasising regional variability and responsiveness to short-term climatic fluctuations rather than sustained recovery or tipping behavior.

This is a mixed picture on whether Arctic winter sea ice might reach a tipping point or not. Recent winter ice reductions in the Barents–Kara Seas have resulted largely from anthropogenic forcing rather than feedbacks, though significantly amplified by internal climate variability (Siew et al., 2024). Wunderling et al. (2024) reviewed potential tipping interactions, noting winter Arctic sea ice might exhibit threshold-like behavior linked to ocean–ice feedbacks and the Atlantic Meridional Overturning Circulation. However, they noted that current evidence does not yet support an irreversible collapse of Arctic winter sea ice. At the same time, abrupt reductions remain plausible at certain warming thresholds, even if these are not feedback-driven tipping events, as indicated in recent CMIP6 analyses (Terpstra et al., 2025).

Other recent work suggests the potential for tipping behaviour in winter sea ice. In a sea ice model, Hankel & Tziperman (2023) show a clear bifurcation: beyond a critical forcing the winter-ice equilibrium vanishes, driving an abrupt, hysteretic transition to a permanently ice-free Arctic. Observationally-constrained detection studies further show that CMIP6 still underestimates greenhouse-gas control on sea-ice loss, implying the threshold for year-round ice collapse lies closer to today's climate than CMIP5 suggested (Kim et al. 2023). Finally, carbon-removal ensemble experiments indicate that even after CO_2 is drawn back to pre-industrial levels, most models retain an approximate 1 million km² winter-ice deficit — evidence of incomplete recovery and long-lived hysteresis (Yu et al. 2025).

Antarctic sea ice has shown alarming trends recently, with a gradual increase up to 2014 broken by a precipitous decline beyond natural bounds of variability since, rivalling Arctic losses (Abram et al., 2025). 2023 saw a record-low extent, attributed to anomalously warm ocean conditions and unusual wind patterns (Espinosa et al., 2024). Raphael et al. (2025) found compelling evidence of a structural regime shift in Antarctic sea ice since the mid-2010s, characterised by unprecedented consecutive low-ice events and decreased recovery capability, signaling potential tipping behavior. Recent improvements in satellite observations have also revealed a reversal in surface freshening in the Southern Ocean, with increasing salinity since 2015 associated with reduced stratification, which could accelerate sea ice loss through increased ocean heat loss (Silvano et al., 2025). Abram et al. (2025) proposes that the Antarctic sea ice regime shift may feature self-perpetuating dynamics even below 2°C, but it is not yet clear if future projections of decline reflect this or lagged ocean warming.

Recent analysis of abrupt shifts in CMIP6 model results suggest abrupt shifts in Arctic summer sea ice occur in some simulations between 1.0 and 4.6°C, in winter sea ice between 2.4 and 5.4°C, and in Barents sea ice between 1.3 and 2.3°C (Terpstra et al., 2025; Angevaare & Drijfhout, in review) (see Table A2.2.1 in Appendix for details). Similarly, abrupt shifts are also detected around Antarctica in a number of simulations between 0.5 and 5.3°C. However, these abrupt shifts are not necessarily tipping points without confirming self-perpetuating dynamics.

Based on this new research, the GTP community maintains its assessment of Arctic summer sea ice and Barents Sea ice as not tipping systems. Arctic winter sea ice is assessed as uncertain regarding tipping point behavior, as while recent studies suggest there are possible threshold effects and rapid ice loss from significant warming, there is not yet strong proof that this would be irreversible due to self-perpetuating feedbacks. Improved modelling and longer observations of sea ice will help to clarify potential tipping dynamics. We also maintain our assessment of Antarctic sea ice potentially exhibiting tipping behavior as uncertain, reflecting that while there is mounting evidence of a fundamental and possibly irreversible shift in Antarctic sea ice conditions (Raphael et al., 2025), and there are feedbacks that could potentially sustain this shift (Silvano et al., 2025), there is insufficient research confirming the dynamics involved and the likely endpoint.

Mountain glaciers

For more on tipping points in glaciers, see
4.4 Mountain glaciers case study

What it is

Outside of the ice sheets of Greenland and Antarctica, ice bodies occur as mountain glaciers, gaining ice in higher altitudes before flowing to lower altitudes where they lose mass. In general glaciers are shrinking and projected to shrink further with global warming, but this mass balance is subject to various feedbacks with the potential for nonlinear responses to a changing climate as a result (Marzeion et al., 2018; Hock et al., 2019; Meredith et al., 2019; Rounce et al., 2023). These feedbacks include changing flow rates from increased meltwater generation, increased retreat of calving glaciers from a warming ocean, drop of glacier surface elevation increasing melt rates and possibly also decreasing snow accumulation, and increased dustiness and surrounding vegetation reducing local albedo. Under certain circumstances the above feedbacks can result in self-sustained mass loss of individual glaciers (Winkelmann, Steinert & Armstrong Mckay et al., 2023). Although these feedbacks act mainly on local scales, there is on average a tendency for regional similarities and thus synchronous transitions between different states of glaciers and their downstream impacts.

What's new

In GTPR23, mountain glaciers were assessed as a tipping system at the regional scale with medium confidence, but as not a tipping system at the global scale with medium confidence (Winkelmann, Steinert & Armstrong Mckay et al., 2023). This assessment has since been confirmed by a number of further considerations and studies. The most recent global-scale compilation of glacier mass loss (The GlaMBIE team, 2025) found that glaciers worldwide lost 273 ± 16 gigatonnes annually from 2000 to 2023, with an increase of 36 ± 10 per cent from 2000–2011 to 2012–2023. These numbers correspond to a loss of between 2 and 39 per cent of regional glacier ice mass, about 5 per cent globally. The glacier mass loss found has already passed the IPCC AR6 lowest mass-loss projections over the period from 2000 to 2040. Glacier mass loss 2000–2023 is about 18 per cent larger than the mass loss from the Greenland Ice Sheet and more than twice that from the Antarctic Ice Sheet. A recent global glacier modelling intercomparison (Zekollari and Schuster et al., 2025) highlights the substantial regional diversity of already committed and further equilibrium response of glaciers worldwide, supporting the GTPR assessment of glaciers being tipping systems at regional scale, rather than global.

While GTPR23 focused mainly on processes of glacier dynamics and mass balance, also the atmospheric forcings behind glacier mass changes underlie nonlinear behaviour, that in turn can then cause nonlinear glacier development. Temperature-precipitation relations are weakly understood and quantified (Ding et al. 2014). While in some glacier regions the increased humidity of the warming atmosphere leads to increased snowfall and accumulation, in other cases precipitation undergoes a transition to a higher percentage of the liquid phase (Hock et al., 2019). In addition to changes in the regional atmospheric forcing, glacial landscape changes such as glacier area loss, exposure of rock and debris, formation of lakes, or increased vegetation cover will change temperature and wind patterns (Shaw et al. 2023). The feedback of these changes on the glaciers themselves is poorly understood, including for instance the transition between sublimation-dominated to melt-dominated glacier ablation regimes (Marshall 2021). The shift of polythermal glacier regimes (a mixture of ice zones at and zones below the pressure melting point) to temperate thermal regimes (all ice at pressure melting point) is also expected with atmospheric warming, but associated processes and consequences, for instance on meltwater refreezing, runoff, glacier dynamics and even mechanical glacier stability (Gilbert et al. 2018), are little understood (Marshall 2021).

Bolibar et al. (2022) suggest a number of nonlinearities in the relation between temperatures and snowfall, melt and in particular their positive and negative extremes that impact glacier mass balance. The combined impacts of these nonlinear changes in individual forcings can compensate each other towards quasi-linear behaviour. The latter overall forcing combines then with feedbacks related to glacier topography. In that context, Bolibar et al. (2022) point out the particularly important differences between mountain glaciers, which can retreat to higher average elevations where melt rates are reduced (negative, self-stabilising feedback, GTPR23), and flat glaciers (on global average the ones with largest ice volumes), where mass loss reduces average surface elevation and enhances melt rates (positive feedback, GTPR23). Studies for Alaska glaciers confirm GTPR23 findings that topographic controls, in particular elevation distributions, on surface mass balance of ice fields and glaciers can lead to tipping behavior on local to regional scales (Davies et al., 2022; Davies et al, 2024). The causes and impacts of glacier tipping at the local- to regional scale are explored in the case study on tipping dynamics in an Alaskan (USA) glacial system.

Based on these considerations and new research, we maintain our assessment of mountain glaciers being a tipping system at the regional scale with medium confidence, but as not a tipping system at the global scale (medium confidence).

Permafrost

What it is

Permafrost consists of ground frozen for at least two consecutive years (Harris et al., 1988), and underlies about 14 million km^2 (15 per cent of the land surface area) in the Northern Hemisphere (Obu, 2021; Steinert et al. 2023). Freezing prevents organic matter from tundra or boreal forest ecosystems entering the soil from decomposing, resulting in the buildup of over ~1000 GtC in the top 3m of permafrost soils on land (Hugelius et al., 2014). However, global warming is leading to some of this permafrost beginning to thaw, allowing the preserved organic matter to degrade and emit greenhouse gases in the process, primarily as CO_2 but with a proportion as high-warming methane where permafrost is waterlogged (Walter Anthony et al., 2014). Much of the carbon loss is likely irreversible due to the slow formation timescales of permafrost and sustained microbial decomposition of previously frozen organic matter, leading to continued carbon emissions over centennial to millennial timescales and reinforcing warming through a positive feedback loop (Schwinger et al. 2022; de Vrese & Brovkin et al. 2021; Park et al. 2025; Ji et al. 2025). Furthermore, permafrost thaw does not occur uniformly, as some areas experience localised abrupt thaw, leading to rapid carbon loss and landscape destabilisation, i.e., degradation of ice-rich permafrost, and subsequent rapid slope slumping, ground subsidence and the formation of thermokarst landscapes. These processes could amplify emissions by 40 per cent under high emission scenarios but are not currently represented in Earth system models (Turetsky et al. 2020). While large-scale permafrost thaw is gradual, these regional abrupt thaw processes involve positive feedbacks such as thermokarst formation that can lead to self-sustained thawing processes, allowing for localised tipping to take place (Nitzbon et al., 2020). However, at the regional to global scale permafrost thaw is expected to aggregate to a quasi-linear response to global warming (Nitzbon et al. 2024).

What's new

In GTPR23, land-based permafrost was assessed as a tipping system at the regional scale (medium confidence), but not as a tipping system at the global scale (medium confidence). Equally, subsea permafrost was not identified as a tipping system (medium confidence) (Winkelmann, Steinert & Armstrong Mckay et al., 2023). Since GTPR23, several new publications have advanced understanding of permafrost thaw in the context of tipping dynamics.

Evidence suggests that permafrost thaw remains characterised by multiple regional-scale tipping processes, including abrupt thermokarst lake formation and slope slumping, rather than exhibiting a single global tipping threshold (Nitzbon et al., 2024). A recent analysis of CMIP6 model results identified individually small but widely distributed (collectively aggregating to over >1M km^2) abrupt shifts in land permafrost frozen soil moisture content in eight models between 1.0 and 3.8°C of global mean warming, and in soil frozen water content in 19 models between 1.2 and 3.3°C (Terpstra et al., 2025) (Table A2.2.1). Localised, abrupt thaw events (Webb et al. 2025) contribute cumulatively but gradually at the global level, thus reaffirming that permafrost degradation progresses incrementally and heterogeneously. The presence of multiple steady states in permafrost systems indicates the potential for local tipping of ecosystems and soil carbon storages on centennial timescales (Brovkin et al. 2025). Further, Earth System simulations suggest that changes in permafrost hydrology can gradually, rather than abruptly, impact hydroclimate in the tropics and subtropics. The permafrost soil state and consequential carbon fluxes of such processes have the potential to be underestimated in low-resolution climate models (Schickhoff et al. 2024).

Recent findings from NOAA's 2024 Arctic Report Card (2024) revealed that Arctic tundra ecosystems have shifted to net carbon sources earlier than projected, driven by intensified permafrost thaw and record wildfire seasons. This transitioning of Arctic ecosystems from carbon sinks to sources is amplifying climate feedbacks at regional scales. A previously overlooked feedback mechanism linking permafrost thaw to reduced cloud cover, amplifying Arctic warming and its global impacts was identified by de Vrese at al. (2024).

Localised abrupt thaw expose deeper layers of organic material to microbial decomposition, significantly increasing emissions in a short period, and significantly contributing to methane emissions from inundated areas (Park et al. 2025), while emissions from deep Arctic lake sediment could be more substantial than previously thought (Freitas et al. 2025). As such, abrupt thaw hotspots across the Arctic highlight the vulnerability of permafrost regions even under present-day conditions. Using the CESM2 model coupled with CLM5, Park et al. (2025) further determined that permafrost carbon emissions will persist for centuries even under scenarios of aggressive climate mitigation and net-negative emissions. Their model simulations indicate irreversible commitments to continued carbon release from thawed permafrost, further reinforcing the long-term implications of regional tipping processes.

A warming Arctic enhances the risk of causing localised abrupt thaw and increases its magnitude and therefore also increases the risk of tipping cascades, where permafrost degradation - in addition to its carbon-climate feedback - interacts with other Earth system components, such as boreal forest dieback (Alfaro-Sánchez et al. 2024), including wildfire occurrence (Kim et al., 2024) or a modified ocean circulation (Schwinger et al. 2022, Park et al. 2025, Steinert et al. 2025) and carbon uptake efficiency (Nielsen et al. 2024), potentially accelerating global climate change. Further, adaptive emission driven MPI-ESM simulations show that, while average annual permafrost carbon emissions of ~0.3–0.7 GtC/yr are small compared to present-day fossil fuel emissions (~10 GtC/yr), permafrost thaw can still reduce the carbon budget by ~11–13 per cent by 2300 under 2°C or 3°C warming scenarios (Georgievski et al., 2025).

Based on this new research, the GTP community maintains its assessment of land-based permafrost as a tipping system at the regional scale with medium confidence, reflecting ongoing evidence of localised tipping processes. It also maintains medium confidence that subsea permafrost is not a tipping system, as well as that land-based permafrost is not a tipping system globally, given the absence of a unified global threshold.

2.2.6 Potential tipping points in the biosphere

The 'biosphere' consists of all life on Earth and includes the major biomes of tropical, temperate, and boreal forests, more open ecosystems across grasslands, savannas, and drylands, and aquatic ecosystems across freshwater, coastal, and marine environments.

In this section, we describe each of these biomes, their evidence for tipping dynamics, and relevant new research in turn. Based on this, we have reassessed the status of several systems, including lowering the minimum warming threshold for the Amazon, adding river deltas and peat bogs as potential tipping systems, and clarifying local- to regional-scale dynamics in the Congo and temperate forests (Figure 2.2.3).

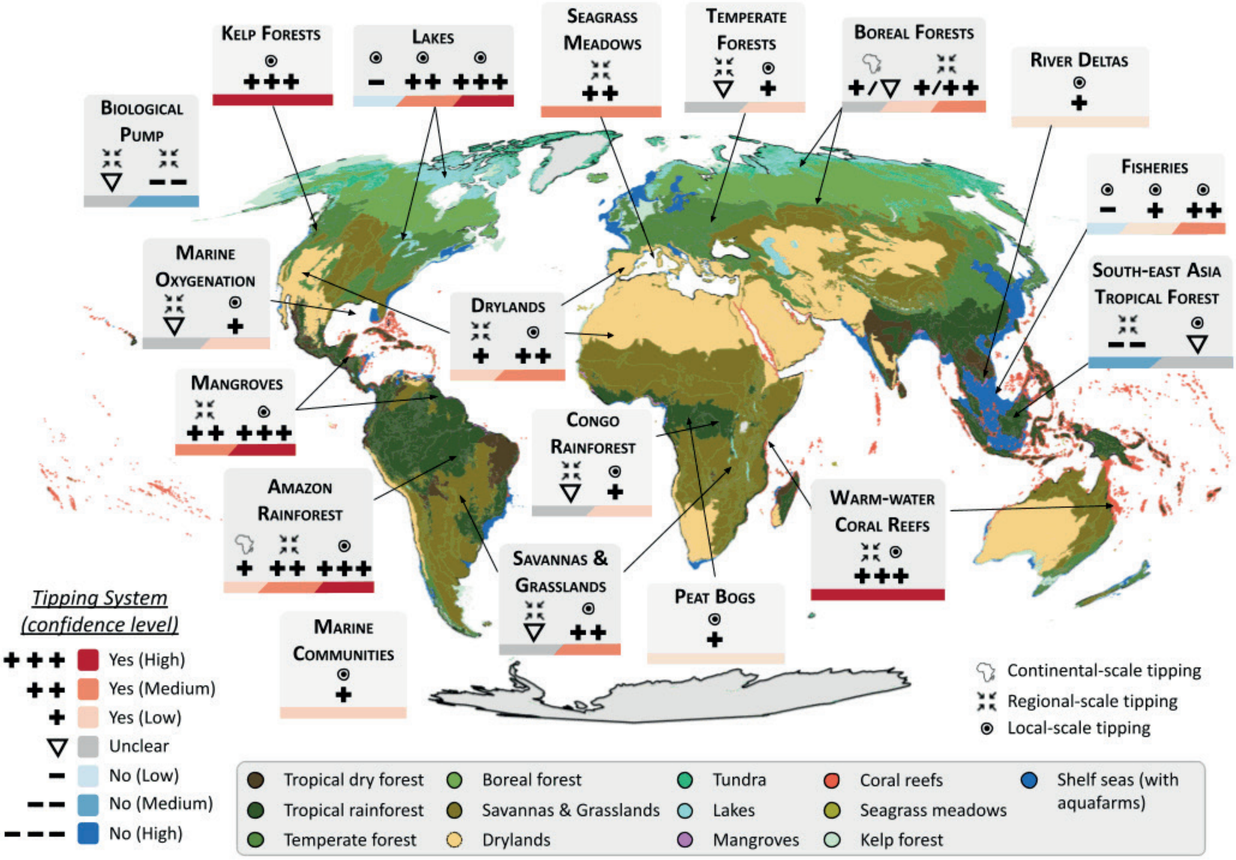

Figure 2.2.3: Map of biosphere systems considered in this chapter. Systems are marked by the coloured areas, with terrestrial biomes and mangroves based on biogeographic biomes (Dinerstein et al., 2017), and lakes and ocean biomes on IUCN functional biomes (Keith et al., 2022) (lakes are shown over other biomes for tundra only; fisheries are spread across the global ocean, but are marked only on key coastal seas for simplicity (Steinert, 2023)). Labels indicate which of the systems are in this report considered a tipping system (+++ high confidence, ++ medium confidence and + low confidence), which are not (– – – high confidence, – – medium confidence and – low confidence), and which are currently uncertain (∇).

Tropical forests

What it is

Known for their high levels of biodiversity (Slik et al., 2015; Pillay et al., 2021; Aguirre-Gutiérrez et al. 2025), tropical forests cover ~1.95 billion hectares and store substantial amounts of carbon within their biomass and soils (circa 471 +/- 93 GtC) (Pan et al., 2011; SPA, 2021; Ornetto et al., 2022). They form a key part of the interconnected Earth system and have far reaching impacts on the climate through evapotranspiration and cloud formation. They are mainly threatened by deforestation, for example to create pastures, land-cover change, for example to plantations, and droughts and wildfires being worsened by climate change (Sternberg, 2001; Franco et al., 2025). There are many tropical forest feedbacks, but two key positive feedback mechanisms, acting at different spatial scales, have been identified which may drive tipping points in tropical forests: the forest-rainfall feedback at regional scales and the fire-vegetation feedback at local scales (Flores & Staal, 2022; A. McKay, Sakschewski & Roman-Cuesta et al., 2023). The forest-rainfall feedback operates at a regional level, with moisture being recycled throughout tropical forests, thus reducing the impact of rainfall variability on forest health; however deforestation and climate change-induced drought extremes can reduce this moisture recycling and force the forest towards a tipping point (Staal et al., 2020). This feedback is present in the Amazon (Zemp et al., 2017; Staal et al., 2018) and Congo forests (Staal et al., 2020), however it is less important in Southeast Asian and Australasian rainforests where ocean-derived rainfall is plentiful. At a local level, the fire-vegetation feedback can cause a transition from tropical forests to a more open state (such as savanna or degraded dry forest). Less dense tree cover can lead to increased likelihood of fires due to the spread of grasses and local drier air, thus further reducing tree cover (Cochrane et al. 1999).

What's new

Global

Remote sensing by satellites of major forest disturbances (mainly wildfires and droughts) were recently used to calculate a hydrologic sensitivity index, establishing critical thresholds beyond which forest loss drives drastic changes in water yield and climate conditions (Domínguez-Tuda & Gutiérrez-Jurado, 2024). In tropical rainforests, a threshold near 16 per cent tree cover reduction at local-to-landscape scales was identified, beyond which water yields notably decrease and warming trends intensify.

Amazon rainforest

For more on tipping points in the Amazon rainforest, see *4.1 TheAmazon rainforest case study*

In GTPR23, the Amazon rainforest was assessed as a tipping system with high confidence at the local scale, medium confidence at the regional scale and low confidence at the continental scale, with medium confidence in it involving abrupt / large rate change, medium confidence in irreversibility over decadal/centennial timescales, and a threshold range for dieback of 1000-1250 mm mean annual rainfall, ~400 to ~450 mm maximum accumulated water deficit, a dry season length of 7-8 months, deforestation levels of 20-40 per cent and ~3.5°C (2-6°C) of global warming (A. McKay, Sakschewski & Roman-Cuesta et al., 2023).

Since GTPR23, the Amazon has faced droughts and extreme warmth associated with the 2023-24 El Niño event, which has led to water stress, increased fires, and reduced greenness (Jiménez et al., 2024). A major recent synthesis of research on the potential for critical transitions (such as dieback) in the Amazon forest found that by 2050 the potential effects of compounding disturbances on Amazonian systemic resilience could see around 10-47 per cent of Amazon forests facing combined stresses beyond critical thresholds, potentially triggering irreversible regime shifts and exacerbating regional climate change (Flores et al., 2024). Based on this, Flores et al. (2024) suggested precautionary limits of 1.5°C and 10 per cent deforestation (requiring restoration of 5 per cent of the biome) to avoid broad-scale ecosystem transitions, the latter reduced from the 20-25 per cent precautionary limit of Lovejoy & Nobre (2018).

Similarly, under review modelling suggests that while regional dieback would occur at 3.7-4.0°C without deforestation (in line with A. McKay et al. (2022)), deforestation reaching 22-28 per cent of current forest extent would reduce the warming threshold to 1.5–1.9°C of global warming and make dieback more widespread (Wunderling et al., in review). Recent analysis of abrupt shifts in CMIP6 model results detected some abrupt shifts in Amazon vegetation between 0.9 and 5°C (Terpstra et al., 2025) (Table A2.2.1), but they were not consistent across models, and do not necessarily represent tipping dynamics. Running CMIP5/6 models until 2300 and including slower transitions reveals localised to regional scale dieback in nine out of twelve models, with location and thresholds (global warming 1.5-10.2 °C, local surface air temperatures >32.2 ± 4.8°C, precipitation <1394.3 ± 306.0 mm/yr) highly model-dependent (Melinkova et al., 2025).

A simpler land-surface-atmosphere model has found that under projected rainfall decreases deforestation of 45 and 55 per cent could trigger dieback, but this model did not feature spatial variation or more complex vegetation dynamics (Hajdu et al., 2025). Conversely, Yoon & Hohenegger (2025) found that better representing atmospheric convection in a storm-resolving model limited rainfall's sensitivity to deforestation, although only in a short simulation. Under high emission scenarios, it has been estimated that more than 25 per cent of the forest in Central Amazonia could become a net carbon source under high emission scenarios, with drying trends reducing biomass and triggering regime shifts particularly if eastern Pacific temperatures rise >1.5°C (globally, >2.3°C) (Nath et al., 2024), while based on estimates of root zone moisture storage the area of forest at risk of regime shifts jumps by ~1.7–5.8 times (relative to <2°C warming) (Singh et al., 2024).

Potential 'early warning signals', in the form of 'slowing down' in system response to disturbances which can indicate resilience loss prior to a tipping point, have previously been identified in the Amazon in empirical data (Boulton et al., 2022) and models (Boulton et al., 2013; Bochow & Boers 2023). However, recent studies have found a more heterogeneous or unclear response of forest resilience than earlier estimates, while other co-drivers of resilience loss can mask slowing down (Blaschke et al., 2024; Grodofzig et al., 2024; van Passel et al., 2024). Despite this, more widespread resilience loss is still expected due to climate change in the future, and areas with greater deforestation or disturbance are already less resilient (Wang et al., 2024) and leading to greater seasonality in rainfall in those regions (Qin et al., 2025).

In GTPR23 the potential impacts of AMOC slowdown or collapse on the Amazon Rainforest were unclear, but several new studies have shone new light on this (see the Interactions & Cascades section).

Based on this new research, the GTP community maintains its assessment of the Amazon rainforest being a tipping system with low confidence at the continental-scale, medium confidence at the regional-scale, and high confidence at the local-scale (with robust evidence but low to medium agreement). While evidence has grown for larger-scale tipping, particularly on the basis of the assessment of Flores et al. (2024), and we now have high confidence in irreversibility over decadal/centennial timescales, continued model limitations and disagreements over location and thresholds limits current confidence level. However, we lower the minimum warming threshold from 2 to 1.5°C based on recent assessments of warming/deforestation synergies (Flores et al., 2024; Wunderling et al., in review; Melinkova et al., 2025), with the lower end of this range more likely when considering both warming and deforestation.

Congo rainforest

In GTPR23, the Congo rainforest was assessed as a tipping system with low confidence at the local scale, but unlikely to tip as a result of climate change, with low confidence in it involving abrupt / large rate change, low confidence in irreversibility over decadal/centennial timescales, and a threshold range of ~1350 mm mean annual rainfall (A. McKay, Sakschewski & Roman-Cuesta et al., 2023). Since then, remote-sensing based assessments of local-scale bistability of high and low tree cover in the Congo have been refined (Zwaan et al., 2024). While the hypothesis of local-scale bistability is supported (Staver et al., 2011; Aleman et al., 2020), the results indicate that transitions between closed forest and open savanna could instead pass through a state of coexistence, which would likely smoothen out tipping points between these states over larger spatial scales. In contrast, estimates based on root zone moisture storage project that the Congo Basin forest area at risk of critical transitions grows by ~0.7–1.7x under higher warming scenarios (relative to <2°C warming) (Singh et al., 2024).

Based on consistent evidence for bistability but continued limited agreement and evidence for wider scale tipping dynamics under future climate projections, we maintain our assessment of it being a low confidence tipping system at the local scale, and add that it is uncertain at regional scales. Overall, tipping may be more localised in comparison to the Amazon (Zwaan et al., 2024).

Southeast Asian rainforest

The Southeast Asian rainforest was assessed in GTPR23 as an uncertain tipping system at the local scale and not a tipping system with medium confidence at the regional scale, with low confidence in it involving abrupt / large rate change, low confidence in irreversibility over decadal/centennial timescales, and a threshold range of ~1550 mm mean annual rainfall (A. McKay, Sakschewski & Roman-Cuesta et al., 2023). In the absence of substantial new research on this area, we maintain this assessment here.

Boreal forests & tundra

What it is

Boreal forests occupy ~1.14 billion hectares in the high latitude regions of the northern hemisphere (Pan et al., 2011). They face disturbances from fire and insect outbreaks, as well as logging (Kuuluvainen & Gauthier, 2018). Situated in an area with amplified climate change, there are two potential tipping points associated with boreal forests - one at its northern edge, where forest may expand into the tundra, and the other at the south, where the forest may dieback and transition to an open steppe/prairie landscape. Southern boreal forest dieback could be driven by the fire-vegetation feedback (Joos et al., 2001; Lucht et al., 2006; Lenton et al., 2008; Abis and Brovkin 2017; Rotbarth et al. 2023). With high latitude temperatures increasing, there is evidence of increased survival rate of seedlings in the tundra and an advancing shrubline, with potential positive feedbacks (such as albedo and soil moisture feedback) leading to further forest expansion (Myers-Smith et al., 2011).

What's new

Dieback

In GTPR23, boreal forest dieback was assessed as a tipping system with medium confidence at the regional scale and low confidence at the continental scale, with medium confidence in it involving abrupt / large rate change, low confidence in irreversibility over decadal/ centennial timescales, and a threshold of ~4°C (range 1.4-5°C) (A. McKay, Sakschewski & Roman-Cuesta et al., 2023).

Recent simulations found that boreal forests may be shifting from the current multi-stable state towards a unimodal semi-open state with 30-50 per cent tree cover in the coming decades (Rotbarth et al., 2025). Such a shift would likely increase the risk of forest fires, leading to potentially substantial releases of stored carbon. However, these results are based only on the inferred relationship between tree cover change and mean annual temperature, with added stochasticity to represent process noise, and do not consider other important factors affecting the boreal forest dynamics, such as permafrost thaw or water and nutrient availability.

Warming will likely have consequences for boreal forest biodiversity and the likelihood of dieback. An average increase in tree species diversity by 12 per cent has been observed across boreal forests between 2000 and 2020 (Xi et al., 2024). However, a negative impact was observed in areas of extreme warming (>0.065 °C /yr), suggesting that exceeding a certain threshold of warming could have detrimental effects. Repeated cycles of clear-cutting in boreal forests are also reducing old and large trees, deadwood diversity, and altering soil composition, causing a long-term decline in species richness (Lunde at al., 2025).

A recent satellite observations-based hydrologic sensitivity index (Domínguez-Tuda & Gutiérrez-Jurado, 2024) indicates that areas impacted by forest loss with a tree cover reduction higher than 18 per cent exhibited more pronounced warming trends and a rapid rise in hydrologic responses compared to areas with smaller losses. Similarly, it has been shown that tree growth in Eurasian larch forests is being increasingly limited by rising temperatures and the associated drought stress, leading to negative response to warming (Li et al., 2023). Recent findings also show that across northwestern North America warming and disturbances are affecting vegetation resilience, which declined significantly in the southern boreal forest, including some regions exhibiting overall greening, but increased in much of the Arctic tundra (Zhang et al., 2024).

Based on this new research, we assess that while there is some increased evidence for dieback at the regional scale, we maintain our assessment at medium confidence in the absence of more evidence, and maintain low confidence at the continental scale.

Northern expansion

Boreal forest northern expansion was assessed in GTPR23 as a tipping system with low confidence, with low confidence in it involving abrupt / large rate change, low confidence in irreversibility over decadal/ centennial timescales, and a threshold of ~4°C (range 1.5-7.2°C) (A. McKay, Sakschewski & Roman-Cuesta et al., 2023). Since GTPR23, there have been several new publications relevant to this tipping system.

On the boreal forest's northern edge, transitional forests located between boreal forests and tundra are experiencing consistent increases in vegetation height and density (Montesano et al., 2024). These changes are driven by Arctic amplification and are expected to continue through 2100 across all climate scenarios. Furthermore, a population of white spruce (*Picea glauca*) across an Arctic basin in North America has been documented advancing at rates that cannot be sustained by warming alone (Dial et al., 2022). However, significantly reduced tree growth has also been found on thawing permafrost in the higher latitudes of North America (Alfaro-Sánchez et al., 2024), as trees need to invest more into remaining upright on destabilised grounds. Recent analysis of abrupt shifts in CMIP6 model results detected some abrupt shifts in boreal vegetation between 0.8 and 4.9°C, mostly for northward expansion (Terpstra et al., 2025) (Table A2.2.1), but they were not consistent across models, and do not necessarily represent tipping dynamics.

Based on this new research, while there is some agreement that climate change will likely induce tipping points in the expansion of the boreal forest, the still limited evidence base means the GTP community maintains its assessment of this being a tipping system with low confidence at the regional scale.

Temperate forests

What it is

Temperate forests make up 16 per cent of the global forest area (Hansen et al., 2010; Pan et al., 2011). The majority of temperate forests are spatially fragmented and are managed, low biodiversity ecosystems (Potapov et al., 2017; Sabatini et al., 2021). These management practices are likely to lead to large areas of forests with a lower resilience to perturbations, with forests exposed to droughts, heatwaves and pest outbreaks (Allen et al., 2010; Buras et al., 2019; Billing et al., 2020; Senf et al., 2020; Zhang et al., 2021; Carnicer et al., 2021; Benyon et al., 2023; Forzieri et al., 2022), with a potential of widespread dieback from these. Temperate forests may experience localised feedback dynamics from fire and bark beetle attacks in common with boreal forests (see above). Further investigation is required to establish the strength of the forest-moisture feedback in temperateforests. Large uncertainties remain around whether temperate forests may experience tipping points across a large scale (A. McKay et al., 2022), with some assessments suggesting this is unlikely at present (Thom, 2023).

What's new

In GTPR23, temperate forest dieback was assessed as a tipping system with low confidence due to limited evidence, with medium confidence in it involving abrupt / large rate change, low confidence in there not being irreversibility over decadal/centennial timescales, and uncertainty around any threshold ranges (A. McKay, Sakschewski & Roman-Cuesta et al., 2023).

Since GTPR23, there have been several new publications relevant to this tipping system. A recent satellite observations-based hydrologic sensitivity index (Domínguez-Tuda & Gutiérrez-Jurado, 2024) identified a threshold of around 46 per cent tree cover reduction for temperate coniferous forests, which leads to cooler climate conditions and higher water yield once surpassed. For Mediterranean woodlands, a threshold of roughly 54 per cent emerged, indicating relatively higher resilience but also rapid hydrologic shifts once that critical point is crossed. However, the degree to which these hydrological shifts involve tipping dynamics is unclear.

Several recent studies show new evidence of localised resilience loss and potential tipping points in different regions of temperate forests. In northwestern China, ecosystem productivity and photosynthetic efficiency have decoupled since 2010 (Zhang et al, 2024). This indicates a loss of ecosystem resilience in these forests, which under rapid warming/drying flags a near-term dieback threshold in water-stressed regions. In Europe, the 2018-20 drought event led to a breakdown in standard forest dynamics in a German Beech forest (Mathes et al., 2023). The drought's intensity potentially induced a nonlinear weakening of dominant trees, and future drought events of this or greater intensity could lead to a regime shift in such Beech forests.

Recent analysis of the relationship between forest fragmentation and ecosystem resilience revealed a clear nonlinear decline in resilience once forest connectivity dropped below critical thresholds (e.g. when number of patches per unit area increases beyond 0.89) (Fu et al., 2024). In other words, when forest areas become too fragmented, their ability to recover from disturbances, such as droughts, fires, or storms, is significantly reduced. Notably, the study found that agricultural expansion had a more detrimental impact on forest resilience than urban development. While some degree of fragmentation may promote habitat diversity, exceeding certain fragmentation levels leads to a sharp and lasting decline in ecosystem stability, underscoring the importance of preserving large, contiguous forest areas.

While this new research supports the presence of tipping points in some temperate forest systems, and several temperate ecoregions have been subject to increasingly extreme heatwaves (Barriopedro et al., 2011; Sutanto et al., 2020; Lucarini et al., 2023), due to the evidence remaining limited the GTP community maintains its assessment of temperate forest dieback was assessed as an uncertain potential tipping system at the regional scale. However, we now assign low confidence to temperate forest tipping at the local scale.

Savannas & grasslands

What it is

Savanna and grassland are ecosystems dominated by grass cover intermixed, in savannas, with variable tree cover (Bond et al., 2008; Staver et al., 2018). They face threats from conversion to agriculture (Stevens et al., 2022; Strömberg & Staver, 2022), woody encroachment (Stevens et al., 2017; Rosan et al., 2019), afforestation for carbon mitigation (Parr et al., 2024), and climate change via e.g. changes in rainfall variability (D'Onofrio et al., 2019), with major associated losses in ecosystem functions especially on the ground (Ding & Eldridge, 2024). Savannas are distinct, biodiverse ecosystems, not degraded forest systems (Veldman & Putz, 2011; Veldman et al., 2013; Nerlekar & Veldman, 2020) or candidates for afforestation (Parr et al., 2024). In some regions, savannas and forests represent potential alternative stable states (Hirota et al., 2011; Staver et al., 2011; Aleman et al., 2020), with open savanna states leading to a buildup of flammable grass material which can cause wildfires and limit tree growth. This open savanna-fire feedback loop can be disrupted by active and passive suppression of fires (Durigan & Ratter, 2016; Andela et al., 2017), which enables forest expansion into savannas (Stevens et al., 2017). Palaeoecological evidence and fire studies have shown that this savanna to forest transition can be irreversible (Shanahan et al., 2008; Karp et al., 2023). In some arid regions, savannas and grasslands also represent an alternative stable state to low vegetation cover with substantial bare ground (Hirota et al., 2011), discussed more fully in the Drylands section below.

What's new

In GTPR23, savannas and grasslands were assessed as a tipping system with medium confidence at a local-to-landscape scale. Tipping dynamics likely emerge over decades, resulting in low confidence in the possibility of abrupt / large rate change but with medium confidence in irreversibility over decadal/centennial timescales. Mechanisms involve decreases below ~60 per cent flammable cover that could prevent fire percolation, regionally variable and highly localised rainfall thresholds, and the influence of of CO_2 fertilisation. It is unknown to what extent savanna and grassland tipping points might scale up to emergent and synchronised events at larger regional scales, so this potential was assessed as uncertain.

Since GTPR23, there have been several new publications relevant to this tipping system. Higgins et al. (2024) synthesised several past studies arguing for widespread savanna-forest bistability, showing that a range of different approaches all produce savanna-forest bistability but that there is a substantial uncertainty in the climate thresholds associated with tipping points, consistent with our previous assessment. Several publications have also examined the possible contributions of spatial patterning and mosaics to avoiding tipping at larger scales in these systems (Zwaan et al., 2024; van der Voort et al., 2025). Finally, a range of work showed that afforestation is accelerating potentially irreversible losses of savanna ecosystems (Loft et al., 2024; Parr et al., 2024) and has elaborated the potential for lost ecosystem services as a result of savanna encroachment (Ding & Eldridge, 2024).

Based on this new research, the GTP community maintains its assessment of savannas and grasslands being a tipping system with medium confidence at a local to landscape scale, and uncertain at the regional scale.

Drylands

What it is

Drylands consist of numerous vegetation types, including deserts, grasslands, shrublands, woodlands, savannas, Mediterranean forests and tropical dry forests, all defined by their aridity level (where the rainfall is lower than 65 per cent of the 'potential evapotranspiration', including hyper-arid, arid, semi-arid and pre-sub-humid climate zones) (Maestre et al., 2016; D'Odorico et al., 2013). Some of these land cover types are covered in more depth in dedicated sections for 'tropical forests' and 'savannas', as well as the relevant feedback loops of vegetation-fire feedback and vegetation-rainfall feedback. Other feedbacks are possible, including at a small scale, e.g. microbial communities in soil influence the level of soil carbon stocks by decomposing organic. This aids moisture retention in dry soils which is in turn necessary for the decomposition of organic matter, thus forming a feedback loop. Interactions between plants can form important feedbacks in dryland, including around the formation of regular patterns which can occur from plants affecting local soil conditions, such as water and nutrient retention, which create 'islands of fertility' (Eldridge et al., 2024) and can create ecohydrological feedbacks at a large scale through plant connectivity. Additionally, excessive grazing by herbivores can drive changes in plant communities. Evidence exists for vegetation cover bistability in drylands around an aridity level (calculated as one minus the ratio of precipitation to potential evapotranspiration) of between 0.75 and 0.8 (Kefi et al., 2024), with different states of soil fertility, nutrient capture and nutrient recycling (Berdugo et al., 2017). Studies have identified hysteresis in drylands through palaeorecords (Xu et al., 2020), remote sensing (Zhao et al., 2020) and field studies (Berdugo et al., 2017).

What's new

In GTPR23, land degradation in drylands was assessed as a tipping system with medium confidence at the local to landscape scale and low confidence at the regional scale, with medium confidence in it involving abrupt / large rate change, low confidence in irreversibility over decadal/centennial timescales, and three potential thresholds at aridity levels of 0.54, 0.7 and 0.8. Since GTPR23, there have been several new publications relevant to this tipping system.

On mechanisms, self-organised spatial vegetation patterns in drylands can enhance resilience to increasing aridity by facilitating resource redistribution. However, this ability is often lost in degraded ecosystems, with recent work showing this ability may break down beyond an extreme aridity level of 0.8 (Kéfi et al., 2024). Land-atmosphere feedbacks involving existing drylands can also contribute to their own expansion. Warming and drying of air flowing over drylands can lead to reduced precipitation and increased atmospheric water demand in downwind humid regions, causing aridification (Koppa et al. 2024).

On the drivers of stress & thresholds, climate variability and seasonality were identified as significant environmental factors explaining abrupt changes in dryland Normalised Difference Vegetation Index (NDVI; a measure of vegetation greenness derived from satellite observations) (Berdugo et al., 2022). Higher rainfall interannual variability is associated with increased vulnerability to abrupt shifts, while long-term trends in rainfall are a major driver of future abrupt shift susceptibility, with decreasing trends increasing the risk (Bernardino et al. 2025).

Aridity values reaching around 0.8 appears to be a threshold separating zones with contrasting dynamical behaviors for positive and negative abrupt shifts in NDVI (Berdugo et al., 2022). Negative abrupt changes in NDVI are less likely after crossing this aridity threshold, while positive abrupt changes are more likely (Berdugo et al., 2022). Kéfi et al. (2024) found bimodality in vegetation cover in a global dryland data set, which is consistent with the bistability predicted by dryland models and also supports a threshold at an aridity value of 0.8 (consistent with Berdugo et al. (2020)). Human activities, such as grazing, can amplify the effects of aridity on ecological thresholds. For example, grazing in China's drylands can act in synergy with aridity on dryland structure and functioning, and can therefore lower the aridity thresholds at which abrupt decreases in productivity, soil fertility, and plant richness occur (Li et al., 2023).

On the recent dynamics of dryland responses, while gains in vegetation productivity were more frequent than losses in the last two decades, 50 per cent of the areas experiencing significant changes in productivity showed abrupt (rather than gradual) changes in time (Berdugo et al., 2022). Abrupt changes were more common among negative than positive NDVI trends and could be found in global regions suffering recent droughts, particularly around critical aridity thresholds.

On potential indicators of dryland tipping, in a study of global drylands lower functioning was found to be associated with impaired ability of the vegetation to self-organise into patchy spatial structure (Kefi et al., 2024). Trends in spatial patterns observed along large scale dryland gradients matched model prediction, strengthening the idea that patterning is a mechanism of resilience and a possible indicator of ecosystem degradation. Similarly, a machine learning-based approach to detect early warning signals of abrupt shifts in ecosystem functioning was used in one of the world's largest dryland regions, the Sudano–Sahelian zone, and showed its applicability to identify regions that are more likely to undergo a future abrupt shift (Bernardino et al., 2025).

On projections of global dryland expansion, the contribution of reduced precipitation and increased evapotranspiration from existing drylands to ongoing dryland expansion was recently quantified, differentiating it from influences originating in other regions (Koppa et al., 2024). This established that vegetation-climate feedbacks contribute to 50 per cent of the recent desertification of drylands areas, illustrating how existing dry regions contribute to the intensification and spread of aridity worldwide through feedbacks. However, an investigation of the effects of future climates on dryland productivity found that climate change might promote desertification in less than 4 per cent of current dryland areas, with the fertilisation effect from CO_2 emissions likely overcoming the projected increase in arid conditions in other areas (Zhang et al., 2024).

Based on this new research, the GTP community maintains its assessment of drylands being a tipping system with medium confidence at the local to landscape scale and low confidence at the regional scale.

Freshwater ecosystems

What it is

Freshwater ecosystems include lakes, ponds, wetlands, and rivers, all subject to major climate impacts. Lakes are present across much of the world and represent an iconic early example of ecosystem tipping points, hysteresis and resilience (Holling, 1973; Scheffer et al., 1993; Scheffer & van Nes, 2007). Closely intertwined with the wellbeing of communities connected with them, lakes form part of a socio-ecological system which may be affected by rapid changes in lake state. Empirical evidence exists for tipping points in shallow lake systems (Scheffer et al., 2001; Tátrai et al., 2008), the most common type of lake globally. Anthropogenically driven eutrophication in lakes can be persistent, and difficult to reverse due to internal phosphorus-loading, whereby phosphorus stock-piled during periods of high pollution is mobilised from the sediment to surface waters following pollution reduction (Jeppesen et al., 1991; Spears & Steinman, 2020). Lake warming enhances this effect, which together with nutrient pollution can also lead to an increase in greenhouse gases released from the lake, thus feeding back to global warming, but this may be countered to an extent by increased carbon burial processes (Anderson et al., 2020). Critical phosphorus concentrations in shallow lakes are known to be highly variable with lake depth, retention time and fetch (Janse et al., 2008). Modelled and empirical studies suggest thresholds in the range of 80–120 and 40–60 mg total phosphorus per m^{-3} lake water, respectively, for forward and reverse switches in both temperate and tropical systems (Wang et al., 2014; Springmann et al., 2018), though limitations in contemporary empirical data to explain non-linear relationships between chlorophyll a and nutrient concentrations in lakes requires further attention (Davidson et al., 2023).

Another potential tipping point for shallow lake systems involves increased levels of dissolved organic matter (DOM) from terrestrial sources due to land cover changes, such as afforestation, and a changing climate (Creed et al., 2018). This process, also known as 'browning', occurs in boreal systems and can lead to increased stratification, net heterotrophy and anoxia, and ultimately increased greenhouse gas release (Jeppesen et al., 1991; Spears & Steinman, 2020), thus suggesting a potential positive feedback loop. The timescale of this 'browning' feedback loop is still uncertain (Hessen et al., 2024). In permafrost regions, appearance or loss of waterbodies is tightly linked to permafrost thaw (e.g. thermokarst formation), and as such what could be considered a lake system tipping point is in fact a result of an underlying permafrost thaw tipping point (Hessen et al., 2024). Rivers are not addressed in detail in this report, yet both extreme flood and droughts have major impact on wetlands, deltas, coastal areas and a renga of human activities. Glacial fed rivers clearly will be affected by disappearing glaciers (Milner et al 2008).

What's new

In GTPR23, eutrophication-driven anoxia in lakes was assessed as a tipping system with high confidence at the localised scale, with high confidence in it involving abrupt / large rate change and medium confidence in irreversibility over decadal / centennial timescales. DOM-loading, also known as 'browning', in lakes was assessed as a tipping system with medium confidence at the local scale, with low confidence in it involving abrupt / large rate change, medium confidence in irreversibility over decadal / centennial timescales, and a threshold range of >10 mg DOC/l. Other potential abrupt changes in lake ecosystems were identified in GTPR23, including disappearance / appearance of freshwater bodies, switch between Nitrogen and Phosphorus limitation, salinisation and the spread of invasive species. Some of the transitions to saline ecosystems are permanent and give rise to losses of biodiversity and changes in functions and services (Cunillera-Montcusí et al., 2022), but these were not classified as tipping points due to an absence of clear self-sustaining feedbacks. Several of these tipping points will imply positive feedback in terms of increased GHG emission (Rosentreter et al. 2021).

Since GTPR23, there have been several new publications relevant to this tipping system. Hessen et al. (2024) discussed candidate tipping points for lakes, while the concept of tipping points vs. 'tipping sets' have been explored using lake eutrophication as a case study (Mathias et al., 2024). Lake drainage has been studied as a tipping point case (Liu et al., 2024), while the use of remote sensing for assessing lake tipping points has also been discussed (Gilarranz et al., 2022; Lenton et al., 2024). Meanwhile, recent analysis found that compound weather extremes (heatwaves and extreme rainfall) in 2022 drove abrupt 'browning' shifts across multiple West Greenland lakes, altering biological and biogeochemical structure (Saros et al., 2025).

Recent works also address the link between permafrost thaw and expansion (or loss) of permafrost ponds linked to this. The widespread increase in thermokarst ponds has been linked to topography (Abolt et al., 2024), while other regions are prone to substantial loss of surface waters due to permafrost thaw, with Northern Sweden for example seeing thermokarst pond area and number decreasing by 6 and 27 per cent per decade, respectively, between 2003 and 2021 (Seeman & Sannel, 2024). Of particular relevance is the work by Brovkin et al. (2025), arguing that permafrost and freshwater systems in the Arctic are inextricably linked in their tipping dynamics, and that hydrological changes in the permafrost region could have impacts on global hydroclimate.

GTPR23 only dealt with lakes, but given the prevalence of wetlands, their susceptibility to climate change (and other anthropogenic forcings), and not least their role as major greenhouse gas sources, they, should also be considered as potential freshwater tipping systems. For deltas, a number of drivers have been identified, also including cases of positive feedbacks, that may profoundly and rapidly change the physical and ecological properties of large deltas (Törnqvist et al. 2020; van de Vijsel et al. 2024). The use of remote sensing has also been used for detecting regime shifts and loss of resilience in coastal wetlands, covering a salinity gradient from fresh to marine ponds and wetlands (Martinez et al. 2024). For many wetlands, change in hydrology, water saturation and thus redox conditions due to degradation will shift systems from sinks to sources of CO_2, and determine the ratio between methanogenesis and methanotrophy. Zou et al. (2024) estimated a strong increase in greenhouse gas release from wetlands due to drought, and redox state of wetlands can be seen as a tipping point in the context of redox processes. However, tipping points for these systems implies irreversible losses of ecosystems with their key properties (rather than continued functioning with altered dynamics), and it is not always clear that positive feedback loops and hysteresis are as prevalent in all of these systems as for lakes.

Bogs, and notably peat bogs are globally important long-term sinks of carbon acting as major conduits of greenhouse gases, depending on temperature and water saturation. Waddington et al. (2025) recently argued that peatland ecohydrological resilience is a nonlinear function of water storage dynamics, with implications for carbon storage and fluxes when critical tipping points have been exceeded. Peatland in the Congo may have a rainfall-linked threshold, and has been suggested as a potential tipping system if drying led to carbon release (Crezee et al., 2022; Garcin et al., 2022). Ombrotrophic (only precipitation-fed) peat bogs are highly vulnerable to rainfall and catchment properties, and have bistable properties linked to water table both in terms of carbon storage, greenhouse gas emissions and community composition (Lamentowicz et al. 2019; Loisel & Bunsen 2020). The extent to which this bistability can reach tipping points to self-sustaining change is not always clear, but especially when it comes to carbon balance and hydrology, there is evidence that regime shifts can be driven by within-system feedbacks (Milner et al. 2020).

Based on this new research, the GTP community maintains its assessment of lakes being a tipping system with high confidence for eutrophication-driven anoxia (i.e. internal loading of phosphorus from sediments under anoxia) and maintains medium confidence for browning-related anoxia, noting growing evidence for the latter (Saros et al., 2025). Loss or gain of permafrost-water bodies has a confidence level closely linked to permafrost thaw. We also add river deltas and peat bogs as potential local tipping systems, with low confidence for the former, and medium confidence for the latter.

Coastal ecosystems (mangroves, tidal wetlands, seagrass meadows, & kelp forests)

What it is

Despite their globally small area, coastal ecosystems such as mangrove forests, tidal saltmarshes, seagrass meadows, and kelp forests are highly biodiverse, and provide critical ecosystem services to many coastal areas (Nordlund et al., 2016; Menéndez et al., 2020; Cooley et al., 2022; doAmaral-Camara et al., 2023, James et al., 2023). They face widespread degradation, primarily from habitat loss but increasingly from climate change impacts including increased weather extremes, severe storms & flooding, sea level rise, moisture and heat stress, and shifting climatological niches (Saunders et al., 2014; Bergstrom et al., 2021; Dunic et al., 2021; Cooley et al., 2022; Duke et al., 2022; Hagger et al., 2022). For tidal wetland systems, there is strong evidence for bistability, with alternate states including mangrove or saltmarsh-dominated. Increased and compound pressures, strongly influenced by annual rainfall, are recorded as triggering the loss of one habitat form at the expense of the other (Feller et al., 2017; Duke et al., 2019; Duke et al., 2021; Hesterberg et al., 2022). With more extreme and repeated damaging a point has been reached where re-establishment is threatened in some areas, leading to ecosystem collapse (Bergstrom et al., 2021). Evidence is more limited for seagrass meadows, but also suggests that feedbacks can drive irreversible regime shifts to algal or unvegetated states in temperate and subtropical regions (Maxwell et al., 2017; Duarte et al., 2018; Kendrick et al., 2019; Cooley et al., 2022; Bartenfelder et al., 2022; Marba et al., 2022; Temmink et al., 2022). Kelp forests can experience feedback-driven regime shifts to a barren state due to trophic cascades resulting from sea urchin dominance or climate-change intensified marine heatwaves (Ling et al., 2015; Filbee-Dexter & Werberg, 2018; Filbee-Dexter et al., 2020).

What's new

Mangrove forests & tidal wetlands

In GTPR23, mangrove forests and tidal wetlands were assessed as regional-scale tipping systems with medium confidence, with thresholds estimated to be reached by 1.5-2°C and late century alongside potential pollution and sea level rise rate thresholds.

Since GTPR23, research on mangroves and tidal wetlands has further established the extent to which mangroves are threatened. While mangroves overall have seen a greening trend since 2001 (Zhang et al., 2024), regionally there have been some large dieback events, with recent research analysing the El Niño-linked 2015-16 dieback event in the Gulf of Carpentaria (Duke et al., 2017), extreme events driving dieback in Australia, the Sundarbans, and Brazil (Sippo et al., 2018), and hailstorm-induced dieback in Mozambique (Machava-António et al., 2024). The capacity of mangrove forests to re-establish has been compromised by rapidly rising sea levels coupled with increased severe weather and El Niño Southern Oscillation (ENSO) events, including ENSO impacts on sea level (Duke et al., 2022; Chung et al., 2023; Zhang et al., 2025), category 3+ cyclones (Duke et al., 2024), drought-hurricane compound events (Amaral et al., 2023), and unprecedented severe flood events and bushfires (Glasby et al., 2023). In the future, one recent study estimated that the combination of climate-change intensified tropical cyclones and sea level rise would put around half of global mangrove area at high to severe risk of loss, and in particular those providing key services to people (Hülsen et al., 2025). Mangroves and tidal wetlands can keep up with relative sea level rise rates up to a threshold of 4-7 mm per year through accretion, but at 2°C of global warming nearly all mangroves would be exposed to 4 mm per year and one third to 7 mm per year, and all nearly tropical and subtropical coastlines would reach 7 mm per year at 3°C (Saintilan et al., 2020; 2022; 2023).

Mangrove habitat is constrained within a very narrow elevational range between mean sea level and the highest tide levels. For the habitat to survive the vegetative structural elements must relocate, a process that can only be achieved over at least a decade, as the time needed for seedling establishment and growth to mature trees is essentially fixed (MacLeod et al., 2023; Duke et al., 2024). As such, this capability can be overwhelmed, and this appears to be being surpassed in some regions (Duke et al., 2022). Furthermore, the indirect impacts of climate change are also negatively affecting key functional groups in mangrove ecosystems, further reducing mangrove resilience (Ferreira et al., 2024). However, landward mangrove expansion is still occurring in some regions, with for example the 2015-16 dieback event in northern Australia happening within a longer-term expansion (Asbridge et al., 2019), while some mangroves demonstrate continued resilience to tropical cyclones (Asbridge et al., 2025).

Based on this research, the GTP community maintains its assessment of mangroves being a tipping system at regional scales with medium confidence, while adding localised mangrove tipping at high confidence. While observations of particular mangroves failing to recover from increasingly extreme events are accumulating, there is strong regional variation in mangrove vulnerability (Rogers et al., 2019), and uncertainty globally in where sediment supply and landward migration can compensate relative sea level rise (Schuerch et al., 2018).

Seagrass meadows

In GTPR23, seagrass meadows were assessed as regional-scale tipping systems with medium confidence, with thresholds estimated to be reached by 1.5°C and mid-century, alongside potential pollution and sea level rise rate thresholds. Since then, new research has shown that in a conceptual mechanistic model of seagrass ecosystems, passing mortality thresholds results in a tipping point from seagrass meadow to a bare state, exposing the sediment to erosion, and reversing the meadow from carbon sink to source (Dakos et al., 2025). This mirrors previous research indicating that seagrass meadows feature feedbacks that can drive self-sustaining regime shifts (Maxwell et al., 2017). Research in the Gulf of Mexico has also shown how even in relatively undisturbed meadows, sea level rise can drive rapid seagrass loss (Capistrant-Fossa & Dunton, 2024). Together this supports the confidence assessment of GTPR23, with further empirical research needed to assess regional variations in tipping thresholds and likelihood.

Kelp forests

GTPR23 assessed kelp forests as a local-scale tipping system with high confidence, with a timescale of months to decades. This assessment is supported by recent research focused on the effects of climate change on kelp ecosystems along the southeastern coast of Australia, particularly highlighting the invasion of overgrazing sea urchins that are expanding poleward due to warming waters (Ling & Keane, 2024). The population of sea urchins has significantly increased here over the past 15 years, leading to the rapid emergence of incipient barrens, areas where kelp has been overgrazed. This suggests that half of the kelp beds within the affected region could collapse by around 2030, posing serious ecological concerns. Further work has also shown the increasing role of marine heatwaves in driving physiological tipping points (Leathers et al., 2024), while a sea urchin outbreak since 2014 on the Californian coast has led to a shift to a patchy mosaic of forest and barrens due to spatial heterogeneity in environmental conditions (Smith et al., 2024).

Other coastal systems

There are several other coastal ecosystems - such as mussel beds, oyster reefs, and salt marshes (cordgrass) - for which evidence exists for potential tipping dynamics (including bistability and self-sustaining regime shifts (Temmink et al., 2023)), that would benefit from targeted assessment here in future.

Warm-water coral reefs

For more on tipping points in coral reefs, see 4.3 Coral reef case study

What it is

Shallow coral reefs in tropical and subtropical waters (hereafter ‘warm-water coral reefs’) are highly complex ecosystems built around the symbiotic relationship of reef-building corals and photosynthetic algae (Wilkinson et al., 2004). Increasingly though, global warming means warm-water coral reefs are experiencing ‘coral bleaching’ events, during which sustained marine heatwaves triggers corals to expel their symbiotic algae due to heat stress (Hughes et al., 2017; 2018a; 2018b; Houk et al., 2020). While natural bleaching events do occur, after which most corals recover, the increasing frequency and intensity of marine heatwaves - which has recently estimated to have increased by circa five times in frequency and intensity in the tropical Atlantic since 1982 (Rodrigues et al., 2025), and the 2023-24 global marine heatwave triggering catastrophic bleaching in previously less affected southern Great Barrier Reef (Byrne et al., 2025) - is increasingly preventing recovery between heatwaves, triggering mortality.

The loss of hard coral structure can trigger a wider ecological regime shift to an algae-dominated state, creating a localised tipping dynamic by which hard coral recovery would be impeded even if global warming were to be halted or reversed (Bland et al., 2018; Darling et al., 2019; Sheppard et al., 2020; Perry et al., 2013; Vercelloni et al., 2020). Globally widespread die-off is expected by 1.5-2°C (IPCC SR1.5 2018; Cooley et al., 2022; Dixon et al., 2022; Setter et al., 2022; McWhorter et al., 2021; Frieler et al., 2013), but regional-scale coral reef mortality is already being observed as localised tipping becomes regionally synchronous (Le Nohaïc et al,.2017; Amir, 2022; Muñiz-Castillo et al., 2019; Obura et al., 2022). Additionally, coral reefs face many other anthropogenic pressures, including pollution from nutrient and sediment runoff, increased weather extremes, overfishing and invasive species and diseases, which can also contribute to localised tipping (Ban et al., 2013; Edmunds et al., 2014; Darling et al., 2019; Cramer et al., 2020).

What’s new

In GTPR23, warm-water coral reefs were assessed as a tipping system at the local and regionally-clustered scales with high confidence, with thresholds region- and reef-dependent but a global warming level of ~1.2°C (1.0-1.5°C) estimated for globally widespread losses. Since then, there has been a multi-year coral bleaching event, which has not been declared closed at the time of final text editing. Observations confirmed that 2023-2025 experienced the fourth global coral bleaching event on record, and the second within the past decade (following events in 2014-17, 2010, and 1998) (NOAA, 2024). In this event, coral bleaching affected every ocean basin, with 83.7 per cent of corals experiencing bleaching-level heat stress by April 2025 (the greatest extent recorded, compared with 65.7 per cent in 2014-17) (NOAA CRW, 2025). In 2024 catastrophic bleaching occurred in the previously less affected southern Great Barrier Reef, with mortality also affecting genera that are considered resilient (Byrne et al., 2025), while Coral Sea heat extremes were the worst for 400 years, putting the Great Barrier Reef at risk of near-annual bleaching (Henley et al., 2024). Final global mortality figures are not yet available while the event continues, but around 14 per cent of coral reef was lost in the 2009-2018 period spanning the previous two global bleaching events (Souter et al., 2020).

Following GTPR23, Pearce-Kelly et al. (2025) explored the potential for coral tipping dynamics in response to various different stressors and their interactions, concluding that a warming threshold of 1.2°C (1–1.5 °C) as well as the long-term impacts of atmospheric CO_2 beyond 350 ppm were appropriate, noting these thresholds have already been passed, and warning that a comprehensive assessment of stressors and interactions has not yet been conducted and would likely result in lower threshold estimates. Cornwall et al. (2024) assessed the potential for ocean acidification to trigger tipping dynamics, and concluded that while evidence for direct physiological-level tipping dynamics is lacking, indirect ecosystem-level tipping is likely beyond 500 ppm of CO_2, particularly due to the differential impacts of acidification on calcification and growth to the detriment of calcifying (e.g. corals, molluscs, foraminifera) and benefit of non-calcifying (e.g. diatoms, fish, non-calcareous seaweed) organisms. Conversely, future decline in coral reef calcification due to climate change could increase the overall ocean carbon sink by around 7 per cent (Kwiatkowski et al., 2025).

Questions have been raised as to whether current coral decline projections are potentially overestimated. In a systematic review of the methods used to make projections of coral responses to climate change, Klein et al. (2024) found that most used deterministic rather than probabilistic approaches, limiting the ability to assess uncertainty, and that methods showing higher impacts (generally simpler 'excess heat' threshold models, often linked to estimated thresholds in 'Degree Heating Weeks', DHW, for which globally consistent values are difficult to establish) were disproportionately cited. Lab-based results also suggest that a broad range of coral species in the Indo-Pacific show sufficient heritability to allow for adaptation to both warming (with some coral species' DHW thresholds potentially increasing to those expected at c. 1-1.7°C) and acidification levels (c. -0.2 pH units) broadly consistent with the Paris Agreement, but would be insufficient for higher emission scenarios (Jury & Toonen, 2024). However, these analyses do not explicitly account for interacting non-climate co-drivers, which could reduce adaptive capacities at the ecosystem level in the field, nor of in-situ applicability of lab results like these, while recent modelling has found that coral range expansion is too slow to counter future declines (Vogt-Vincent et al., 2025).

Based on the latest information, the GTP community maintains its assessment of warm-water coral reefs having localised to regional tipping points with high confidence (medium agreement, robust evidence). This is based on well-documented evidence for coral reefs being vulnerable to regime shifts to various alternative states, and observations of increasingly widespread mortality in responses to increasingly frequent and intense marine heatwaves. We also maintain the warming threshold estimate of ~1.2°C (1-1.5°C), noting that widespread mortality is already being observed at current warming levels of ~1.4°C (WMO, 2025). While laboratory tests suggest some coral species might have the adaptive capacity to cope with Paris Agreement-compliant warming (Jury & Toonen, 2024) this is not validated in in situ contexts. We also note that CO_2 levels above 500 ppm could directly trigger ecosystem tipping points via acidification (Cornwall et al., 2024), while in the long run CO_2 levels remaining beyond 350 ppm also threaten corals through long-term commitment to climate change (Pearce-Kelly et al., 2025).

Marine (benthic & pelagic) ecosystems

What it is

Marine ecosystems - from shelf sea to deep ocean, and sea floor to water column - face substantial pressures from multiple anthropogenic drivers, which has the potential to trigger irreversible regime shifts (Heinze et al., 2021; Jouffray et al., 2020; Bindoff et al., 2019). Overexploitation combined with climate change could cause some fisheries to collapse (Sguotti et al., 2019; Beaugrand et al., 2022). Similarly, warming, habitat loss, and pollution could result in community-wide shifts in wider marine ecosystems in benthic as well as pelagic environments (Conversi et al., 2015; Beaugrand et al., 2019; Möllmann et al., 2021; Ban et al., 2022; Sguotti et al., 2022). Warming is also expected to result in a reduction in the biological pump - the transport of organic carbon from surface to deep waters - as ocean layers become harder to mix, although barring the polar seasonal lipid pump this is currently expected to be a relatively linear process (Jonasdottir et al., 2015; Armstrong McKay et al., 2021; 2022). Finally, low oxygen 'dead zones' are expanding as a result of warming and nutrient pollution, with excess algae growth leading to deoxygenation and further amplified by sediment phosphorus release feedback (Diaz & Rosenberg, 2008; Breitburg et al., 2018; Heinze et al., 2020). However, while many marine regime shifts have been observed and evidence exists for these ongoing changes and the potential for them to reach local to regional-scale tipping points in some cases, confidence is currently mixed due to limited understanding of potential thresholds and hysteresis in these systems.

What's new

In GTPR23, fisheries were assessed as a local-scale tipping system for some larger fish species with low confidence, and high confidence specifically for cod, with a tipping timescale of around a decade. Marine community shifts were assessed as a low confidence local-scale tipping system. The overall biological pump was not considered a tipping system (medium confidence), but specifically the seasonal lipid pump in the Arctic could be a regional-scale tipping system (unclear, decades). Finally, ocean hypoxia was assessed as a low confidence tipping system at the local scale (and unclear at regional-scale), with timescale varying from months to centuries.

Since GTPR23, there have been several new publications relevant to these systems. Vasconcelos et al. (2024) investigated the impacts of climate change on small pelagic fish communities in the Madeira Archipelago over a 40-year span (1980-2019). The research highlights how global warming has led to a regime shift in the small pelagic community, accounting for 88.9 per cent of the observed fluctuations in fish landings and life-history traits of two key species, *Scomber colias* and *Trachurus picturatus*. Cecapolli et al (2025) were able to identify contrasting regime shift dynamics across the three substocks of Atlantic cod in the North Sea, namely that the Southern North sea populations are now in a depleted state following a regime shift, whereas the other two substocks are either recovering or have not experienced a regime shift. Lastly, an analysis of three global datasets of 667 fish populations has identified abrupt shifts in productivity in almost 20 per cent of them (Cano et al., 2025), confirming and expanding on similar findings a decade earlier (Vert-pre et al., 2013). Although the documented regime shifts of these papers support the GTPR23 assessments for marine systems, they also highlight the need for further research on the confidence for the extent of tipping point responses in benthic and pelagic marine systems.

2.2.7 Potential tipping points in ocean & atmosphere circulations

The ocean and atmosphere's circulations consist of the major flowing, fluid portions of the Earth system that transport water, air, and heat around the planet, and drive daily weather patterns. This includes the major overturning circulations in the ocean, as well as monsoon systems, mid-latitude atmospheric dynamics like the 'jet stream', tropical circulation patterns, and interannual 'oscillations' like the El Niño Southern Oscillation. In this section, we describe each of these systems, their evidence for tipping dynamics, and relevant new research in turn.

Based on this, we have reviewed the status of several systems, concluding that the Atlantic meridional overturning circulation (AMOC), convection in the North Atlantic Subpolar Gyre (SPG) and the circulation in the Southern Ocean are tipping systems with medium confidence, the West African Monsoon as tipping system with low confidence, and all other considered systems as uncertain or no tipping system with varying confidence levels (Figure 2.2.4). With respect to GTPR23, the East Asian Summer Monsoon has been added as an uncertain potential tipping system.

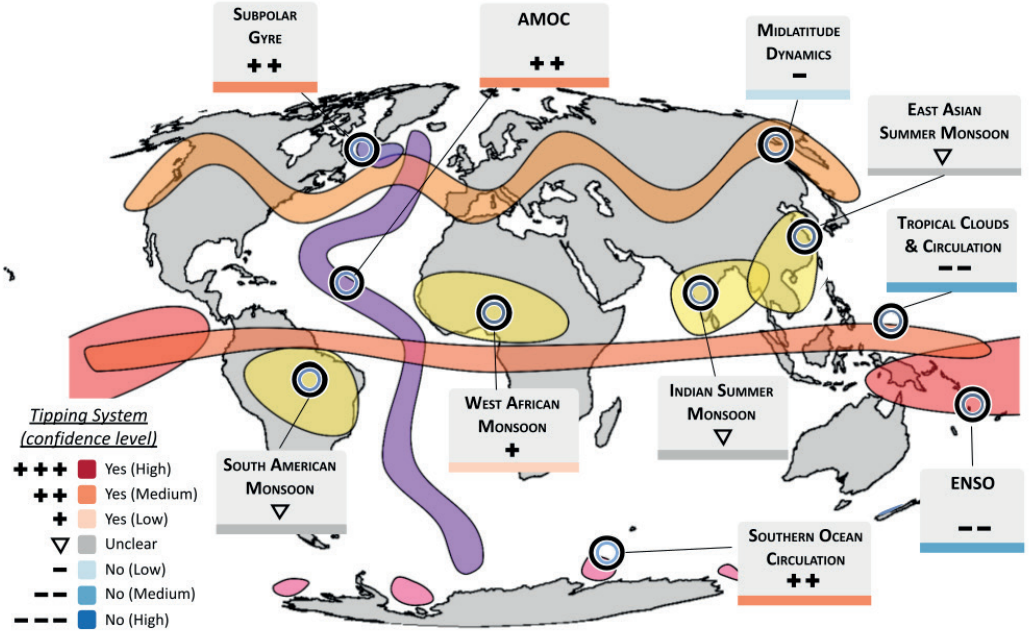

Figure 2.2.4: Potential tipping systems in ocean and atmosphere circulations considered in this chapter. The markers indicate which of the systems are in this report considered a tipping system (+++ high confidence, ++ medium confidence and + low confidence) and which are not (– – – high confidence, – – medium confidence and – low confidence), ▽ indicates systems for which a clear assessment is not possible based on the current level of understanding.

Atlantic meridional overturning circulation (AMOC) & deep convection in the North Atlantic subpolar gyre (SPG)

For more information on the AMOC and SPG tipping points, please see 4.2 Ocean circulation case study

What it is

The Atlantic meridional overturning circulation (or 'AMOC') is the component of the Earth's ocean circulation driven by buoyancy loss at the surface in the north polar region. It describes the movement of warm surface water northwards in the Atlantic, followed by its cooling and densification, and subsequent sinking ('deep convection') in the seas around Greenland, helping to drive the circulation of the global ocean over the course of hundreds of years (Buckley & Marshall, 2015). There are two main regions of deep convection: in the Greenland-Iceland-Norwegian Seas and in the Labrador-Irminger Seas. Climate change, however, can disrupt this circulation by warming and freshening water in the North Atlantic (via increased ice sheet runoff and precipitation), making it harder for it to get dense enough to sink (Arias et al., 2021, Liu et al., 2017). Most model projections show a gradual decline initiated this century (Weijer et al., 2020; Bonan et al., 2025; Drijfhout et al., 2025), which is unprecedented at least in the last 6000 years (Gerber et al., 2025). Palaeoclimate evidence suggests that the AMOC has more abruptly switched to weak or collapsed modes before that (Rahmstorf, 2024). Some models also show weak AMOC states in future projections for extreme and intermediate forcing scenarios (Drijfhout et al., 2025), leading to strong North Atlantic cooling and substantial weather disruption in Europe and the Tropics (van Westen et al., 2025a; van Westen et al., 2025b), and the IPCC assessed in AR6 that many models are currently overly stable (Fox-Kemper et al., 2021; also Arumí-Planas et al. 2024, Dima et al., 2025 and Vanderborght et al., 2025). The AMOC may already have weakened by ~15 per cent over the past 50 years (Caesar et al., 2018; Li and Liu, 2025; Michel et al., 2025), and some studies have detected statistical and physics-based 'early warning signals' (EWS) that could mean AMOC collapse begins within decades (Ditlevsen and Ditlevsen, 2023; van Westen et al., 2024), but whether tipping timings can be projected based on EWS has also been questioned (Latif et al., 2022; Ben-Yami et al., 2024, Terhaar et al., 2025).

Furthermore, the convection branch in the Labrador and Irminger Seas west and south of Greenland (forming part of the Subpolar Gyre, or 'SPG'), has been found to collapse separately to the rest of the AMOC (however being a precursor for AMOC weakening or tipping). This is suggested by palaeoclimate evidence during the transition into the Little Ice Age and by some models (Swingedouw et al., 2021; Arellano-Nava et al., 2022). The risk of a SPG overturning collapse has been evaluated as 40 per cent in low- and medium-emission scenarios when selecting the CMIP6 models that best represent the observed oceanic stratification (Swingedouw et al., 2021).

What's new

In GTPR23, the AMOC was assessed as a tipping system with medium confidence, with a likely timescale of decades to centuries, and an uncertain path-dependent threshold (Loriani et al., 2023).

Since GTPR23, there have been several relevant publications. CMIP6-based projections show marked decline in the Arctic Beaufort Gyre, however the uncertainty of the gyre freshwater content trends is still large both in the models and observations (Athanase et al., 2025, Lin et al., 2023; Wang et al., 2025). Increased freshwater export to the North Atlantic may weaken deep-water convection in key AMOC regions, but so far there is no published observational evidence of this happening. Various freshwater forcing experiments in models of varying complexity reaffirm evidence for potential AMOC collapse: In an ocean-only model, gradual freshwater forcing can trigger intermediate tipping events, leading to abrupt reorganisations of North Atlantic circulation (Lohmann et al., 2024; Lohmann & Lucarini, 2024) in multiple partially collapsed stable states. Four steady states are found using both surface freshwater forcing and changing CO_2 in CLIMBER-X (Willeit and Ganopolski, 2024). A similar behaviour is observed in a high resolution model by Gou et al. (2024), where different convection areas reach tipping points independently. Van Westen et al. (2025) demonstrate that an AMOC collapse can still occur in a strongly eddying ocean-only model under freshwater hosing, indicating that ocean eddies do not prevent tipping. For the first time, an abrupt AMOC weakening has been simulated in Earth System Models without the need for externally imposed freshwater perturbations or an extreme emission scenario (NASA-GISS-E2-1-G in Romanou et al., 2023; MRI-ESM2-0 in Drijfhout et al., 2025). This transition is triggered by stochastic variability in sea-ice transport and melting in the Irminger Sea. The stochastic bifurcation mechanism proposed in Romanou et al. (2023) has been explained by Boerner et al. (2025, in review) in terms of the collision between the `on' state of the circulation with the unstable circulation pattern associated with the `edge' state of the system.

Along similar lines, Gu et al (2024) find that nonlinear processes might amplify stochastic variability, leading to states with convection shutdown in the Labrador Sea. On the other hand, there have been recent studies that have identified contrasting mechanisms influencing the stability of the AMOC. Empirical modelling suggests that noise-induced tipping events are unlikely under present-day variability unless the AMOC is already close to a critical threshold (Chapman et al., 2024). Furthermore, Baker et al. (2025) report a stabilising feedback present in CMIP6 models on a centennial time-scale, wherein sustained wind-driven upwelling in the Southern Ocean counteracts AMOC weakening—even under scenarios of extreme greenhouse gas forcing and freshwater input. However, these simulations are relatively short and may therefore correspond to a transient state. Also, the small AMOC strengths reported in several scenarios resemble the residual circulation persisting after collapse in extended simulations (Drijfhout et al., 2025; van Westen and Baatsen, 2025; van Westen et al., 2025). The effect of the CO_2 ramping rate on the weak or collapse state of the AMOC has also been addressed (Hankel, 2024).

In terms of direct and proxy observation, Terhaar et al. (2025) suggest that the AMOC has not weakened in the last 60 years as derived from surface heat flux reconstructions serving as proxy indicator. Also, based on experiments with an idealised model, Zimmermann et al. (2025) advocate for cautious use of purely statistical early warning indicators since they may raise false alarms about approaching critical. On the other hand, a newly developed, physics-based observable early warning signal for AMOC tipping (representing the strength of the salt-advection feedback (Vanderborght et al., 2025)) suggests that the AMOC has destabilised over the past 40 years when applied to reanalysis and assimilation products (Van Westen et al., 2024), supported by deep-learning based reconstructions (Michel et al., 2025). Furthermore, this indicator is biased positively in CMIP6 models, implying that these models may underestimate the risk of tipping (Arumì-Planas et al., 2024; van Westen and Dijkstra, 2024).

In GTPR23, like the AMOC, the SPG was assessed as a tipping system with medium confidence, however with a shorter timescale of years to decades, and a likely warming threshold range of 1.1 to 3.8°C (Loriani et al., 2023). Since GTPR23, there have been new publications providing additional evidence for SPG as a tipping system. Proxy records from bivalve shells provide empirical evidence that the SPG crossed a tipping point during the transition into the Little Ice Age, with early warning signals appearing before the abrupt SPG weakening in the 14th century. The destabilisation was likely triggered by freshwater input from melting glaciers during the Medieval Warm Period, followed by an anomalous export of Arctic sea ice into the subpolar North Atlantic (Arellano-Nava et al., 2022). A broader compilation of bivalve proxy records suggests that the subpolar North Atlantic experienced two periods of stability loss in recent times: one preceding the 1920s North Atlantic circulation regime shift, and the second in recent decades, indicating that the SPG region may be moving towards a tipping point (Arellano-Nava et al., 2025 in press).

Recent observations show that the SPG is undergoing strong freshening and reduced convection activity. The eastern SPG system has recently experienced its largest freshening of the past 120 years, primarily due to changes in ocean circulation (Holliday et al., 2020). Two convective shutdowns in the Labrador Sea were observed in 2021 and 2023, with the latter being more intense. In 2023, convection shoaled to depths of less than 700 m, linked to extensive near-surface freshening driven by extreme Arctic sea-ice melt and enhanced by freshwater release from the Beaufort Gyre (Yashayaev, 2024). This freshening also spread to the Irminger Sea, reaching depths of up to 1,500 m (Fried et al., 2024). These events highlight the growing vulnerability of the SPG to crossing a tipping point.

Turning to model evidence, an analysis of abrupt shifts in CMIP6 models finds that 24 out of 57 models exhibit an abrupt SPG weakening, occurring within a global warming range of 0.3°C to 0.3°C, with a median critical temperature of approximately 1.5°C above pre-industrial levels (Terpstra et al., 2025). In another study still under review, 'abrupt changes' and 'state transitions' are detected in the SPG in three models at 1.2-4.1°C and in 10 models at 1.2-5.6°C respectively (Table A2.2.1), and abrupt shifts are also detected in the AMOC in nine models between 1.1 and 3.9°C (Angevaare & Drijfhout, in review). However, such abrupt shifts do not necessarily represent tipping points without confirming self-perpetuating dynamics. Menary et al. (2025) further classify different types of abrupt SPG changes, raising the need to define robust metrics and causal mechanisms (Falkena et al., in review) for the identification of abrupt events.

Based on this new research, the GTP community maintains its assessment of both AMOC and SPG being tipping systems with medium confidence, however acknowledging the increase in amount and agreement of evidence. For both, conceptual and low-complexity models suggest alternative stable states, further evidenced by palaeo records and process-based state-of-the-art climate models. Uncertainty persists around the magnitude of freshwater and thermal forcing that could initiate tipping, and the proximity to a potential tipping point.

Southern ocean overturning circulation

What it is

Ocean convection also occurs in the Southern Ocean (SO) around Antarctica, forming the second branch of the global ocean overturning circulation alongside the AMOC (Fox-Kemper et al., 2021; Heuzé et al., 2021). Sea ice formation and strong offshore winds help produce dense salty water that sinks from the Antarctic shelves to the deep ocean, forming the Antarctic Bottom Water mass (Holland and Kwok., 2012; Abernathey et al., 2016). The response of the SO overturning to global warming is less well studied than the AMOC, and is limited by the lack of Antarctic meltwater inclusion in models (Fox-Kemper et al., 2021; Heuzé et al., 2021; Purich & England 2023), but evidence has accumulated for an ongoing and continued decline (Lago & England, 2019; Liu et al., 2022; Gunn et al., 2023; Li et al, 2023; Zhou et al., 2023; Rosser et al., 2025 in review), and palaeo records suggest it has previously collapsed in response to meltwater pulses and could do so again (Skinner et al., 2010; Hayes et al., 2014; Gottschalk et al., 2016; Jaccard et al., 2016; Huang et al., 2020; Turney et al., 2020; Abram et al. 2025).

What's new

In GTPR23, Southern Ocean convection was assessed as a tipping system with medium confidence, with a likely timescale of decades and an unknown threshold (Loriani et al., 2023). Additionally, there is the prospect of abrupt change in continental shelf circulation, leading to sudden rising ocean temperatures in contact with the Antarctic ice shelves (Li et al., 2023; Purich and England, 2023; Abram et al. 2025). Cold ice shelf cavities in the Weddell and Ross Seas may be particularly vulnerable to warming under future climate scenarios, which could dramatically increase basal melting and contribute to sea level rise. This has been highlighted as another tipping mechanism (Hellmer et al., 2012; 2017; Siahaan et al., 2022; Naughten et al., 2023).

Over the past two years since GTPR23, a handful of studies have further investigated Southern Ocean convection and water mass change tipping systems, with much of the research effort concentrated on sea ice variability, but with some additional studies of indicators of ocean overturning change and future projections. On Southern Ocean convection and overturning, Gunn et al. (2025; in review) combines historical observations (1985-2024) and model projections of the upcoming decades (2041-2050) to assess changes in the abyssal Southern Ocean. They show that long-term freshening of the abyssal ocean has slowed and even reversed in some locations, as Dense Shelf Waters may no longer be reaching the abyssal ocean. Rosser et al., (2025; in review) demonstrate that the Southern Ocean overturning circulation collapses across nearly all CMIP6 models, even under strong mitigation scenarios.This disruption of the long-standing connection between the continental shelf and the abyss unfolds over decades and is driven by ice shelf melt and subsequent freshening. As the projected changes out to 2050 are already consistent with recent observations to 2025, there is evidence that model projections may underestimate the pace of change in the real system. This analysis indicates a potential tipping point in the ocean overturning connection between water over the shelf and water in the abyssal ocean.

Recent Antarctic sea-ice decline has raised further concerns that elements of the Antarctic ocean-ice system are changing more rapidly than first predicted. Since GTPR23 progress has been made in understanding its causes but uncertainty remains about the consequences for ocean convection. Using a reanalysis data product (Josey et al., 2024) and observations alongside models (Song et al 2024), recent work has shown that as sea ice cover is reduced, particularly in the Weddell, Bellingshausen, and Ross Seas, ocean heat loss to the atmosphere has doubled, also shifting the timing of peak heat loss. This intensification of winter heat loss leads to enhanced storm activity and also increased formation of dense surface water, but at locations far from the Antarctic shelf where dense shelf water is formed. A recent paper linking sea ice decline, heat loss, and a post-2015 surface salinity trend was misreported in the media as indicating an "SMOC reversal", but the implications for deep convection were not discussed in that study (Silvano et al., 2025). Being remote from where Dense Shelf Water is formed, this effect is unlikely to contribute to changes in the abyssal overturning cell. However, advection and mixing of that off-shelf water mass may eventually impact the formation of dense water on the shelf, but the implications for Antarctic Bottom Water (AABW) formation remain unsubstantiated and is further complicated by decreased sea ice production, which diminishes AABW production. Nevertheless, this work highlights the potential interaction of different tipping points; namely, meltwater reduced AABW formation over the shelf (Li et al., 2023), contrasting changes in water masses off the shelf where sea ice loss has occurred (Josey et al., 2024)). In another study, using a coupled ocean-sea ice-ice shelf model forced by CMIP6 model-mean projected atmospheric conditions, Xie et al. (2025) find a decrease of more than half the rate of dense shelf water formation in the Ross Sea and a 300 metre thinning of AABW in the deep ocean by 2100. This reduction, a signature of an overturning slowdown in the region, is caused by the combined effects of meltwater-driven freshening with declining sea ice production.

A recent review of abrupt change around Antarctica finds evidence for emerging rapid, interacting and sometimes self-perpetuating changes in the Antarctic environment (Abram et al. 2025). The study finds that Antarctic sea-ice coverage has reduced to levels far below its natural variability of recent centuries, with evidence that future changes could be more abrupt, nonlinear and potentially irreversible than Arctic sea-ice. The study also reviews evidence that the recent slowdown in the Southern Ocean overturning circulation is set to intensify this century, driven by increasing rates of ice melt around Antarctica. A slowdown of the SO overturning circulation in turn reduces the uptake of carbon by the oceans (Liu et al., 2022) and also causes further shelf water warming (Li et al., 2023; Purich and England, 2023), which are both expected to drive further ice shelf melt; an amplifying feedback that could lead to an eventual collapse in the SO overturning circulation.

Based on this new research, the GTP community maintains its assessment of the Southern Ocean overturning circulation as being a tipping system with medium confidence (high agreement, medium evidence), with evidence growing that the formation of Dense Shelf Water is declining and could reach a tipping point, but uncertainty remaining around the role of sea ice and interactions with ice shelf cavities.

Monsoons

What it is

Monsoons describe the large seasonal changes in the direction and strength of prevailing winds driven by seasonal insolation and local temperature differences between land and ocean, leading to heavy summer rainfall over land. Several subcontinental scale monsoon systems are recognised, including the Indian Summer Monsoon (ISM), the East Asian Summer Monsoon (EASM), the West African Monsoon (WAM), and the South American Monsoon (SAM). Today these are seen as being interconnected as part of one global monsoon system (Geen et al., 2020) strongly linked to the seasonal migration of the Intertropical Convergence Zone (ITCZ), where northern and southern hemisphere trade winds converge. The EASM however, extends to the subtropics, and is influenced by mid-latitude frontal systems and the jet stream as well as the Tibetan Plateau (Molnar et al., 2010; Son et al., 2019). Rainfall projections are subject to high uncertainty in climate models, with projections of overall strengthening of the global monsoon precipitation in the future (Hsu et al., 2012). Early tipping point studies suggested that the ISM could tip to a weak state as a result of aerosol emissions (Lenton et al., 2008; Levermann et al., 2009). Similarly, the East Asian Summer Monsoon (EASM) was proposed to tip once an oceanic humidity threshold is crossed (Schewe et al., 2012). However, more recent studies have cast doubt on both hypotheses (Boos and Storelvmo, 2016; Seshadri, 2017). Palaeo records from the 'African Humid Period' also suggest that the WAM might interact with Sahel vegetation in a way that could tip this combined system to a wetter and greener state (Charney 1975). In case of an AMOC collapse, the ITCZ and thus monsoons could strongly shift southwards, as evidenced by palaeo studies (Stager et al., 2011).

What's new

In GTPR23, the WAM was assessed as a tipping system with low confidence, and ISM and SAM assessed as unclear (Loriani et al., 2023). Since GTPR23, there have been several new publications relevant to these tipping systems. By simulating a generic monsoon system on an aquaplanet, Katzenberger & Levermann (2025) introduce a new understanding that monsoons can be considered to undergo periodic tipping between stable 'on' and 'off' states. Changing climate conditions could thereby push the system towards a permanently altered state. Using an intermediate complexity model, Recchia and Lucarini (2023) showed the distinct response of the South and East Asian monsoon to anthropogenic forcings, emphasizing that aerosol forcing, rather than GHGs forcings, has the potential to strongly reduce the intensity of the monsoonal precipitation, with stronger impacts expected in the East Asian sector.

Furthermore, Loriani et al (2025) have included the EASM (not considered in GTPR23) in their assessment, classifying it as an uncertain tipping system based on limited understanding about potential tipping processes. Like the other monsoon systems, EASM could be subject to the effects of an AMOC collapse (Ben-Yami et al., 2024). A recent analysis of CMIP6 models reveals a projected increase of extreme wet seasons frequencies, precipitation and interannual variability of the EASM (Katzenberger and Levermann, 2024), albeit not reporting major systematic shifts. Stronger evidence stems from proxy records indicating several abrupt and irreversible regime shifts since the Last Glacial Maximum (Lu et al, 2025), linked to abrupt shifts in the AMOC and Saharan vegetation. Finally, recent analysis of abrupt shifts in CMIP6 model results detected some abrupt shifts in the Indian Summer Monsoon (at ~0.8°C global warming) but not other monsoons (Terpstra et al., 2025) (Table A2.2.1), but they were not persistent, and do not necessarily represent tipping dynamics. Based on this research, the GTP community maintains its assessment of the West African Monsoon being a tipping system with low confidence. Similarly, for the South American and Indian Monsoon the assessment of an uncertain tipping system is maintained. The same classification of an uncertain tipping system is made for the now-added East Asian Summer monsoon.

El Niño southern oscillation ('ENSO')

What it is

The El Niño-Southern Oscillation (ENSO) is the dominant interannual mode of variability in Earth's climate (Timmermann et al., 2018). Every three to five years, the 5-6°C difference between the warmer western tropical Pacific and cooler eastern tropical Pacific maintained by easterly trade winds becomes weakened, resulting in an 'El Niño' event (the warm phase of ENSO). Conversely, during a 'La Niña' event (the cold phase of ENSO) this temperature gradient intensifies. Both phases lead to substantial weather pattern shifts around the Earth, with substantial impacts on people and ecosystems (e.g. Holbrook et al., 2020; McPhaden et al,. 2020; Callahan & Mankin 2023). Climate models differ, but despite overall stronger trade winds, colder eastern equatorial Pacific, and weaker ENSO events since the 1990s/2000s (Capotondi et al., 2015; Ma & Zhou, 2016; Fedorov et al., 2020; Seager et al., 2022; Wills et al., 2022; Heede and Fedorov 2023a), global warming is generally expected to result in an increase in ENSO variability, leading to more extreme El Niño and La Niña events (Cai et al., 2015; 2018; 2022; Heede and Fedorov 2023b; Wang et al., 2023). Palaeorecords suggest that the amplitude and frequency of ENSO events has gradually increased during the Holocene (Freund et al., 2018; Grothe et al., 2020; Lawman et al., 2022) and that a 'permanent El Niño-like state' may have existed in the Pliocene 3 million years ago (Wara et al,. 2005; Fedorov et al., 2006, 2013, 2015; Tierney et al., 2019), leading to the suggestion that ENSO might feature a tipping point towards a permanent or extreme state (Lenton et al. 2008). However, the evidence so far does not support a threshold beyond which a self-sustaining regime shift to such a state occurs (Loriani et al., 2023).

What's new

In GTPR23, ENSO was assessed as not a tipping system with medium confidence (Loriani et al., 2023). Since GTPR23, there have been several new publications relevant to this tipping system. In particular, the 2023-24 strong El Niño event has helped to drive record-breaking global temperatures across land and sea (Jiang et al., 2025), with substantial implications for ecosystems. While a rare extreme, models indicate that such large jumps in temperature are not unexpected during strong El Niño event when combined with the current global warming trend (Terhaar et al., 2025), and may have been made more likely by the prolonged La Niña event (itself potentially linked to global warming (Wang et al., 2023)) preceding it (Raghuraman et al., 2024). These results suggest a combination of underlying global warming, a strong El Niño, and the particular timing and pattern of this and the preceding La Niña could largely drive the observed the recent jump in global temperatures, rather than being a regime shift in global warming or a change in ENSO dynamics, which will be confirmed if temperatures revert to the long-term trend (Terhaar et al., 2025).

For the future, recent research continues to support an increase in ENSO variability and extreme El Niño event frequency, with an analysis of ENSO dynamics during past glacial changes indicating that cooler conditions led to less ENSO variability and fewer extreme El Niño events (Thirumalai & DiNezio et al., 2024; corroborating e.g. Brown et al., 2020), and therefore the inverse can be expected with future warming. Bayr et al. (2024) recently argued that ENSO could be considered a tipping system on the basis of stronger El Niño events potentially triggering other tipping systems via higher global temperatures, but this warming is temporary, and no self-sustaining state shift is observed or projected within ENSO's own dynamics, which is key to be considered a tipping system (rather than impacts on other systems). As such, the GTP community maintains its assessment of ENSO not being a tipping system with medium confidence.

Midlatitude dynamics

What it is

A key aspect of the mid-latitude atmospheric circulation is the 'jet stream', a band of strong westerly winds with largest velocities at an altitude of 7-12 km which separates cold polar air masses from temperate lower-latitude air masses. The jet features large 'meanders' (linked to planetary, or Rossby, waves) which normally move and dissipate but can become quasi-stationary, leading to high-impact climate extremes. A local example of such persistent weather features are atmospheric 'blocking' events, which are closely associated with several extremes including wintertime cold spells and summertime heatwaves (Kautz et al., 2022) and conditions favouring wildfires (Luo et al., 2025). Global warming has likely already led to a poleward shift of the mid-latitude jet (Woolings et al., 2023) and a similar trend is expected to continue in the future (Oudar et al., 2020). At the same time, amplified Arctic warming is leading to a reduced meridional temperature gradient between the high and low latitudes. This has been posited to slow down the mid-latitude circulation and the jet stream, increasing the latter's waviness. An enhanced waviness, in turn, would favour more persistent midlatitude weather and the connected extreme events (Kornhuber & Tamarin-Brodsky, 2021; Coumou et al., 2018). Observations indeed evidence a slowdown of the boreal mid-latitude summer storm tracks over the last several decades likely associated with anthropogenic emissions (Chemke & Coumou 2024). However, the strength of the poleward shift and the degree to which jet waviness and midlatitude weather persistence have increased and/or can be linked to Arctic warming has been disputed (Blackport & Screen, 2020; Riboldi et al., 2020). Potential tipping points in jet stream dynamics have been suggested (Drijfhout et al., 2013; Steffen et al., 2018), but little evidence exists for a warming threshold beyond which such behaviour might become self-sustained.

What's new

In GTPR23, mid-latitude atmospheric dynamics was assessed as not a tipping system with low confidence (Loriani et al., 2023). Since GTPR23, there have been new investigations relevant to this tipping system, with a focus on how a future, warmer Arctic will affect mid-latitude waviness. Key results concern future changes in the meridional temperature gradient, the role of Arctic sea-ice and the relationship between jet speed and jet waviness. Arnheim et al. (2025) analysed large ensembles of climate model simulations and concluded that climate change leads to a less wavy jet. They further found that the more recent set of simulations produced a weaker Arctic Amplification, displaying an enhanced reduction of waviness and blocking compared to an earlier model version. The effects of Arctic amplification on the jet stream and midlatitude circulation may be partially countered by Arctic sea-ice loss, which contributes to a slow-down of the wintertime North Atlantic jet stream (Jiang et al., 2025). Finally, past arguments for a future, wavier mid-latitude circulation have mostly assumed that slower jets are more wavy and persistent, but the link between jet speed, waviness and persistence has recently been challenged by Baatelan et al. (2024) and Banderier et al., (2025), who found that weakened mid-latitudinal jet strength does not equate to increased waviness and that waviness can increase in the absence of clear persistence changes. In contrast, recent work has found evidence for increasing frequency of planetary wave resonance events in historical data (Li et al., 2025) and in future model projections (Guimarães et al., 2024), but with no indication of tipping dynamics. The latest research strengthens the evidence for the midlatitude atmospheric dynamics not being a tipping system. However, due to a low level of agreement in the literature the GTP community still assesses the midlatitude atmospheric dynamics as not being a tipping system with low confidence (medium evidence, low agreement).

Tropical clouds, circulation, & climate sensitivity

What it is

Clouds - and in particular tropical clouds - play an important role in the Earth's climate system by modulating how much incoming sunlight is reflected and how much heat from the surface is trapped (Forster et al., 2021). In general, high thin clouds tend to let more light through but trap more heat, therefore having a net warming effect, while lower thicker clouds tend to reflect more light but let more heat through, having a net cooling effect. Global warming is affecting cloud dynamics though, with implications for the Earth's climate sensitivity depending on which type of cloud is more favoured. Cloud projections remain highly uncertain though due to poor process representation, but unexpected feedbacks remain possible (Caballero & Huber, 2013; Bellomo et al,. 2014; Bloch-Johnson et al.. 2015; Mauritsen & Stevens 2015; Myers et al. 2018). One such feedback is the loss of subtropical stratocumulus cloud decks, which in one model featured a tipping point in CO_2 concentration beyond which abrupt loss and a global warming feedback of 8°C occurred (Schneider et al,. 2019). Another possibility is an unexpected reorganisation in tropical circulation to a 'super-MJO' (Madden-Julian Oscillation) or superrotation state beyond some level of warming (Caballero & Carlson 2016; Seeley & Wordsworth 2021; Tziperman & Farrell, 2009; Caballero & Huber 2010). However, cloud processes remain a key source of uncertainty in climate models, and little evidence is currently available to support these possibilities (Sherwood et al., 2020).

What's new

In GTPR23, tropical clouds and circulation was assessed as not a tipping system with medium confidence (Loriani et al., 2023). Scientific literature published since then has not directly addressed tipping points in this system, such that the GTP community maintains its assessment of tropical clouds, circulation and climate sensitivity not being a tipping system with medium confidence.

2.2.8 Interactions between tipping systems

What it is

The tipping systems identified in the previous subsections are generally not isolated but interact across scales in space and time (Wunderling/von der Heydt et al., 2024). Here, we define a tipping interaction as any linkage between two tipping systems that is destabilising, stabilising or where competing effects are at play. An example of a well established destabilising interaction is the linkage between GrIS and the AMOC, where meltwater from the GrIS destabilises the AMOC (see e.g. Weijer et al., 2019). An example for a stabilising interaction is the interaction vice versa where a weakening (or tipping) AMOC leads to cooler temperatures around Greenland, which may be strong enough to slow down (or even stop) further GrIS melt (e.g. van Westen et al., 2024; Jackson et al., 2015).

What's new: Summary

We summarise the assessments of the GTP community in Figure 2.2.5. Based on these new and former assessments, the GTP community maintains the following three important conclusions on interactions and cascading transitions between tipping systems.

1. Tipping systems in the climate system are closely interacting, meaning a substantial change in one will have consequences for connected tipping systems.
2. We are quickly approaching global warming thresholds where tipping system interactions become relevant, because multiple individual thresholds are being crossed. These are at levels of 1.5-2.0°C of global warming.
3. While the pure pressure from global warming in its speed and also its magnitude dominates over the role of interactions (which need time to unfold) on tipping risks, the interactions between climate tipping systems seem to further destabilise the Earth system in addition to climate change effects on individual tipping systems.

The following three novel top-level conclusions including the newly assessed interactions are:

1. The majority of interactions between climate tipping systems are destabilising. However, new evidence shows that the interaction from AMOC weakening to Amazon rainforest may be stabilising as well as the interaction from West Antarctic Ice Sheet melt to AMOC stability. 15 interactions are assessed as destabilising, four as stabilising and one as unclear/competing effects (see **Figure 2.2.5**; not counting the interactions of very limited evidence, coloured in grey in **Figure 2.2.5**).
2. Although of unknown and/or limited strength, permafrost loss and Arctic Sea Ice decline may form a vicious cycle where less permafrost could lead to Arctic Sea Ice retreat and Arctic Sea Ice retreat may lead to enhanced inland permafrost degradation.
3. The AMOC has already been identified as an important mediator of interactions in GTPR23 but with the new evidence reported here, it can truly be stated that the AMOC is the global mediator of tipping point interactions. The AMOC alone features in 45 per cent (9 out of 20 interactions, not counting interactions of very limited evidence) of all assessed tipping point interactions (see Figure 2.2.5).

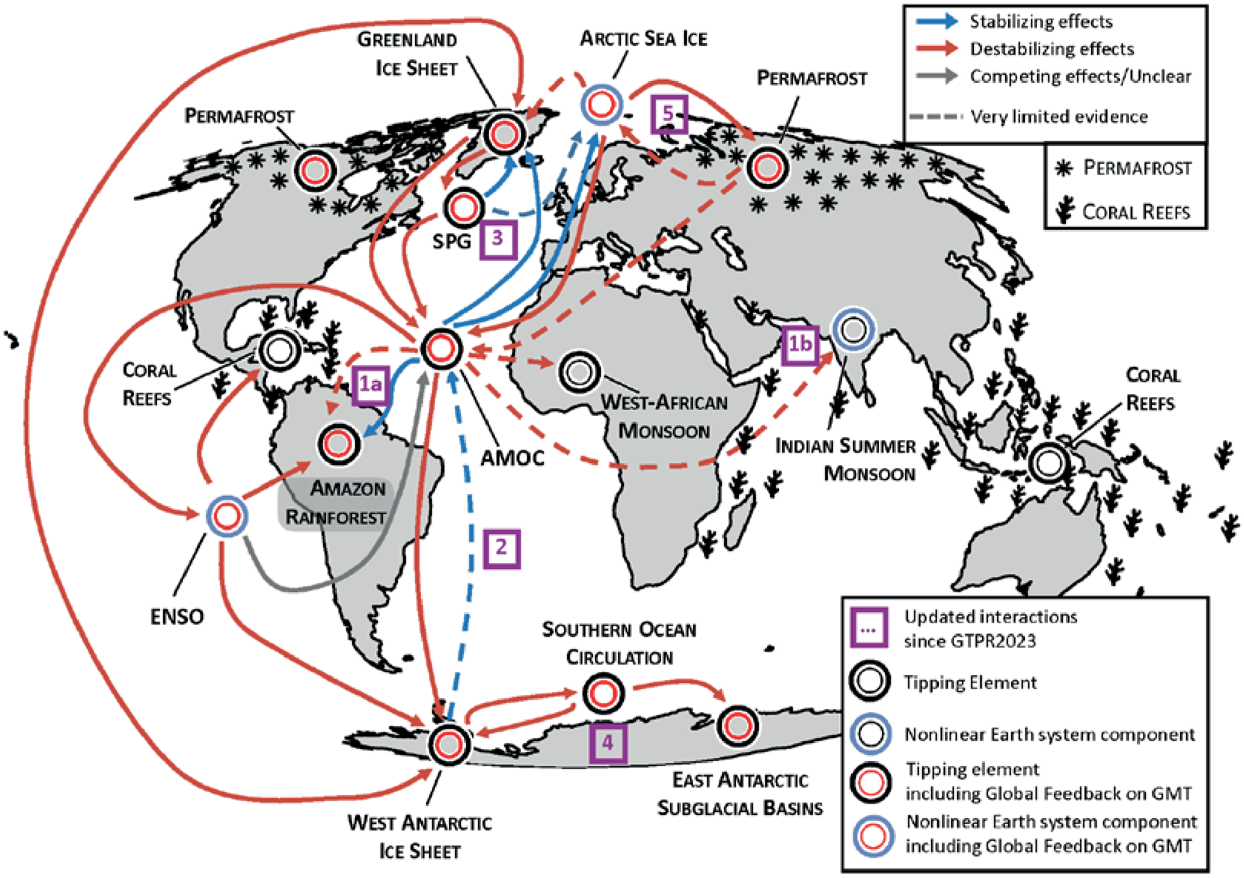

Figure 2.2.5: Update of tipping system interactions based on new evidence presented in this report. The updated interactions are denoted by purple squares and are: (1) Interactions from AMOC to global monsoon systems with the two updates (1a) AMOC→Amazon rainforest: AMOC weakening leads to increased rainfall in the southern part of the forest (blue arrow) but also to decreasing rainfall in the northern part (red dashed arrow); (1b) AMOC interaction with the Indian summer monsoon (red dashed arrow). (2) Interaction between AMOC and the West Antarctic Ice Sheet (WAIS) with limited evidence pointing towards a potential stabilising interaction from WAIS→AMOC (blue dashed arrow). (3) North Atlantic Subpolar Gyre (SPG) and its interactions with AMOC and the Greenland Ice Sheet. (4) Interaction from the Southern Ocean Circulation to the shelf regions of the Antarctic Ice Sheet and WAIS. (5) Interactions between Permafrost and Arctic Sea Ice (red arrows, now with higher evidence levels). The original figure has been updated from GTPR23 (Lenton et al., 2023) and Wunderling/von der Heydt et al. (2024).

Based on new evidence from recently published works presented here, we reassessed and for the first time evaluated the following five new interactions between climate tipping systems. Here, we focus on interactions where new evidence arose since the last Global Tipping Points Report 2023 (Lenton et al., 2023; Wunderling/von der Heydt et al., 2024).

Interaction from AMOC to global monsoon systems

AMOC → Amazon rainforest (via the South American monsoon)

The interaction between the AMOC and Amazon rainforest is complex. In the last report, it was assessed that a weakening AMOC would lead to a southward shift in the Intertropical Convergence Zone (ITCZ) that in turn could lead to increased precipitation in the southern Amazon region while intensifying drying trends in the north (e.g. Bellomo et al., 2023; Orihuela-Pinto et al., 2022). These divergent patterns could stabilise forests in some regions while pushing others towards a degraded or savanna-like state. Indeed, most recent Earth system model and observational-data studies find that a weakening AMOC leads to an increase in rainfall in southern and eastern parts of the Amazon rainforest counteracting the global warming-related decrease in rainfall over these areas (Nian et al., 2023; Ben-Yami et al., 2024; Högner et al., 2025).

Another study confirms a vulnerability increase in northern Amazon forests due to a decrease in rainfall and increase in seasonality, based on palaeoclimatic pollen and microcharcoal data (Akabane et al., 2024). As suspected, these studies suggest a regionally different response of the Amazon rainforest to a weakening AMOC that is now implemented in our updated tipping system interaction map (see Figure 2.2.5). In addition, seasonal precipitation changes after AMOC collapse may exert additional pressure on the rainforest (van Westen et al., 2024).

Importantly, the overall vulnerability of the Amazon rainforest is high: While the increased vulnerability in northern Amazon region combined with deforestation, wildfires and land-use change may have the capacity to trigger a systemic tipping point in the northern Amazon rainforest (Akabane et al., 2024), the effect in the southern Amazon region is different. Here, the effect of increased rainfall due to AMOC weakening is likely not of the same magnitude as drying effects from global warming (Nian et al., 2023; Högner et al., 2025) and strong deforestation, wildfires and land-use change (Albert et al., 2023; Lapola et al., 2023). This means that global warming impacts likely decrease rainfall over the southern Amazon rainforest more than a weaker AMOC would lead to its increase.

AMOC interactions with the West African and Indian monsoon systems

CMIP6 models that feature a bistable AMOC show highly consistent changes in tropical monsoon systems following an AMOC collapse. The West African Monsoon and the Indian Summer Monsoon experience shorter wet seasons and longer dry seasons with mean annual precipitation decreases of 29 and 19 per cent, respectively (Ben-Yami et al., 2024). Therefore, we classify the interaction from AMOC to both monsoon systems as destabilising with yet limited evidence (see Figure 2.2.5).

Interaction between AMOC and WAIS

Several recent studies report AMOC changes in response to meltwater from the Antarctic Ice Sheet and in particular from WAIS as the most vulnerable part of the Antarctic Ice Sheet. Two studies highlight the importance of both oceanic and atmospheric processes for AMOC stability (Shin et al., 2024; An et al., 2024). On short timescales, AMOC weakening in response to meltwater input from WAIS is observed, driven by Rossby wave teleconnections and ITCZ-shift-induced precipitation changes (Shin et al., 2024; An et al., 2024), while ocean-driven strengthening may emerge on longer timescales (Shin et al., 2024). However, under realistic meltwater input from both the Greenland and (West) Antarctic ice sheets, the additional meltwater from the Antarctic Ice Sheet can mitigate an AMOC slowdown, or even prevent its tipping (Sinet et al., 2025; Knight & Condron, 2025). These studies use Earth system models of intermediate and full complexity (CLIMBER-X and CESM). An earlier expert elicitation assessed competing physical effects from WAIS melt to AMOC stability, including a physical mechanism for a stabilising interaction from WAIS disintegration to AMOC stabilisation (Kriegler et al., 2009). In summary, we therefore decide to label the linkage between the West Antarctic Ice Sheet to the AMOC as stabilising (with very limited evidence for now).

North Atlantic subpolar gyre and its interactions

The North Atlantic subpolar gyre (SPG) has been classified a separate potential tipping system in the previous report (Loriani et al., 2023; (Loriani et al., 2023; Armstrong McKay et al., 2022); Armstrong McKay et al., 2022), and the SPG convection has a proposed mechanism for bistability (Born and Stocker, 2014). However, at the time of GTPR23, SPG collapse was not included in the chapter on tipping system interactions because not many studies had considered SPG connections to other tipping systems at that point in time. However, we reconsider this former assessment due to our following new lines of evidence of tipping point interactions: (1) Tipping of the SPG is associated with persistent ceasing of convection in the Labrador Sea and Irminger Sea ocean deep convection areas, with similar but smaller amplitude and more regional consequences for North Atlantic temperatures as an AMOC shutdown (Swingedouw et al., 2021). Therefore, a shutdown of convection in the SPG cools the North Atlantic region and we expect a stabilising link from the SPG to the Greenland Ice Sheet and Arctic sea ice (Li and Born, 2019). Importantly, changes in precipitation patterns can also contribute to the freshwater budget in the SPG region, and can therefore play a role in destabilising the SPG. (2) As the SPG convection regions significantly contribute to deepwater formation for the AMOC, a shutdown of convection in these areas could lead to an initial weakening of the AMOC (Neff et al., 2023; Rahmstorf, 1995) (i.e. destabilising link from SPG to AMOC). (3) Finally the tipping in the SPG is triggered by freshwater input that could be meltwater from a disintegrating Greenland Ice Sheet (Born & Stocker, 2014).

Interaction from the Southern ocean circulation to the shelf regions of the Antarctic Ice Sheet

Recent work has provided growing evidence for a potential transition from cold to warm ocean states in the Filchner-Ronne and Ross Ice Shelf cavities due to changes in the Southern Ocean Circulation. Using an ocean circulation model, Hill et al. (2024) found that temperatures in these cold ice shelf cavities could increase by 2 to 4°C, leading to significant increases in sub-shelf melt rates, building on earlier efforts suggesting that warming has been locked-in in certain regions of Antarctica (Naughten et al., 2023). However, Hoffman et al. (2024) caution that such transitions may not occur uniformly. Their coupled Earth system model, which simulates ocean, land, sea ice, atmosphere, and ice sheet interactions, explores freshwater triggers for tipping points that could rapidly shift ice shelf cavities from cold to warm states, accelerating basal melt rates within a few decades. In addition, remote connections between melt fluxes at different ice shelves could lead to cascading effects, further destabilising ice shelves downstream. Another key driver expected for Antarctic ice shelf mass loss in coming decades are the ongoing positive trends and high variability in the Southern Annual Mode, which causes increased upwelling and subsurface warming and salinification close to ice shelves (and vice versa for negative phases), driving basal mass loss of 40 Gt/yr (around 40 per cent of the average loss) at one standard deviation of this climate mode of variability (Verfaillie et al., 2022; Osotoka et al., 2022).

Interactions with permafrost

Interactions between permafrost and Arctic Sea Ice

There is new evidence that suggests a possible destabilising linkage from declining permafrost to a decrease in Arctic Sea Ice (Nitzbon et al., 2024). The reason is that inland permafrost degradation could increase the land-to-ocean heat transport via rivers (Wang et al., 2021) which in turn has a destabilising effect on Arctic sea ice (Park et al., 2020). We add this interaction as an interaction with limited strength and very limited evidence (see Figure 2.2.5). Vice versa, additional evidence on top of GTPR23 (Lenton et al., 2023) shows that Arctic (winter) sea ice retreat leads to enhanced inland permafrost degradation, based on palaeoclimate (Vaks et al., 2020), and climate model studies (Lawrence et al., 2008). Therefore, this link remains destabilising but its evidence level has increased.

AMOC → Permafrost

Additionally, limited new evidence suggests that an AMOC slowdown would lead to less northward heat transport, which would have a stabilising effect on land permafrost, particularly over northern Europe and Western Siberia (Park et al., 2025). At the same time, an AMOC weakening or collapse would lead to rising sea levels across the northern Atlantic region and may weaken parts of the low-lying permafrost regions through flooding (Schwinger et al., 2023). Vice versa, an AMOC recovery after a shutdown would increase the heat transport and destabilise high-latitude permafrost. Since an estimate of the strength of these competing effects is not assessed yet and may be limited, we do not add an additional link(s) from AMOC to Permafrost.

2.2.9 Appendix

Table A2.2.1: Global warming level (GWL) at which abrupt shifts have been detected in potential tipping systems in CMIP5/6 simulations, with previous tipping threshold estimates for comparison in part informed by CMIP5 abrupt shifts) and the number of models the shift features in [brackets].

System	Abrupt shift GWL thresholds			Tipping point GWL thresholds
	CMIP6 (1ptCO2): Terpstra et al. [2025]*	CMIP6 (SSPs): Angevaare & Drijfhout [in review]**	CMIP5: Drijfhout et al. [2015]***	A. McKay et al. [2022]****
North Atlantic subpolar gyre	0.5-2.9 [24/57]	1.2-4.1 (from abrupt change’) [3]***** 1.2-5.6 (‘state transitions’) [10]	1.4-3.8 [5]	1.1-3.8 (based on Sgubin et al. [2017])
AMOC	-	1.1-3.9 [9]	1.4-1.9 [1]	1.4-8.0
Localised land permafrost	1.0-3.8 [8/46] (total soil moisture content) 1.2-3.3 [19/36] (soil frozen water content)	-	5.6 [1]	1.0-2.4
Amazon rainforest	- [-/7] (inconsistent small shifts 0.9-5.0)	-	2.5-6.2 [2]	2.0-6.0
Boreal forests	- [-/7] (inconsistent shifts 0.8-4.9)	-	7.2 [2]	1.4-7.2
Ind. s. monsoon	0.8 [1/57]	-	-	-
Antarctic sea ice	0.5-5.3 [11/53]	2.0-3.2 [4]	1.4-2.9 [3]	1.4-2.9
Arctic summer sea ice	1.0-4.6 [15/53]	1.3-2.3 (‘abrupt changes’) [7]	-	1.3-2.9
Arctic winter sea ice	3.3-5.4 [14/53]	2.5-5.1 (‘state transitions’) [22]	4.5-8.2 [5]	4.5-8.7
Barents sea ice	0.5-3.0	(included in ASSI)	1.5-1.7 [2]	1.5-1.7

*90 per cent interpercentile range, rounded to one decimal place

**68 per cent range; cannot be directly compared to Terpstra et al. [2025], as latter uses 1ptCO2 scenario rather than SSPs and uses different variables and abrupt shift detection methodology

***From Drijfhout et al. [2015] Table S2

****Literature-based synthesis range

*****Not directly equivalent to events of Drijfhout et al. [2015]

2.3 Implications of overshooting 1.5°C for Earth system tipping points

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Reviewers: Richard Betts, John Dearing, Jonathan F. Donges

Key Messages

- **Global warming has already exceeded 1°C where tipping risk has started to become non-negligible for warm-water coral reefs, Greenland and West Antarctic ice sheets.**
- **Current global warming of 1.35-1.4°C exceeds the central estimate of the thermal tipping point for warm water coral reefs of 1.2°C, therefore tipping is likely underway.**
- **Several systems (land permafrost, Greenland ice sheet, West Antarctic ice sheet and sub-polar gyre) likely have a tipping point around 1.5°C global warming, and several more (mountain glaciers, boreal forests and AMOC) around 2.0°C global warming.**
- **Therefore, overshooting 1.5°C of global warming raises the risk of triggering irreversible tipping events, with each 0.1°C adding to the risk.**
- **Limiting tipping risks requires minimising peak global warming and overshoot duration above 1.5°C, and ultimately reducing global warming below 1.5°C before 2100, and stabilising below 1.0°C on longer timescales.**
- **Tipping systems with fast and slow timescales respond differently to exceeding their tipping points:**
- **Fast systems are vulnerable to even short-lived exceedances and therefore their tipping points constrain the allowable peak warming.**
- **Slow systems can tolerate temporary exceedances of their tipping point but constrain the allowable duration of exceedance and the eventual temperature stabilisation level.**
- **Most tipping systems are expected to amplify global warming if tipped, making it more difficult to return to lower global warming levels in an exceedance period.**
- **Additional pressures, such as anthropogenic stressors, interacting tipping systems, and destabilising Earth system feedbacks, can amplify tipping risks further.**
- **Decreasing direct anthropogenic stressors on the Earth system can reduce the likelihood of climate-induced tipping for some systems (e.g. halting deforestation in the Amazon rainforest).**

2.3.1 Introduction

Humanity is on track to cause levels of global warming that rise above 1.5°C relative to pre-industrial levels (Reisinger et al., 2025; Bevacqua et al., 2025; Bustamante et al., 2023). Indeed, current legally-binding policies are taking us towards highly uncertain future global warming estimates of 2.2-3.4°C (mean: 2.7°C) later this century (Climate Action Tracker, 2024). To eventually limit warming levels at or below 1.5ºC, it is now almost inevitable that there will be a period of overshoot during which the warming limit will be temporarily exceeded.

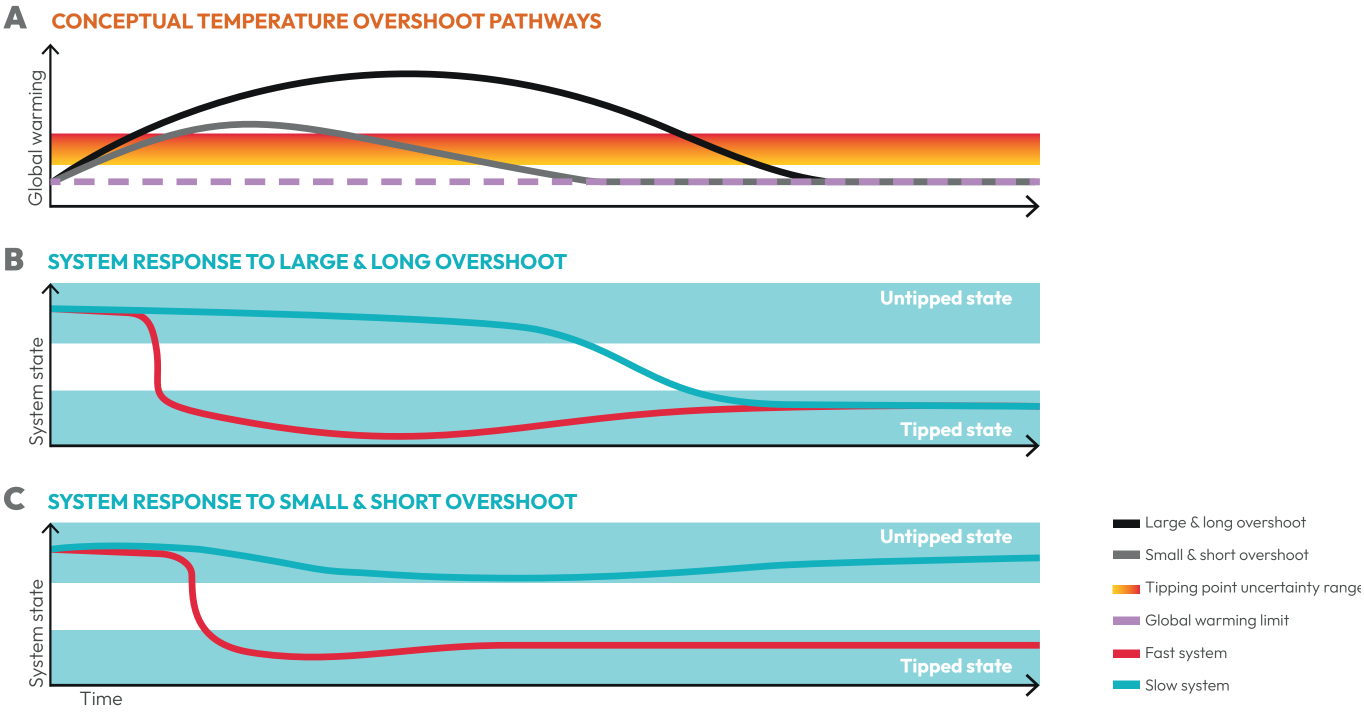
Temperature overshoot refers to pathways of global warming (averaged over a climatological period of e.g. 30 years) that first exceed a warming level (such as 1.5°C), followed by an eventual return to, or below, the warming level - as opposed to exceedance scenarios that permanently surpass a warming level. Therefore, temperature overshoots are often characterised by their peak warming, duration, and final stabilisation level (Schleussner et al., 2024; Schwinger et al., 2022). Two conceptual overshoot pathways over a specific global warming level are illustrated in Figure 2.3.1.

During such overshoots, there is an increased risk of crossing uncertain tipping points (i.e., pathways temporarily exceed the tipping point uncertainty range in Figure 2.3.1). While temperature overshoot pathways have many negative consequences on biogeophysical and biogeochemical systems, as well as socioeconomic and human impacts, and equity concerns, assessing whether they cross tipping points is critical, as this poses the added risk of triggering irreversible and self-reinforcing Earth system shifts.

Here, considering the response timescale of a system is important. Tipping systems can be categorised by their typical timescales in relation to the timescales of climate change: slow systems (e.g. ice sheets) respond over timescales much longer than climate change itself, while fast tipping systems (e.g., Subpolar Gyre, monsoons, or warm-water coral reefs) respond on similar or faster timescales (Lenton et al., 2024; Ritchie et al., 2021; Bochow et al., 2023; Swingedouw et al., 2021).

By overshooting (i.e. temporarily crossing and returning to or below) a certain temperature level, this can also mean that a tipping point is at least temporarily crossed. For a large and long-lasting crossing of a tipping point, there is a high risk of triggering tipping systems, even for slow tipping systems (Figure 2.3.1B). However, a temporary crossing of a tipping point will not necessarily result in triggering the tipping of some inherently slow systems, tipping may be avoided if the temperature overshoot is small and short (Figure 2.3.1C).

Ideally, such crossing of tipping points should be avoided, but this may already be too late for some tipping systems. As outlined in Chapter 2.2, the lower uncertainty ranges of some Earth system tipping points could have already been exceeded (Figure 2.3.2). Further committed warming is inevitable and almost certain to exceed 1.5°C, therefore exceeding the lower bounds of uncertainty ranges of additional tipping points. Nevertheless, limiting the magnitude and duration of temperature overshoot can still play a crucial role in avoiding the tipping of systems. Hence, fundamental questions arise on what the limits for peak warming and overshoot duration are to avoid tipping specific systems (Ritchie et al., 2021).


A CONCEPTUAL TEMPERATURE OVERSHOOT PATHWAYS

B SYSTEM RESPONSE TO LARGE & LONG OVERSHOOT

C SYSTEM RESPONSE TO SMALL & SHORT OVERSHOOT

Figure 2.3.1: Response of fast and slow systems with a common tipping point to different overshoot pathways. (a) Two idealized global warming overshoot pathways that exceed a global warming limit (purple dashed line), reach some peak warming before returning and stabilising at the limit. These overshoot pathways temporarily cross an uncertain tipping point (burning ember range) that is here assumed to be the same for both a fast and a slow system. One pathway has a large peak and long overshoot duration (black) over a temperature limit (purple dashed line), the other a small peak and short overshoot duration (grey). (b) For the large and long overshoot over a temperature level, the fast system (red) tips very quickly after the tipping point is crossed, while for the slow system (blue), tipping is delayed. (c) For the small and short overshoot over a temperature level, the fast system (red) again tips, but tipping is avoided for the slow system (blue) despite also temporarily crossing its tipping point.

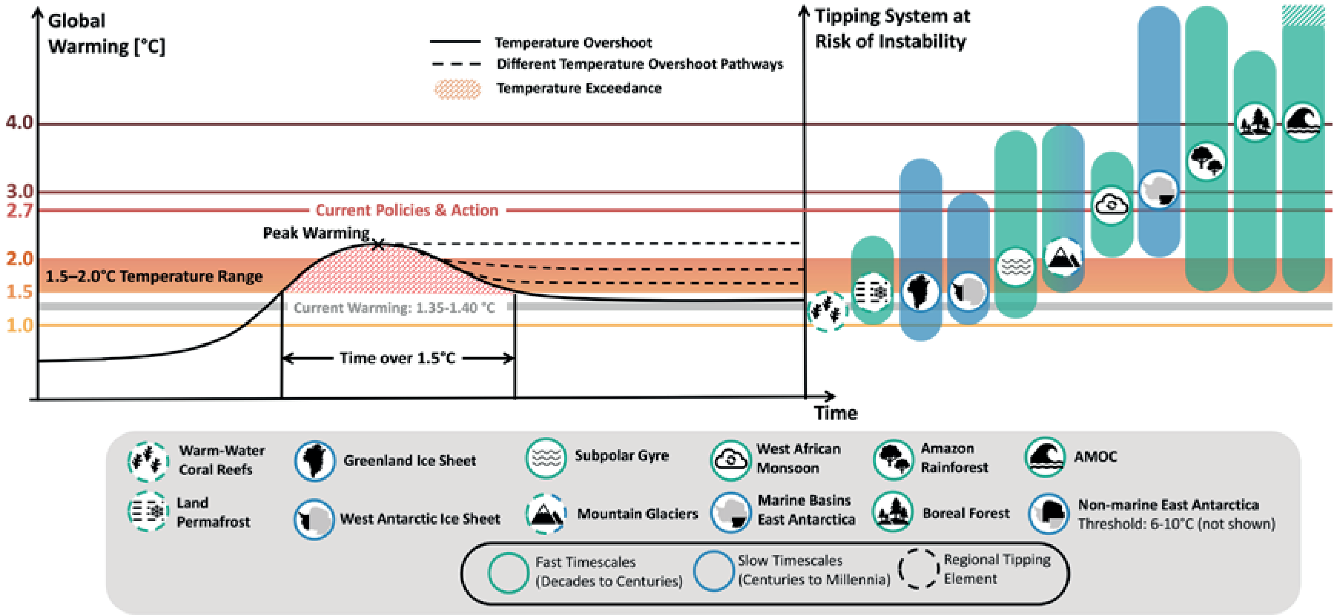


Figure 2.3.2: Overshooting 1.5°C risks crossing Earth system tipping points. Illustrative temperature overshoot pathway, exceeding and then returning to below 1.5°C (solid black line) and other stabilisation pathways (dashed black lines), dependent on uncertainties in future emissions and Earth system feedbacks. The depicted overshoot pathways at least temporarily crosses several Earth system tipping points: whether or not tipping occurs depends on the peak warming, time spent over the tipping point and the tipping system's response timescale. Icons denote tipping systems (global tipping systems are shown with a solid edge; regional tipping systems are shown with a dashed edge; local tipping systems are not shown; best-estimate tipping points based on data from Lenton et al., 2023, and in case of no updates, from Armstrong McKay et al., 2022). Uncertainties of tipping points are shown as shaded bars. Current policies & Actions lead to temperature increases of 2.2-3.4°C (mean of 2.7°C shown here; Climate Action Tracker, 2024).

2.3.2 Risk of triggering tipping systems during and after overshoot

Multiple systems of the Earth system could have their tipping point below 2°C of global warming and for some it could be below 1.5°C (Lenton et al., 2023; Armstrong-McKay et al., 2022; see Figure 2.3.2; Chapter 2.2). From a Monte Carlo analysis, even under the most optimistic emission scenarios of limiting warming to 1.5°C and stabilizing temperatures at this level, it is considered as likely as not (33-66% probability) that three tipping systems will tip (Figure 2.3.3a). One of these systems will virtually certainly (>99% probability) tip - this is the warm-water coral reefs, given the upper range of their tipping point is 1.5°C (Figure 2.3.2). Other candidates that are vulnerable to tipping include the North Atlantic Subpolar Gyre, Land Permafrost, and the Greenland and West Antarctic ice sheets. Delayed climate action and stabilising global warming at 2°C would change the probability of five systems tipping from very unlikely (<10% probability) to as likely as not (33-66% probability), and mountain glaciers, boreal forests and the AMOC are the additional tipping systems that risk being tipped. Stabilising global warming at 3°C would likely (>66% probability) cause eight tipping systems to undergo tipping.

A mathematical theory exists that relates overshoot characteristics and system timescale to determine what temperature trajectories can avoid triggering tipping (Ritchie et al., 2019) – as illustrated in Figure 1, systems with a slow response timescale are more likely to avoid tipping. This theory implies that if the time a tipping point is exceeded for is doubled then the peak amount the tipping point is exceeded by needs to be reduced by a factor of four to maintain the same level of tipping risk. Utilising this theory, we here assess the tipping risk for overshoots of the 1.5°C level (Figure 2.3.3b).

Limiting the temperature overshoot beyond 1.5°C to a duration of 100 years could substantially reduce the number of systems that undergo tipping (compare Figure 2.3.3a / Figure 2.3.3b). For a peak warming of 2°C, the number of systems that are as likely as not (33-66% probability) to tip drops from five to three and tipping five becomes very unlikely (<10% probability) if warming is brought back to 1.5°C (or below) within 100 years. A 100-year overshoot of 1.5°C with a peak warming of 3°C halves the number of systems likely (>66% probability) to be tipped (from eight to four) relative to staying at 3°C. However, to limit such an overshoot scenario with a large peak to 100 years would require extraordinary carbon removal rates that are unlikely to be feasible (Schleussner et al., 2024).

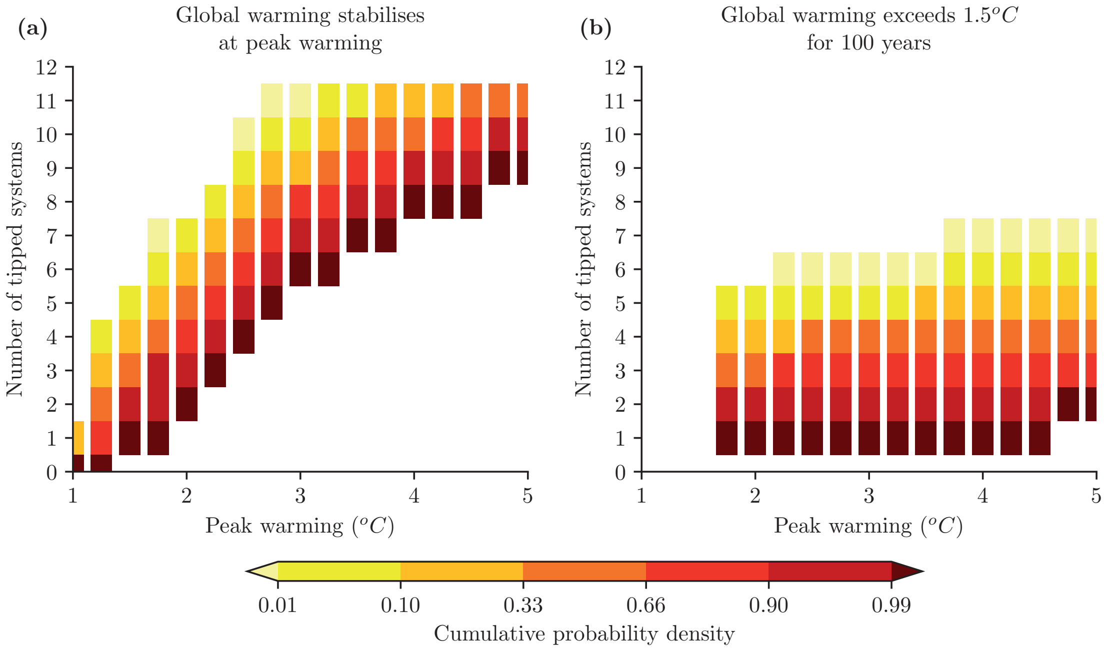


Figure 2.3.3: Tipping risk for Earth system tipping systems with and without temperature overshoot. (a) Cumulative number of tipped systems if global warming stabilises at different peak levels but does not return, and (b) cumulative number of tipped systems for different peak warming levels with overshoot beyond 1.5°C lasting for 100 years. Colour is used to represent the cumulative probability density of the number of tipped systems using the IPCC likelihood scale (IPCC-SPM, 2021): <1% Exceptionally Unlikely, <10% very unlikely, <33% unlikely, 33-66% about as likely as not, >66% likely, >90% very likely, >99% virtually certain). The same global and regional tipping systems are considered as in Figure 2. These values are determined by using the upper and lower estimates for the tipping point and tipping timescales given in Lenton et al. (2023), and if not provided, from Armstrong McKay et al. (2022).

Box 2.3.1: Risk assessments for tipping during overshooting temperature targets

When facing potentially severe and irreversible consequences from tipping events, we need a framework for assessing tipping risks under uncertainty. Due to limited predictability of exact tipping events (Ben-Yami et al., 2024), a probabilistic risk assessment approach (Abrams et al., 2023) becomes essential - similar to methods used in insurance and actuarial industries. This approach has recently been embraced in various reports for tipping points research (Saye et al., 2025; Laybourn et al., 2024; Trust et al., 2024) and helps quantify the likelihood of crossing tipping points under different emission scenarios (Möller et al., 2024; Wunderling et al., 2023; Deutloff et al., 2025).

Within this risk framework, we can systematically address two key types of uncertainty:

Tipping element uncertainties: Risk assessments must account for uncertainties in tipping point locations, system timescales, and interactions between tipping elements. Tipping point location uncertainty ranges vary widely across elements - from relatively narrow (1.0-1.5°C for warm-water coral reefs) to very broad (1.4-8.0°C for the AMOC). Further, tipping elements like the Amazon rainforest and ice sheets form a coupled system with interactions that are not fully understood (Dekker et al., 2018; Wunderling et al., 2021, 2024; Falkena & von der Heydt, 2024).

Scenario uncertainties: Global mean temperature (GMT) responses to emission scenarios carry considerable uncertainties due to carbon cycle feedbacks and climate sensitivity variations (IPCC AR6 WGI Chapter 4; Lee et al., 2021). Specific uncertainties in overshoot pathways include timing of peak warming relative to net-zero emissions (Corner et al., 2023), and the duration and magnitude of overshoots (Schleussner et al., 2024). These scenario uncertainties must be assessed probabilistically (Kikstra et al., 2022; Nicholls et al., 2022) and considered alongside tipping element uncertainties.

Figure 2.3.4 extends this analysis to consider different overshoot durations for different levels of tipping risk. Using the best estimates from the latest literature (Lenton et al., 2023; Armstrong McKay et al., 2022), tipping systems with fast timescales and a low tipping point (subpolar gyre and warm-water coral reefs) are the most susceptible to tipping even for short overshoot durations. In contrast, systems with slow timescales and a low tipping point (Greenland and West Antarctic ice sheets) may avoid tipping if the overshoot duration is sufficiently short and warming stabilises below their tipping point (Figure 2.3.4 a). However, these ice sheets have a non-negligible probability that their tipping point is below 1.5°C. Therefore, following a precautionary principle approach (i.e. 10% or even 1% tipping risk) that seeks to limit the devastating long-term consequences of committing to ~10 metres of sea-level rise from tipping these systems, means that limiting the time over 1.5°C is not sufficient (Figure 2.3.4 b, Figure 2.3.4 c). Instead, warming must return to below 1.0°C in the long term (Stokes et al., 2025).

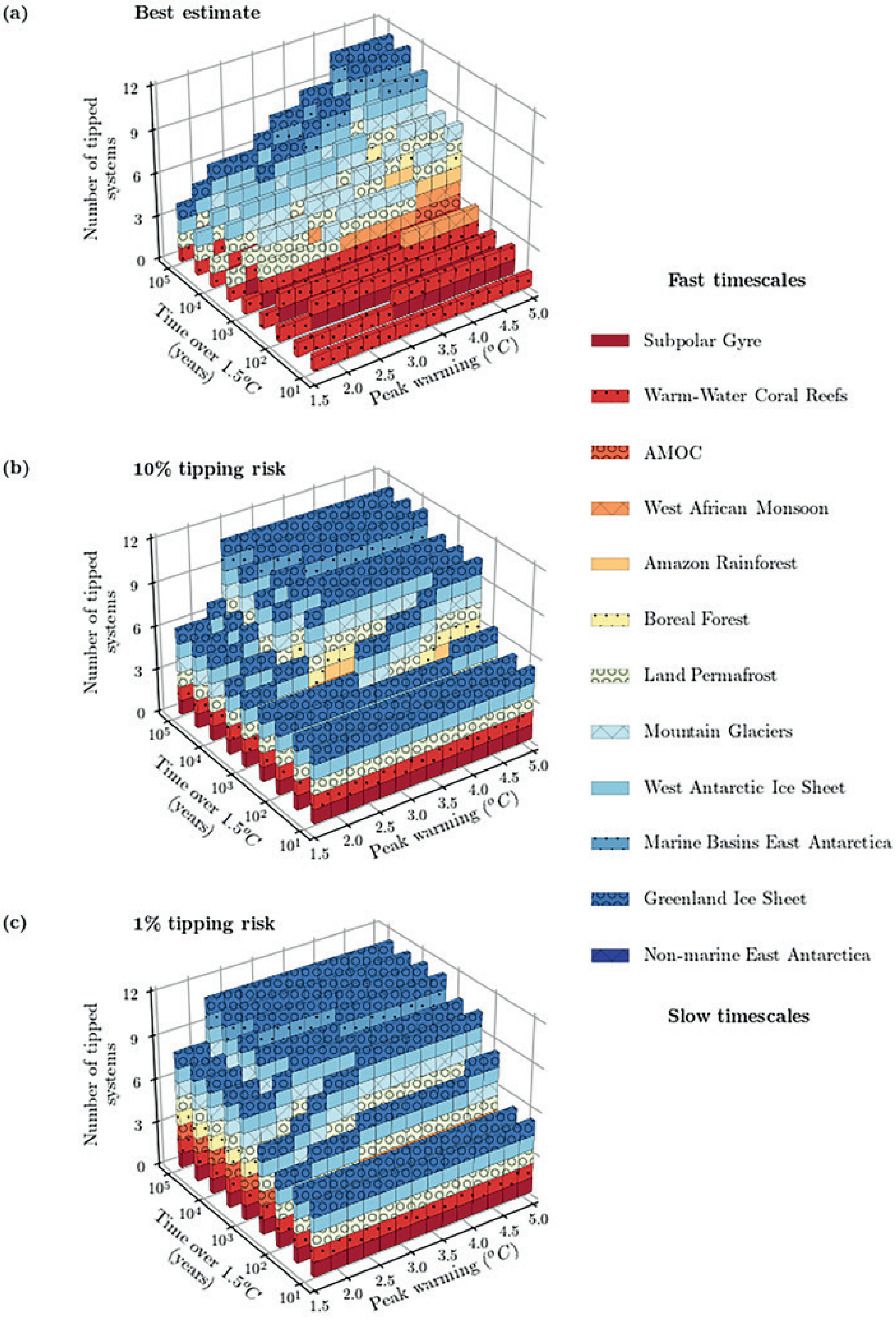


Figure 2.3.4: extends this analysis to consider different overshoot durations for different levels of tipping risk. Using the best estimates from the latest literature (Lenton et al., 2023; Armstrong McKay et al., 2022), tipping systems with fast timescales and a low tipping point (subpolar gyre and warm-water coral reefs) are the most susceptible to tipping even for short overshoot durations. In contrast, systems with slow timescales and a low tipping point (Greenland and West Antarctic ice sheets) may avoid tipping if the overshoot duration is sufficiently short and warming stabilises below their tipping point (Figure 4a). However, these ice sheets have a non-negligible probability that their tipping point is below 1.5°C. Therefore, following a precautionary principle approach (i.e. 10% or even 1% tipping risk) that seeks to limit the devastating long-term consequences of committing to ~10 metres of sea-level rise from tipping these systems, means that limiting the time over 1.5°C is not sufficient (Figure 4b, c). Instead, warming must return to below 1.0°C in the long term (Stokes et al., 2025).

2.3.3 Additional pressures on tipping systems

In addition to direct global warming impacts, further pressures such as direct anthropogenic interference (e.g. deforestation), tipping system interactions and Earth system feedbacks may threaten the stability of tipping systems, and the feasibility of realising/maintaining warming stabilisation levels (Willcock et al., 2023). This means that tipping points measured in units of global mean warming may effectively be lower than their reported values in the recent literature (e.g., Lenton et al., 2023; Armstrong McKay et al., 2022) where they are mainly studied in isolation, consequently reducing the scope for overshoots that do not cause tipping.

Additional anthropogenic pressures: Biosphere tipping systems suffer from additional anthropogenic influences such as deforestation in the Amazon forest systems, or overfishing and pollution in warm-water coral reefs. Combined with global warming, these additional pressures may cause these tipping systems to have their tipping point to be effectively lower than that for global warming alone (e.g. Hughes et al., 2018; Lovejoy & Nobre, 2018; Setter et al., 2022; Lenton et al., 2023, Pearce-Kelly et al., 2025). For instance the Amazon rainforest may have a tipping point between 2.0-6.0°C (Flores et al., 2024) if impacted by global warming only (see Fig. 2). However, when deforestation is accounted for as well, the tipping point of the Amazon rainforest may reduce to levels well within the Paris climate target (between 1.5-2.0°C), (see 4.1 The Amazon rainforest case study and 4.3 Warm-water coral reefs case study).

Interactions between tipping systems: Most direct interactions between tipping systems are assessed as destabilising (Wunderling et al., 2024; Lenton et al., 2023, see also section 2.2.8). Therefore, interactions between tipping systems exert additional pressure on the stability of tipping systems and become relevant at 1.5°C of global warming or higher (Wunderling et al., 2024). This is sometimes referred to as “tipping cascade risk”, where increasing temperatures trigger a first system into tipping that in turn lowers the temperature tipping points for subsequent tipping systems (Wunderling et al., 2021).

Earth system feedbacks: Further, there may be Earth system feedbacks that alter the risk for triggering tipping systems. Relevant feedbacks include (but may not be limited to) the following three categories:

1. A majority of tipping systems would cause feedbacks that increase global warming levels if they tip (Armstrong McKay et al., 2022; Deutloff et al., 2025). For instance, the large ice sheets would add up to 0.2°C of additional global warming if they disintegrate and likewise 0.2°C for a dieback of the Amazon rainforest. However, there are also few but potentially strong negative feedbacks on global temperatures (e.g. 0.5°C cooling due to AMOC tipping). Therefore, the overall effect of temperature feedbacks of disintegrated tipping systems on tipping risks remains uncertain and requires improved constraints of their feedback mechanisms, direction and magnitude (Bdolach et al., 2025).
2. Second, changes in the land and ocean carbon sinks under ongoing global warming may affect global warming pathways themselves. So far, around 60% of all emissions have been taken up by land and ocean carbon sinks and only the remaining 40% contribute to atmospheric CO2-increase and global warming (Friedlingstein et al., 2025). There is now growing evidence of a long-term weakening of land carbon sinks that are also tipping systemss (e.g. in the Amazon rainforest or permafrost; Gatti et al., 2021; Ke et al., 2024). On the other hand, while also weakening on the long term, ocean carbon sinks seem to be comparatively stable across Earth System Models (Tokarska et al., 2019; Schwinger et al., 2022; Koven et al., 2023; Sanderson et al., 2024).
3. Third, there exist several feedback loops within the Earth system that could amplify global warming (Ripple et al., 2023, Lenton et al., 2023), such as cloud feedbacks (Bjordal et al., 2020; Ceppi & Nowack, 2021) or the permafrost carbon feedback (MacDougall et al., 2020; Steinert & Sanderson, 2025). They could make it harder to reduce global temperatures after an overshoot, for instance should carbon sinks get weaker.

2.3.4 Conclusion

The Global Carbon Budget (Friedlingstein et al., 2025) reports that current rates of global carbon emissions remain high and are still increasing, and therefore, at least, a temporary overshoot of 1.5°C is becoming almost inevitable (Reisinger et al., 2025; Bevacqua et al., 2025). In addition to already having potentially exceeded some tipping points, this places many further tipping systems of the climate system at risk of crossing their tipping point. This calls for a comprehensive risk assessment approach to quantify tipping likelihoods for overshoot pathways (see Box 2.3.1).

Additionally, achieving the required rapid reversal in warming that would prevent many tipping systems from tipping implies substantial net negative emissions. The longer CO2 emission reductions are delayed, the larger net negative emissions must be. Additionally, the larger the overshoot over a certain temperature level, the larger the need for negative emissions and the implications of those for our planet’s critical biophysical systems. Current pathways that overshoot 1.5°C and return to this level by 2100 with 50% probability require up to five times the current rates of carbon dioxide removal (Smith et al., 2024). Additional feedbacks have the capacity to impede the reversal of warming, such as the potential of permafrost thawing and Amazon rainforest dieback amplifying global warming (e.g., Deutloff et al., 2025) or the weakening of land carbon sinks under climate change.

This means that five (the warm-water coral reefs, the land permafrost, the Greenland and the West Antarctic Ice Sheets and the North Atlantic subpolar gyre) systems of the Earth system may reach their tipping points below 1.5°C of global warming, and up to eight (in addition: the mountain glaciers, the boreal forests and the AMOC) below 2.0°C of global warming. The warm-water coral reefs tipping point with a central estimate of 1.2°C is likely already transgressed by current global warming levels (best estimates are between 1.34 and 1.41°C (WMO, 2025). The risk of tipping for individual tipping systems is found to increase for larger and longer overshoots over a specific temperature level such as 1.5°C. Fast tipping systems (e.g. the subpolar gyre) may be more at risk of tipping when their tipping points are crossed temporarily and therefore act as a constraint on the limits for acceptable peak global warming. The slow tipping systems respond on timescales slower than climate change and therefore set limits on overshoot duration (Ritchie et al., 2019; Ritchie et al., 2021).

However, it is critical to remark that some tipping points such as those for warm-water coral reefs and the ice sheets may have already been crossed (Stokes et al., 2025; Pearce-Kelly et al., 2025). Therefore, even a return to 1.5°C may still not be sufficient to prevent the ice sheets from tipping in the long term (Stokes et al., 2025). Instead, warming will need to be further reduced, to levels at or below 1.0°C. Therefore, urgent climate action to minimise tipping risks is required, also in light of additional anthropogenic pressures, interactions between tipping systems, Earth system feedbacks as well as uncertainties in tipping point locations and system timescales. This means that peak temperature, overshoot duration, and warming stabilisation level must be limited to sufficiently low levels to prevent Earth system components from tipping in the short and long term.

2.4 Earth system tipping point risk assessment

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Reviewers: David Armstrong McKay, Norman J. Steinert, Jonathan Rosser, Jonathan F. Donges, Luke Kemp

Key messages

Earth system tipping points have huge impacts that demand further research

- There is an urgent need for dedicated research on the impacts of crossing Earth system tipping points especially their systemic, cascading impacts through societies.
- We provide an initial analysis of these impacts relying heavily on inferences from general climate impact literature applied to anticipated tipping point changes.
- Our assessment suggests that crossing Earth system tipping points will cause profound risks across nine critical domains, including food security, energy infrastructure, economic stability and social cohesion, affecting billions globally.
- Earth system tipping points are a national security issue as food, water and heat stresses will impact populations. If climate change is unchecked then mass mortality, forced displacement and severe economic losses become likely.

All regions and billions of people face major impacts from Earth system tipping points

- Critical tipping point risks exist for small islands and East Asia from ice sheet loss, for South Asia, Southeast Asia and Central America from monsoon disruption, for West Africa from AMOC collapse and monsoon disruption and for North Asia from permafrost thaw and boreal forest tipping.
- Major tipping point risks exist for Northeast America from AMOC collapse and ice sheet loss, for Northwest Europe from AMOC collapse and suggests impacts of Amazon dieback are purely regional.
- The greatest population is ultimately at risk from monsoon disruption, followed by ice sheet loss, AMOC collapse and the loss of warm-water coral reefs.

Regional vulnerabilities to Earth system tipping points reveal extreme inequality

- Small Island Developing States face complete uninhabitability, South and Southeast Asia's 3+ billion people depend on vulnerable monsoon systems and Arctic communities face total ecosystem transformation.
- Developed regions primarily face infrastructure and economic challenges.
- The most extreme gaps in regional preparedness for tipping point risks are in Small Island Developing States, West Africa, Central America and the Amazon basin.

2.4.1 Introduction

This chapter provides an assessment of the systemic risks Earth system tipping points pose to human societies and ecosystems across all global regions, introducing a framework for risk evaluation that addresses the fundamental inadequacies of traditional approaches.

The impacts of Earth system tipping points manifest through biophysical changes in Earth system components that can translate into profound risks for human systems. Despite the gravity of these risks, significant research gaps persist in both the understanding of biophysical impacts and the translation of these impacts into systemic risks for human societies. These gaps include the scarcity of direct tipping point impact studies, weak understanding of cross-sectoral cascade mechanisms and inadequate translation of biophysical changes into policy-relevant risk assessments. Furthermore, the risks of Earth system tipping points are not addressed by existing global governance institutions, necessitating new frameworks that can address the systemic nature of these risks across multiple policy domains (JRC, 2025a; Pereira et al., 2024; Milkoreit et al., 2024; Pereira et al., 2023).

There remains limited understanding of the complex pathways through which biophysical changes translate into systemic risks at different spatial and temporal scales (Simpson et al., 2021; Lawrence et al., 2020; Ruiter et al., 2020). These cascading failures can rapidly escalate from single system disruptions to compound catastrophic scenarios where multiple Earth system components collapse simultaneously, overwhelming adaptive capacity and creating irreversible damage that exceeds the sum of individual impacts. Moreover, there is a notable scarcity of empirical data and comprehensive research on the specific impacts and pathways of Earth system tipping points, further complicating risk assessment and policy responses. However, significant advances are expected through ongoing international initiatives (such as TIPMIP (Winkelmann et al., 2025)) aimed at improving our understanding of tipping points by increasing Earth System Model representation of tipping points and making the output data freely available for further analysis.

Here, we conduct a first Earth system tipping point risk assessment, drawing on available data and approaches. While this is necessarily imperfect given the current state of knowledge, it represents a critical first step toward filling the substantial gap in tipping point risk evaluation. This approach aligns with emerging frameworks for assessing high impact-low likelihood climate risks (Wood et al., 2023), recognizing the need for new methodologies when traditional approaches prove inadequate for extreme scenarios. We synthesize available evidence to translate biophysical Earth system changes into policy-relevant risk currencies, providing a foundation for future research and decision-making while clearly identifying areas where knowledge remains limited.

Given the relative scarcity of research specifically examining the systemic risks from Earth system tipping points, this analysis draws upon two complementary approaches: (1) the limited but growing body of direct research on tipping point impacts and (2) inferences derived from the established literature on climate change impacts applied to the anticipated biophysical changes from tipping events. This approach allows us to synthesize potential consequences based on what we know about how human and natural systems respond to environmental changes of the magnitude and type expected from tipping points.

2.4.2 Assessment approach

Here we make an initial attempt to characterise and communicate the societal and ecosystem risks associated with Earth system tipping points. We synthesise scientific literature to identify the most impactful tipping points for human society and dependent ecosystems. While we aim to be as comprehensive as possible, we recognise that there is ample scope for continued improvement and co-development with scientific and user communities. Our assessment methodology builds directly on the risk framework established in Chapter 2.1, which emphasized the inadequacy of traditional impact-probability matrices for tipping point risks. Following Chapter 2.1's approach, we categorize risks using severity levels (low / moderate / major / critical) and the temperature threshold assessments from Chapter 2.2.

Risk currencies

Before examining specific systemic risks from tipping points, it is essential to frame these risks in terms of what we call "risk currencies" (Roberts et al., 2021) - the fundamental concerns that drive policy decision-making across all levels of governance. As established in Chapter 2.1, risk currencies represent the translation of Earth system impacts into risks that are intuitive for and connected to the fundamental governance concerns. In other words, risk currencies represent the core values and priorities that policymakers are mandated to protect and that societies depend upon for stability and prosperity.

Our analysis is organized around the following nine key risk currencies (Pereira et al., 2025) :

- Food security
- Energy security
- Humanitarian crisis and displacement
- National security
- Financial and economic risks
- Infrastructure and built environment
- Public health
- Biodiversity and ecosystems
- Water resources

Risk register

We use the risk currencies to construct a "risk register" that aims to summarize the potential societal impact of Earth system tipping points in a succinct, policy relevant manner. The risk register concept is introduced in Chapter 2.1.

Standard government risk registers typically use impact-probability matrices plotting potential consequences against likelihood calculations, an approach that has become deeply embedded in institutional risk management practices worldwide. However, this conventional framework is fundamentally inappropriate for tipping points for several interconnected reasons that go beyond simple uncertainty quantification (Laybourn et al., 2024). These include: the simplistic collapsing of complex interactions between hazard, vulnerability and exposure into a single "risk"; the inability to account for interactions between risks (e.g. one risk affecting the likelihood of another, or two risks occurring simultaneously and compounding); and a bias towards well-defined risk events, which might neglect slower-moving stresses.

The high uncertainty surrounding these risks makes their likelihood difficult to assess with the confidence necessary for major management decisions. This uncertainty stems not just from incomplete data, but from the fundamental nature of complex systems operating near critical thresholds (Bathiany et al., 2016, 2018). Traditional probabilistic approaches require well-characterized historical patterns and stable system behavior, neither of which applies to tipping points operating in unprecedented conditions under anthropogenic climate change (Armstrong McKay et al., 2022; Lenton et al., 2008, 2019).

This could create a systematic misinterpretation of risk where high uncertainty is routinely misconstrued as low likelihood, leading to dangerous complacency in risk management, which is particularly problematic when considering the potentially high societal impact of tipping points. The COVID-19 pandemic provides a stark illustration of this problem, where high uncertainties associated with pandemic risk led some governments to treat these scenarios as low-probability events, resulting in inadequate preparedness despite clear scientific warnings about the inevitability of pandemic emergence (Laybourn et al., 2024; UK Government, 2024). As noted by the UK COVID-19 Inquiry, both the Royal Academy of Engineers and the inquiry itself concluded that “a fixation on likelihood is inappropriate for such threats as it ‘can be difficult to assess with a high degree of confidence across all risks’” and that “uncertainty and the inability to accurately judge likelihood can breed a dangerous complacency.”

Additionally, traditional risk assessment frameworks fail to capture the nonlinear dynamics inherent in threshold effects and the potential for abrupt changes (Scheffer et al., 2009). These frameworks assume proportional relationships between causes and effects, whereas tipping points are characterized by disproportionate responses where small changes can trigger massive system reorganization (Lenton et al., 2008). Furthermore, unlike economic or political sudden shifts that societies can potentially recover from, climate-driven tipping dynamics, once triggered, are often irreversible over timescales relevant to human civilizations. Post-collapse recovery in these cases cannot be expected within centuries to millennia, fundamentally distinguishing these risks from other systemic threats and emphasizing their severity for long-term planning and risk management. The conventional approach also struggles with the temporal complexity of tipping points, where risks may appear low in the near term but escalate rapidly once thresholds are crossed and with the systemic nature of cascading risks that can create “domino effects” across multiple Earth system components (Klose et al., 2021; Wunderling et al., 2021).

Given these fundamental limitations, several alternative approaches could provide more appropriate frameworks for tipping point risk assessment, drawing inspiration from advances in disaster risk reduction and complex systems analysis:

- **Impact vs. Proximity to Thresholds:** This approach would plot potential impacts against how close systems are to identified tipping thresholds, using observable indicators and early warning signals (Lenton et al., 2024) rather than probabilistic forecasts. This leverages current scientific understanding of threshold dynamics while avoiding the false precision of probability estimates. Recent advances in early warning systems for tipping points, including statistical indicators of critical slowing down and machine learning approaches, provide increasingly sophisticated tools for threshold proximity assessment (Dylewsky et al., 2023; Bury et al., 2021; Bathiany et al., 2016).
- **Impact vs. Adaptive Capacity:** This framework would assess potential consequences against the capacity of affected systems (social, economic, ecological) to adapt and respond to changes (Folke et al., 2010). This shifts focus from predicting when changes will occur to evaluating societal resilience and transformation capacity, drawing on extensive literature from resilience science and adaptive management.
- **Impact vs. Exposure/Vulnerability:** This approach would map potential impacts against the exposure and vulnerability of different populations, sectors and regions, similar to frameworks used in disaster risk reduction under the Sendai Framework for Disaster Risk Reduction 2015-2030 (UNDR, 2015). This emphasizes the distributional aspects of tipping point risks and can inform targeted intervention strategies, following established methodologies from the disaster risk reduction community.

Here we lead with the temperature threshold approach (impact vs. proximity to thresholds) as introduced in Chapter 2.1 in our primary risk register, as it provides the most scientifically grounded foundation given current knowledge of tipping points. This avoids traditional likelihood-probability, and relies on the best available scientific estimates of temperature thresholds at which each tipping point is triggered. This approach focuses on proximity to known physical thresholds rather than statistical likelihood calculations, providing policy-relevant information about which tipping points may be triggered under different warming scenarios. However, we explore the adaptive capacity and vulnerability dimensions through detailed regional and sectoral analyses, which examine how the same physical changes translate into differential risks across regions and policy domains depending on exposure, vulnerability, and adaptive capacity.

Overall approach

To populate the risk register and provide a comprehensive risk assessment, we map Earth system tipping point hazards to biophysical impacts and direct regional impacts (and associated risks) and we map them through systemic interactions and risk currencies to assess systemic and cascading risks.

First we systematically analyze how passing each tipping point translates into measurable physical changes across temperature, sea level, precipitation, atmospheric circulation, ocean circulation, biogeochemical cycles, modes of variability and extreme events. A summary is provided in Table 2.4.1. This provides the scientific foundation for understanding the direct impacts of different tipping points on specific regions and for understanding how biophysical changes propagate through Earth system components to create cascading impacts.

From this we undertake a regional impact assessment using the IPCC SREX reference regions (see below). This shows how different tipping points create uneven geographical vulnerabilities, ranging from limited effects to critical system-threatening consequences. We also undertake a systemic risk assessment mapping how these physical changes translate into risks across nine “risk currencies” (critical policy domains) identified above. The mapping between physical impact variables and risk currencies is summarised in Table 2.4.2. This translation bridges the gap between Earth system science and policy-relevant risk currencies that drive decision-making at all governance levels.

Before getting to the results we detail two important aspects.

Use of present-day exposure and vulnerabilities

In this assessment, we aim to describe the societal and ecosystem consequences in the context of present-day exposure and vulnerability indices. While ideally we would consider the social and economic context of the world at the time each tipping point occurs, this approach is not feasible for several interconnected reasons. In the context of centennial-scale climate projections, this has been achieved through the use of integrated assessment models (IAMs) that describe socio-economic development pathways (van Beek et al., 2020; Riahi et al., 2017) that are appropriate to varying levels of greenhouse gas emissions. This framework has proved useful for relating climate outcomes, derived from earth system models (ESMs), to the socio-economic decisions the world would have taken if that climate outcome were to occur. However, these assumptions break down in the context of tipping points, because most tipping point experiments with ESMs are not driven by emissions from IAMs and therefore have no socio-economic context. Additionally, most tipping point modelling is not appropriate for ascertaining a real-world time-frame for the onset, transition and new state of a tipping point mechanism.

Therefore, our approach focuses on present-day vulnerabilities while acknowledging that actual impacts will depend on future adaptive capacity, technological development and societal resilience that cannot be reliably projected decades in advance. It is important to note that both the triggering of tipping points and the manifestation of their impacts operate across widely varying timescales. Tipping point triggering typically occurs within decades of crossing temperature thresholds, but impact onset varies dramatically - from rapid changes like coral bleaching (months to years) and regional climate shifts from SPG collapse (a decade), to slower processes like ice sheet contributions to sea level rise (centuries to millennia) and complete ecosystem transitions (decades to centuries). This temporal complexity means our assessment captures potential end-state impacts rather than the dynamic evolution of risks over time.

Regional impact assessment

Here we examine how tipping points create impacts across 26 IPCC SREX regions (Field et al., 2012) (Figure 2.4.1) with the addition of Small Island States (SIS). This draws from a systematic assessment of major Earth system tipping points (AMOC collapse, Greenland and West Antarctic ice sheet loss, permafrost thaw, monsoon disruption, coral reef die-off, Amazon dieback and boreal forest shifts) across nine risk currencies (food security, energy security, water resources, infrastructure, public health, biodiversity, humanitarian crises, financial systems and national security). We use the SREX regional classification system rather than the more recent AR5 or AR6 regional frameworks due to its coarser spatial resolution, which better matches the limited granularity of available information on tipping point impacts. The broader regional categories in SREX 2012 provide a more appropriate scale for synthesizing the sparse literature on tipping point consequences, while the finer-resolution regions in later IPCC reports would require impact data that does not yet exist for most tipping point-region combinations.

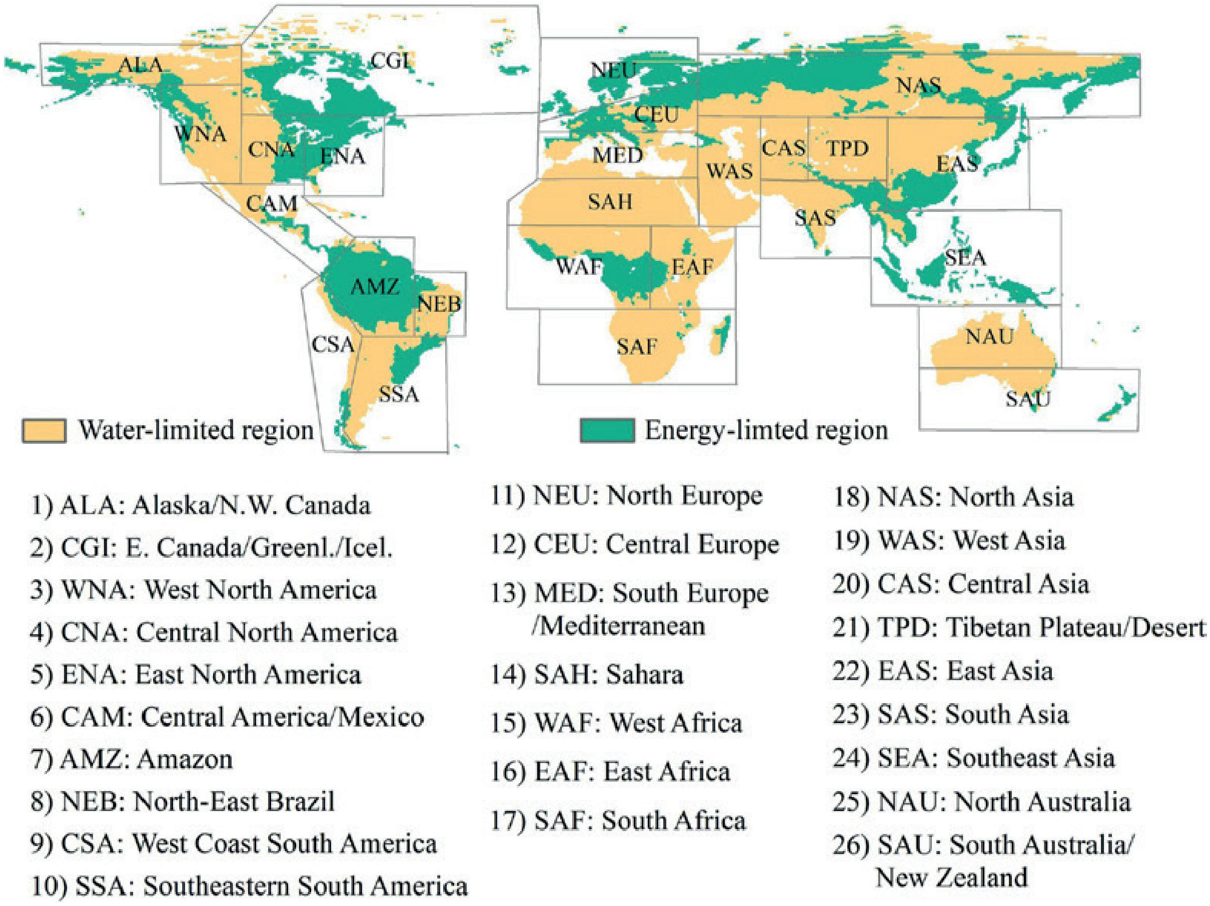


Figure 2.4.1: *The regional classification used in this chapter. We adopt the IPCC SREX reference regions with the addition of Small Island States (SIS) (Image source: (Yin et al., 2022)).*

Table 2.4.1: *Physical impacts of Earth system tipping points. Summary of how each tipping point translates into measurable physical changes across temperature, sea level, precipitation, atmospheric circulation, ocean circulation, biogeochemical cycles, modes of variability and extreme events.*

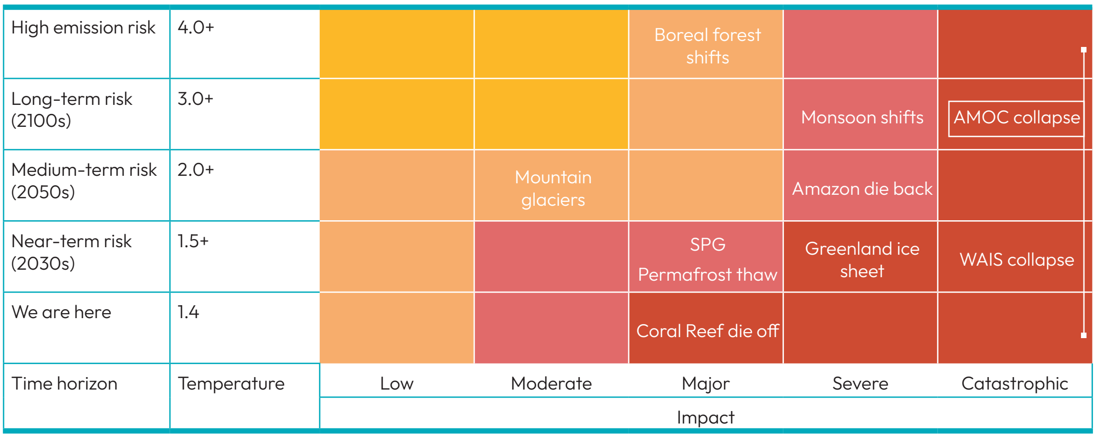
Tipping event	Temperature	Sea level	Precipitation	Atmospheric circulation	Ocean circulation	Biogeochemical cycles	Modes of variability	Extreme events
AMOC collapse	↓↓ N. Atlantic (3-8°C cooling), ↓ N. Europe, ↑ S. Hemisphere	Regional ↑ 0.2-0.3m N. Atlantic coast	↓↓ Sahel, W. Africa monsoon, ↓ Europe growing season, ↑ Amazon	Southward ITCZ shift, altered storm tracks	Fundamental reorganization, ↓ heat transport	↑ CO_2 from reduced ocean uptake, biome changes	NAO changes, ↑ ENSO variability	↓ Hurricane activity, altered European storms
SPG deep convection collapse	Regional cooling N. Atlantic surface waters, ↓ temps NW Europe/E. Canada	Minimal direct effect	↓ Britain/Ireland precipitation, altered NW European patterns	Altered jet stream positioning, modified NAO patterns, shifted storm track pathways	Collapse of deep convection Labrador/Irminger Seas, halted winter mixing	↓ Marine productivity, altered nutrient cycles	Strong NAO variability changes, altered storm tracks eastward	↑ Winter storm intensity, altered North Atlantic weather
Greenland Ice Sheet loss	Local ↑, minimal global effect	↑ ≤7.42m global, uneven distribution	Local shift to rainfall, reduced deflection	Less jet stream deflection	↓ THC, freshwater discharge	Permafrost flooding, ↑ CO_2, CH_4	Altered NAO patterns	Storm surges, icebergs
West Antarctic Ice Sheet collapse	Local ↑, minimal global effect	↑ ≤5.08m abrupt, uneven	Local precipitation shifts	Altered polar circulation	↑ or ↓ THC, new archipelago	Permafrost flooding, ↑ CO_2, CH_4	Unknown changes	Storm surges, icebergs
Permafrost thaw	Regional ↑↑ (up to 12°C amplification)	Minimal direct effect	Altered regional hydrology	Regional circulation changes	Freshwater discharge changes	Major ↑ CO_2, CH_4 release (1,460-1,700 GtC stored)	Regional climate mode changes	Thermokarst formation, ground instability
Monsoon disruption	Regional ↑ summer temperatures	Regional coastal effects	↓↓ Seasonal precipitation (40 per cent reductions observed)	Walker circulation changes, ITCZ shifts	Indian/Pacific Ocean coupling changes	↓ Land carbon storage	ENSO coupling changes	↑ Droughts, heat waves
Coral reef die-off	Regional marine ↑	Loss of coastal protection effect	Minimal direct effect	Minimal direct effect	Local ecosystem changes	↓ Marine carbon cycling	Minimal effect	↑ Coastal storm damage
Amazon dieback	↑ Regional warming, ↓ evapotranspiration	Minimal direct effect	↓↓ Regional (25-35 per cent recycling loss), altered global patterns	Walker circulation changes	Minimal direct effect	Major ↑ CO_2 (150-200 GtC release)	ENSO feedback potential	↑↑ Fire frequency, ↑ droughts
Boreal forest shifts	↓ Winter, ↑ summer regional	Minimal direct effect	↓ Regional precipitation	Regional circulation effects	Minimal direct effect	Major ↑ CO_2 from forest loss	Regional mode changes	↑↑ Wildfire, insect outbreaks
Mountain glaciers	Local ↑, regional cooling effects from altered albedo	Minor direct contribution compared to ice sheets	Altered regional hydrology, reduced seasonal buffering	Minimal direct effect	Altered fjord/coastal circulation patterns	Changed organic matter turnover, freshwater discharge	Regional hydrological variability changes	Glacial outburst floods, coastal erosion

Table 2.4.2: Mapping between tipping point impacts and risk currency variables.

Risk Currency	Physical Impact Pathways	Specific Variables Affected
Food security	Temperature changes, precipitation shifts, sea level rise, ecosystem collapse	Crop yields, fisheries productivity, agricultural land loss, food prices, nutrition security
Energy security	Infrastructure damage, resource availability, demand changes	Power generation capacity, transmission networks, heating/cooling demand, renewable potential, fossil fuel infrastructure
Water resources	Precipitation patterns, hydrological cycles, saltwater intrusion	Freshwater availability, water quality, aquifer contamination, reservoir levels, seasonal flows
Infrastructure & built environment	Sea level rise, permafrost thaw, extreme weather, ecosystem changes	Building foundations, transport networks, coastal defenses, urban planning, asset values
Public health	Temperature extremes, air quality, food/water security, displacement	Mortality, morbidity, mental health, healthcare capacity, disease vectors, heat stress
Biodiversity & ecosystems	Habitat loss, species migration, ecosystem state changes	Species extinction, ecosystem services, carbon storage, pollination, natural capital
Financial & economic risks	Asset damages, productivity losses, market disruption	GDP impacts, insurance costs, stranded assets, credit risks, investment uncertainty
Humanitarian crisis & displacement	Habitability loss, livelihood collapse, resource scarcity	Population displacement, migration flows, refugee crises, community breakdown
National security	Resource conflicts, border pressures, economic instability	Military deployment, border security, international tensions, failed states

2.4.3 Summary risk assessment

First we provide the overall Earth system tipping points risk register (Figure 2.4.1), then we unpack it. Here we summarise striking findings regarding the most impactful tipping points, critical timescales, direct regional impacts (Table 2.4.3) and systemic risks (Table 2.4.4). Then we provide more details structured by risk currency (Figure 2.4.4) and by world region (Figure 2.4.5).



High emission risk	4.0+			Boreal forest shifts		
Long-term risk (2100s)	3.0+				Monsoon shifts	AMOC collapse
Medium-term risk (2050s)	2.0+		Mountain glaciers		Amazon die back	
Near-term risk (2030s)	1.5+			SPG Permafrost thaw	Greenland ice sheet	WAIS collapse
We are here	1.4			Coral Reef die off		
Time horizon	Temperature	Low	Moderate	Major	Severe	Catastrophic
		Impact				

Darker colour shading represents a greater degree of threat posed, which is a function of the temperature threshold and thus proximity of the trigger to the present day and of the impact.

Temperature thresholds are uncertain, which means it cannot be ruled out that tipping points are triggered sooner. This uncertainty is included only for AMOC as an illustrative example.

Figure 2.4.1: *Earth system tipping points risk register. Temperature-threshold-based risk assessment showing when different tipping points may be triggered under various warming scenarios, with impacts categorized by severity. Temperature thresholds are based on best available scientific estimates from Chapter 2.2 and the literature (including Armstrong McKay et al. 2022), incorporating potential interactions between tipping points and updated model assessments. Some thresholds may differ from individual previous assessments due to consideration of tipping point interactions, updated scientific evidence, refined estimates of system stability and potential model biases toward overstability—as a risk assessment, we err toward lower thresholds to avoid underestimating risks. The color-coding reflects both impact severity and proximity to current warming levels: tipping points with severe impacts at lower temperature thresholds deserve more immediate attention than similar-impact events occurring only at higher warming. For example, a moderate impact event like mountain glacier loss at 2°C warming (orange) is more urgent than a moderate impact event at 3°C warming (yellow), while severe events like Greenland Ice Sheet collapse at 1.5°C (light red) are higher priority than severe events like monsoon shifts at 3°C (orange).*

The assessment reveals several critical insights for global risk management:

Highest impact tipping points

- Monsoon disruption would affect the largest number of people globally, with over 5 billion people dependent on monsoon systems across South Asia, Southeast Asia, East Asia and West Africa. Monsoon weakening is very likely to cause severe food and water security impacts, with potential 40 per cent reductions in seasonal precipitation observed in some regions, critically threatening agricultural systems that support billions. Monsoon disruption would likely have major impacts on regional energy systems dependent on hydroelectric power, with massive cooling demand increases during altered seasonal patterns.
- Ice sheet loss threatens over 2 billion people in coastal areas globally, with potential for multi-meter sea level rise over centuries creating permanent displacement pressures. The combination of Greenland and West Antarctic Ice Sheet collapse could contribute up to 12+ meters of sea level rise, with severe impacts on coastal infrastructure and agriculture, particularly threatening small island developing states with complete uninhabitability. Ice sheet collapse would likely accelerate AMOC weakening through freshwater discharge, potentially triggering monsoon disruptions, while regional sea level variations could exceed global averages by 30-50 per cent in some coastal regions.
- AMOC collapse is very likely to have severe impacts on food and water security in North and Central Europe, as well as West Africa and is likely to have moderate impacts on energy security across the Northern hemisphere. AMOC collapse will likely impact monsoons globally. It will also likely lead to significant sea level rise for north Atlantic coastal regions. These impacts are likely to lead in turn to moderate to high economic insecurity. AMOC collapse would also affect several other Earth system tipping points, including very likely accelerating West Antarctic Ice Sheet collapse to moderate extent, potentially affecting Amazon dieback and could stabilise Greenland Ice Sheet collapse to a low extent. AMOC collapse would likely trigger monsoon weakening globally through southward shifts of the Intertropical Convergence Zone.
- Coral reef die-off would affect over 500 million people dependent on reef systems for food security, coastal protection and economic livelihoods. The ongoing Fourth Global Coral Bleaching Event has affected 83.8 per cent of the world's coral reef area, demonstrating that reefs have crossed critical thresholds. Coral reef loss is very likely to eliminate critical protein sources for 150+ million people while removing natural coastal protection that reduces wave energy by up to 97 per cent. It is likely to lead to economic losses, particularly in the Coral Triangle region where economic losses could exceed $75 billion from tourism and fisheries collapse alone. Coral reef die-off would likely accelerate under multiple tipping point interactions, with ocean acidification from permafrost carbon release and altered ocean circulation from AMOC collapse creating compounding stresses that prevent recovery even if global temperatures stabilize.

Critical timeframes

- Immediate risks (2025-2035) include coral reef die-off and SPG collapse under current warming trajectories, which are already showing signs of approaching critical thresholds.
- Medium-term risks (2035-2050) include Amazon dieback, monsoon instability and ice sheet loss acceleration, with multiple tipping points potentially triggered within the Paris Agreement range of 1.5-2°C global warming.
- Long-term risks (2050-2080) involve the possibility of multiple system failures and cascading effects, with the highest cascade risks identified as:
    - AMOC collapse → Monsoon weakening → Global precipitation shifts
    - Ice sheet loss → AMOC weakening → Sea level acceleration
    - Permafrost thaw → Boreal shifts → Arctic amplification

Most vulnerable regions and populations

Table 3 summarizes the combined direct impacts of different tipping points on each world region. This reveals striking patterns of geographical inequality, with some regions facing existential threats while others experience primarily economic and infrastructure challenges. Small Island Developing States, South Asia, Southeast Asia, West Africa and Arctic regions face critical system-threatening level impacts, while many developed regions in temperate zones face major impacts requiring significant adaptation but not ones that threaten societal collapse.

- Small Island Developing States face existential threats from sea level rise affecting 1+ million people, representing the first potential climate refugees at a national scale. Many coral atolls and low-lying islands could face complete inundation with even 1-2 meter sea level rise, while economic costs could reach 100 per cent+ of GDP rendering entire nations uninhabitable.
- South Asia emerges as the region with the highest absolute population exposure, with 2+ billion people critically dependent on monsoon systems vulnerable to disruption. The Ganges-Brahmaputra Delta alone, supporting 90 per cent of Bangladesh's rice production, faces severe threats from sea level rise that could displace 15 million people from even modest sea level rise scenarios.
- Southeast Asia faces critical vulnerabilities affecting 600+ million people, particularly through Coral reef die-off in the Coral Triangle region containing the highest marine biodiversity globally. The Mekong Delta, producing 50 per cent of Vietnam's rice, faces severe threats from sea level rise, while major coastal megacities including Bangkok, Ho Chi Minh City and Jakarta could be severely threatened.
- Arctic and Northern communities face massive ecosystem transformation affecting indigenous populations whose traditional ways of life depend on stable permafrost, sea ice and boreal forest systems. With 70 per cent of current infrastructure in permafrost regions potentially facing high thaw potential by 2050, entire communities may require relocation.
- West Africa has 400+ million people dependent on monsoon systems strongly connected to AMOC stability, in a region that has already experienced seven political coups in three years, suggesting potential climate-political stability linkages.

Sectoral impact assessment

- Food Security faces the most widespread impacts, with tipping points threatening agricultural systems supporting billions through altered precipitation patterns, temperature changes and extreme weather intensification. The scale ranges from localized impacts affecting millions to global food system disruption.
- Energy Security faces major challenges from changing precipitation patterns affecting hydroelectric power, sea level rise threatening coastal energy infrastructure and altered weather patterns affecting renewable energy potential.
- National Security implications include resource conflicts, climate migration pressures and economic disruption, with particular risks in already politically unstable regions like the Sahel.
- Financial and Economic Systems face challenges from the nonlinear and irreversible nature of tipping events that would challenge traditional risk assessment models and insurance frameworks, with potential for systemic financial instability.

Next we provide more details, unpacking the results in terms of risk currencies (Figure 2.4.4) and then detailing impacts by world region (Figure 2.4.5).

Table 2.4.3: Tipping element direct impact matrix by IPCC SREX region. Direct impacts of each tipping point are mapped across all global regions using the IPCC SREX reference regions showing how different tipping points create uneven geographical vulnerabilities.

Region	AMOC collapse	Ice sheet loss	SPG collapse	Permafrost	Boreal forest	Monsoons	Coral reefs	Amazon	Mountain glaciers
Small Islands (SIS)	🟧	🟥	🟩	🟩	🟩	🟥	🟥	🟩	🟩
South Asia (SAS)	🟥	🟥	🟩	🟧	🟩	🟥	🟥	🟨	🟧
Southeast Asia (SEA)	🟧	🟥	🟩	🟩	🟩	🟥	🟥	🟨	🟩
East Asia (EAS)	🟧	🟥	🟩	🟧	🟧	🟥	🟥	🟨	🟩
North Asia (NAS)	🟧	🟧	🟩	🟥	🟥	🟩	🟩	🟩	🟩
West Africa (WAF)	🟥	🟥	🟨	🟩	🟩	🟥	🟧	🟩	🟩
Eastern N. America (ENA)	🟥	🟥	🟨	🟩	🟧	🟩	🟧	🟩	🟩
Central America (CAM)	🟥	🟥	🟩	🟩	🟩	🟥	🟥	🟨	🟩
Northern Europe (NEU)	🟥	🟧	🟥	🟧	🟥	🟩	🟩	🟩	🟧
Alaska/NW Canada (ALA)	🟨	🟧	🟩	🟥	🟥	🟩	🟩	🟩	🟥
Amazon (AMZ)	🟧	🟧	🟩	🟩	🟩	🟥	🟩	🟥	🟩
East Africa (EAF)	🟧	🟧	🟩	🟩	🟩	🟥	🟥	🟩	🟩
Western N. America (WNA)	🟨	🟥	🟩	🟨	🟧	🟥	🟩	🟩	🟧
Tibetan Plateau (TIB)	🟩	🟩	🟩	🟥	🟧	🟥	🟩	🟧	🟥
Central Europe (CEU)	🟧	🟧	🟧	🟩	🟧	🟩	🟩	🟩	🟩
West Asia (WAS)	🟧	🟥	🟩	🟨	🟩	🟧	🟥	🟩	🟧
Southern Europe (MED)	🟧	🟥	🟨	🟩	🟩	🟩	🟩	🟩	🟩
Central Asia (CAS)	🟨	🟩	🟩	🟧	🟧	🟧	🟩	🟩	🟧
Northeast Brazil (NEB)	🟧	🟥	🟩	🟩	🟩	🟥	🟥	🟧	🟩
North Australia (NAU)	🟨	🟧	🟩	🟩	🟩	🟥	🟥	🟨	🟩
South Australia (SAU)	🟩	🟧	🟩	🟩	🟩	🟩	🟧	🟩	🟩
Eastern Canada / Greenland (CGI)	🟧	🟥	🟧	🟥	🟥	🟩	🟩	🟩	🟥
Southeast S. America (SSA)	🟧	🟥	🟩	🟩	🟩	🟧	🟩	🟥	🟩
West Coast S. America (WSA)	🟨	🟧	🟩	🟨	🟩	🟧	🟨	🟥	🟫
Southern Africa (SAF)	🟨	🟧	🟩	🟩	🟩	🟧	🟧	🟩	🟩
Central N. America (CNA)	🟨	🟩	🟩	🟨	🟨	🟧	🟩	🟩	🟩

Legend:

🟫 CRITICAL = System-threatening impacts
🟧 MAJOR = Significant adaptation required
🟨 MODERATE = Manageable impacts requiring some adaptation
🟩 LOW = Limited impacts

Table 2.4.4: Potential systemic risk impacts of passing different climate tipping points. Physical changes translate into risks across nine critical policy domains.

Tipping event	Food security	Energy security	Water resources	Infrastructure & built environment	Public health	Biodiversity & ecosystems	Financial & economic risks	Humanitarian crisis & displacement	National security
AMOC collapse	↓↓ Agricultural productivity N. Europe (32 per cent to 7 per cent arable land), monsoon disruption affecting 2B+ people	↑ Heating demand Europe, ↓ hydroelectric from precipitation changes	↓↓ Precipitation patterns (-0.5 to -2 mm/d), hydrological disruption	Massive adaptation costs (€500B+ Europe), storm track changes	Cold stress, food insecurity health impacts	Major ecosystem shifts, forest stress	€500B+ protection costs, agricultural losses	10M+ displacement Europe	Resource conflicts, Sahel political instability
Subpolar gyre deep convection collapse	Atlantic fisheries collapse (cod, herring), European food security	Altered renewable energy potential	Limited direct water impacts	Increased storm risks coastal infrastructure	Food insecurity from fisheries loss	Marine ecosystem fundamental shifts	Fisheries economic collapse	Coastal fishing community displacement	Resource conflicts over marine resources
Greenland Ice Sheet collapse	Saltwater intrusion coastal agriculture	Coastal energy infrastructure threatened	Massive freshwater discharge, saltwater contamination	Multi-meter SLR (up to 7.42m), coastal infrastructure loss	Displacement health impacts, contaminated water supply	Coastal ecosystem complete loss	Trillions in coastal asset losses	Millions displaced from coastal cities	Arctic geopolitical tensions, border pressures
West Antarctic Ice Sheet collapse	Coastal agricultural land loss	Coastal power plants at risk	Freshwater supply contamination	Multi-meter SLR (up to 5.08m), infrastructure submersion	Health system strain from displacement	Marine ecosystem disruption	Insurance market collapse coastal regions	Island nations uninhabitable	International refugee crises
Permafrost thaw	↓ Agricultural zones, soil constraints in thaw regions	Critical pipeline/infrastructure damage, Trans-Alaska Pipeline threatened	Hydrological changes, thermokarst lake formation	70 per cent permafrost infrastructure at risk by 2050	Carbon feedback acceleration health impacts	Massive boreal ecosystem shifts, wetland formation	Infrastructure replacement costs trillions	Arctic indigenous community displacement	Arctic sovereignty challenges
Coral reef die-off	↓↓ Reef fisheries (150M+ people Coral Triangle), protein source loss	Coastal energy infrastructure vulnerability	Loss of coastal protection from storm surge	↓ Natural coastal protection, ↑ storm damage	Food insecurity, storm-related injuries and deaths	>99 per cent coral biodiversity loss under 2.5°C	$75B+ tourism/fisheries losses Coral Triangle alone	Small island nation complete displacement	Resource conflicts over marine territories
Amazon dieback	Regional precipitation loss affecting agriculture	↓ Hydroelectric potential, biomass energy disruption	25-35 per cent precipitation recycling loss, river navigation disruption	Fire risks to infrastructure, transportation disruption	Fire smoke health impacts, heat stress	50-70 per cent conversion to savanna, massive biodiversity loss	$957B-3,589B economic damages over 30 years	Indigenous peoples displacement, millions affected	Regional political instability, Brazil-neighbors tensions
Boreal forest shifts	Forest-agriculture transitions, wildfire risks to crops	Biomass energy disruption, wildfire risks to power transmission	Watershed changes, fire impacts on water quality	↑↑ Wildfire risks to infrastructure, forest industry collapse	Wildfire smoke health emergencies	Largest global ecosystem transformation	Forest industry economic collapse	Rural community abandonment	Resource conflicts over forest transitions

Table 2.4.4: Continued

Tipping event	Food security	Energy security	Water resources	Infrastructure & built environment	Public health	Biodiversity & ecosystems	Financial & economic risks	Humanitarian crisis & displacement	National security
South Asian monsoon disruption	Critical threat to 2B+ people, rice production collapse	Massive cooling demand impacts, hydroelectric disruption	Primary water source for billions disrupted	Urban infrastructure strain from monsoon variability	Heat stress, water-related disease	All major ecosystems dependent on monsoon	Economic disruption for 1/4 world population	Mass internal displacement, international migration	Regional conflicts over water resources
West African monsoon collapse	400M+ people agriculture dependent on monsoon	Hydroelectric generation severely affected	Primary water source hundreds of millions	Sahel infrastructure adaptation needs	Heat stress, food/water insecurity	Sahel ecosystem shifts forest-grassland	Agricultural economy collapse	Mass displacement from Sahel	Political instability (7 coups in 3 years)
East Asian monsoon disruption	1.5B+ people agricultural productivity threatened	Energy system impacts from monsoon changes	Water resources for massive populations	Infrastructure planning disruption	Heat/humidity health impacts	Regional ecosystem disruption	Major economic disruption East Asia	Internal displacement pressures	Regional tensions over water/food
Mountain glaciers	Regional impacts on glacier-fed agriculture	Altered hydroelectric potential, seasonal variability	Critical impacts on glacier-dependent regions	Glacial outburst flood risks, coastal changes	Limited direct impacts	Major ecosystem transformations in fjords/mountains	Tourism losses, infrastructure adaptation costs	Indigenous community displacement, cultural losses	Arctic sovereignty challenges, border access changes

2.4.4 Systemic threats in terms of risk currencies

To understand how Earth system tipping points translate into tangible policy and governance challenges, we must examine their impacts through the lens of what societies fundamentally depend upon for stability and prosperity. The following analysis organizes tipping point consequences across nine critical *risk currencies* that represent the core values and priorities policymakers are mandated to protect: food security, energy security, humanitarian crisis and displacement, national security, financial and economic risks, infrastructure and built environment, public health, biodiversity and ecosystems and water resources. This aims to bridge the gap between Earth system science and policy-relevant impacts, demonstrating how tipping points in the Earth system cascade through interconnected human systems to create systemic risks.

Food security

Earth system tipping points pose severe threats to global food production through multiple pathways. Food systems are highly vulnerable to tipping point impacts as they are affected by multiple dimensions (Wheeler and von Braun, 2013), with sensitivity to precipitation and temperature (Lenton et al., 2023). Simultaneous harvest failures across major crop-producing regions are a threat to global food security, driven by concurrent weather extremes from strongly meandering jet streams (Anderson et al., 2019, 2024; Gupta et al., 2023; Kornhuber et al., 2023; Hasegawa et al., 2022; Mehrabi and Ramankutty, 2019; Tigchelaar et al., 2018; Zscheischler et al., 2018).

Tipping points also threaten food security through indirect pathways, including altered pest and disease dynamics as changing temperature and precipitation patterns expand the geographic range and seasonal activity of crop pests and pathogens (Deutsch et al., 2018).

AMOC collapse demonstrates the scale of potential agricultural disruption, with research showing it would cause widespread cessation of arable farming in Northern Europe. In Britain, suitable farmland would drop by as much as 32 per cent, decreasing agricultural output by £346 million annually (Ritchie et al., 2020). Regional cooling in Northern Europe could cause widespread agricultural system collapse, while altered precipitation patterns would affect agricultural systems supporting billions across affected monsoon regions. The West African, Indian Summer and East Asian monsoons would be disrupted with shorter wet and longer dry seasons and less overall rainfall, affecting food production for populations dependent on these systems (Ben-Yami et al., 2024; Ben-Yami et al., 2023).

Amazon dieback would severely disrupt food systems through crop failures and declining fish stocks, with rising food prices and reduced nutrition access particularly affecting the 30 million regional residents. Indigenous and traditional communities face acute risks as their food security depends on intact forest-river ecosystem interactions (Begazo-Curie and Vranken, 2025; Leal Filho et al., 2025; Monteverde et al., 2024; Banerjee et al., 2022; Tregidgo et al., 2020). Coral reef collapse would eliminate reef fisheries supporting 150+ million people in the Coral Triangle region alone, with complete loss of this primary protein source for many small island populations creating severe food security crises.

Research on "non-tipping" climate impacts suggests that the abrupt and severe changes characteristic of tipping events would amplify food security risks through crop yield volatility, supply chain disruption and price shocks beyond what gradual climate change would produce (Tchonkouang et al., 2024; Mirzabaev et al., 2023; Ortiz-Bobea et al., 2021; Davis et al., 2020). The often irreversible nature of tipping point changes means agricultural systems cannot rely on temporary adaptation but must undergo fundamental transformation to cope with permanently altered growing conditions.

Energy security

Energy systems face critical vulnerabilities from climate change through infrastructure damage, supply disruption and demand volatility (Yalew et al., 2020; van Vliet et al., 2016). Earth system tipping points could amplify these existing vulnerabilities, potentially making infrastructure damage, supply disruption and demand volatility permanent and irreversible. Sea level rise from ice sheet collapse threatens coastal nuclear plants, refineries and LNG terminals, while permafrost thaw puts 70 per cent of current infrastructure in permafrost regions at high risk by 2050, including critical assets like the Trans-Alaska Pipeline (JRC, 2025b; Manos et al., 2025; Langer et al., 2023). Permafrost and boreal forest changes create extreme wildfire risks to power transmission networks documented across Alaska, Canada and Siberia (Virkkala et al., 2025; Kim et al., 2024; Scholten et al., 2024; Buma et al., 2022).

Supply security faces major disruption through altered precipitation patterns affecting hydroelectric generation. AMOC collapse could severely reduce hydroelectric potential across Europe and West Africa through precipitation changes (Jackson et al., 2015), while monsoon disruptions threaten systems supporting billions across South and Southeast Asia (Ben-Yami et al., 2023; Zhao et al., 2023; Chemison et al., 2022; Sandeep et al., 2020; Amrith, 2016; Loo et al., 2015; Intergovernmental Panel on Climate Change, 2014). Amazon dieback could reduce regional hydroelectric potential by 25-35 per cent through precipitation recycling loss (Lenton et al., 2023). Mountain glacier retreat would fundamentally alter regional hydrology, with glaciers contributing up to half of downstream discharge while buffering seasonal variability, affecting hydroelectric generation potential for the nearly 1.5 billion people living in glacier-influenced regions globally.

Demand patterns face unprecedented volatility from temperature regime changes. AMOC collapse would require massive increases in heating energy demand across Northern Europe while altering renewable energy potential through changed offshore wind patterns (Ritchie et al., 2020). The irreversible nature of tipping point changes means energy systems cannot rely on temporary adaptation but must undergo fundamental transformation, with cascading failures becoming more likely as multiple tipping points interact across energy value chains.

Humanitarian crisis and displacement

Tipping point impacts create cascading humanitarian emergencies through ecosystem collapse, resource scarcity and livability challenges. Extreme events including droughts in the Amazon region are disruptive to the food and transport systems of Indigenous peoples and communities who depend on local resources, with lower river water levels affecting transportation, food security and health, potentially influencing migration from rural areas (Lenton et al., 2023). As traditional knowledge systems, ecosystems and forest-based livelihoods deteriorate, entire communities may lose their ability to sustain themselves, creating self-reinforcing cycles of socio-ecological vulnerability (Pinho et al., 2015).

Mountain glacier retreat creates profound cultural losses for Indigenous communities whose identities and traditional knowledge systems are inseparable from glacial landscapes. For Tlingit communities in southeast Alaska, rapid deglaciation disrupts relationships with glaciers spanning millennia, depriving future generations of cultural touchstones and traditional practices while forcing adaptation of harvest and land management systems (Ord, 2024). Small Island Developing States face complete loss of territory that would trigger unprecedented questions of statehood and require total population relocation, creating new categories of climate refugees.

AMOC collapse would create displacement pressures affecting millions across Europe and West Africa. West Africa monsoon disruption threatens 400+ million people dependent on monsoon precipitation patterns, with the potential for unprecedented humanitarian displacement in a region that has already experienced multiple military coups since 2020, suggesting limited capacity to manage climate-driven migration (Ben-Yami et al., 2024; Kipo-Sunyehzi & Lambon, 2025; Larémont, 2021; Mulitza et al., 2008; Neupane & Cook, 2013; Peterson, 2024; Surazu, 2024; Taruvinga, 2023). The southward shift of the Intertropical Convergence Zone would trigger acute humanitarian emergencies as shortened wet seasons and reduced rainfall render pastoralist and farming livelihoods impossible across vast areas of the Sahel, forcing millions to abandon their homes and traditional territories (Defrance et al., 2017, 2020; Mulitza et al., 2008). Rural migration during extended dry periods, combined with displacement from irregular intense flooding that destroys settlements, would create cascading humanitarian crises as drought and flood refugees overwhelm urban areas and neighboring regions already struggling with 8 million internally displaced persons and a 172 per cent increase in humanitarian need since 2016 (International Rescue Committee., 2023).

Research on climate-induced displacement provides a foundation for understanding how the scale and irreversibility of tipping point impacts would generate unprecedented migration pressures. While existing displacement studies focus on gradual climate impacts (Duijndam et al., 2025; Almulhim et al., 2024; Hoffmann et al., 2024; Askland et al., 2022), tipping point research warns that crossing these thresholds could trigger 'catastrophic impacts on human societies' including mass displacement suggesting that the irreversible nature of tipping point changes would generate migration pressures that exceed current projections based on linear climate impacts.

National security

Earth system instability threatens national security through resource conflicts, border pressures from climate migration and economic disruption (Laybourn et al., 2024). Climate variability is directly linked to economic impacts and political stability, with the AMOC strongly connected to precipitation over the Sahel, a region that has experienced at least five successful military coups since 2020 (Kipo-Sunyehzi and Lambon, 2025; Ben-Yami et al., 2024; Peterson, 2024; Surazu, 2024; Taruvinga, 2023; Larémont, 2021; Neupane and Cook, 2013; Mulitza et al., 2008).

Earth system tipping points create complex cascades between conflict and cooperation that challenge traditional national security frameworks. Research specifically examining tipping point-security linkages identifies how climate tipping events can trigger cascading dynamics where initial cooperation attempts may collapse into conflict spirals, or conversely, where crisis-driven cooperation can emerge from conflict situations (Scheffran et al., 2025). These dynamics are amplified by negative social tipping processes that Earth system destabilization can trigger, including social anomie, political radicalization and polarization, mass displacement, resource conflicts and financial destabilization that can reinforce ecological breakdown through reduced adaptive capacity (Spaiser et al., 2024). The interconnected nature of Earth system tipping points means that cascading failures - such as AMOC collapse simultaneously triggering monsoon disruption and Amazon dieback - could overwhelm existing security frameworks designed for singular threats, creating self-reinforcing cycles where climate-induced social instability reduces society's capacity to address climate risks while generating unpredictable shifts between cooperation and conflict that exceed current diplomatic and military planning scenarios.

Amazon degradation increases risks of violent conflict through riots and protests over rising food prices and resource shortages, tensions between displaced populations and host communities and potential for authoritarian shifts driven by social radicalization and climate-induced unrest (Scheffran et al., 2025; Spaiser et al., 2024). Mountain glacier retreat in Alaska creates international governance challenges as icefields straddle borders and deglaciation may create more points of access across the US-Canada border, raising national security and defense considerations.

Insights taken from the literature on climate-conflict linkages (Mach et al., 2019; Burke et al., 2015; Hsiang et al., 2011) suggests that tipping point impacts would exacerbate existing vulnerabilities and create new sources of instability. The cascading impacts could include political destabilization as established political systems face legitimacy challenges from climate-induced hardships, potentially leading to social unrest and violence as people turn against political elites unable to provide effective responses to multiplying crises.

Financial and economic risks

Melting of the Antarctic Ice Sheet could impose severe costs on Small Island Developing States and increase the worldwide social cost of carbon emissions (Dietz and Koninx, 2022). Ecosystem tipping points pose risks to economic stability through reduced food and energy security, damage to assets such as real estate and infrastructure and health risks that impair household productivity (Bloom et al., 2024; Burlig and Preonas, 2024; Pereira et al., 2024; Yang et al., 2023; Dietz and Koninx, 2022; Hjort et al., 2022; Hallegatte and Walsh, 2021; Lapola et al., 2018; Hsiang, 2010). However, most existing economic assessments of climate tipping points have taken a narrow approach, focusing primarily on relating GDP to mean annual temperature effects while neglecting the broader systemic impacts (Keen, 2020). For instance, early studies suggested that AMOC collapse might actually be economically beneficial due to regional cooling effects, leading to counterintuitive conclusions that such events could reduce the social cost of carbon (Dietz et al., 2021; Anthoff et al., 2016). These studies use standard damage functions that rely on simple temperature-damage relationships which are inadequate for normal climate change and completely fail for tipping points. A recent study of AMOC weakening demonstrates this problem clearly - incorporating just one additional impact pathway - the reduction in ocean carbon uptake that leads to higher atmospheric CO_2 and accelerated global warming - reveals economic damages of several trillion US dollars that completely offset the supposed benefits (Schaumann and Alastrué de Asenjo, 2025). This AMOC carbon feedback alone could flip the economic consequences of AMOC weakening from a net benefit to a net cost to society, highlighting how current damage functions systematically underestimate tipping point impacts by ignoring critical Earth system feedbacks.

Furthermore, financial markets may trigger "Minsky moments" (Kaldorf and Rottner, 2024; Miller and Dikau, 2022; Behlul, 2011) - sudden collapses in asset values - as investors anticipate future tipping point risks, even before physical thresholds are crossed, creating cascades that move outside the climate system into financial systems. The insurance sector particularly faces withdrawal from climate-vulnerable regions, creating uninsurable "climate deserts" (Boomhower et al., 2024; Kousky et al., 2024; Storey et al., 2024) where economic losses from extreme events already amount to 1 per cent of GDP in the euro area and are expected to rise without action (Alogoskoufis et al., 2021). The systemic nature of climate change for financial stability suggests the need for macroprudential responses including systemic risk buffers and exposure concentration limits, though modeling complexity and uncertainty present significant challenges. Uncertain climate policies may induce destabilizing swings in green asset prices, while unexpected transitions could leave high-carbon firms with stranded assets, translating into credit risk for funding institutions.

Infrastructure and built environment

Infrastructure systems face threats from Earth system tipping points through physical damage, design standard obsolescence and cascading system failures (Bhattacharya et al., 2025; Fekete and Nehren, 2024; de Abreu et al., 2022; Palin et al., 2021; Hawchar et al., 2020). Sea level rise from ice sheet collapse would create unprecedented challenges (Kopp et al., 2014, 2017; Hinkel et al., 2014), with losses and protection costs potentially as high as hundreds of billions of Euros for Europe alone (Vousdoukas et al., 2020) and 70 per cent of permafrost infrastructure at risk by 2050, requiring massive adaptation investments or community relocation (Hjort et al., 2022).

AMOC collapse would fundamentally alter storm tracks and precipitation patterns, making existing infrastructure inadequate, while boreal forest shifts create extreme wildfire risks to transportation networks and power transmission systems documented across northern regions (Bellomo and Mehling, 2024; Fekete and Nehren, 2024; Bellomo et al., 2023; Walker et al., 2019; Jackson et al., 2015). The unprecedented scale of tipping point changes could overwhelm existing adaptation measures and require fundamental rethinking of design standards, as these irreversible shifts render existing infrastructure planning assumptions obsolete, forcing complete system redesigns rather than incremental adaptations (Buhl and Markolf, 2023; IPCC, 2022; Zhang et al., 2020). Indeed, current climate change is already outpacing adaptation measures as seen with recent extreme events, with ongoing impacts outpacing global mitigation efforts and adaptation progress slowing when it should be accelerating (UNEP, 2024; Newman and Noy, 2023; Magnan et al., 2022; Currie-Alder et al., 2021).

Public health

Public health systems face compounding emergencies from climate change through direct health impacts, healthcare system disruption and cascading crises that exceed system capacity (Romanello et al., 2024; van Daalen et al., 2024; Ebi, Capon, et al., 2021; Ebi, Vanos, et al., 2021; Kovats and Hajat, 2008), while tipping points could exacerbate these same vulnerabilities beyond current adaptive capacity. Permafrost thaw can accelerate global warming through carbon release (Turetsky et al., 2020; Olefeldt et al., 2016; Schuur et al., 2015) while potentially releasing ancient viruses and pathogens previously trapped in frozen soils, creating amplified health risks and novel disease emergence concerns (Mackelprang et al., 2025; Wu et al., 2022; Revich et al., 2012).

Boreal forest shifts generate extensive wildfire smoke (Phillips et al., 2022; Whitman et al., 2019) creating respiratory emergencies across populations (Aguilera et al., 2021; Reid et al., 2016), while food security collapses threaten nutrition for billions, with monsoon disruption affecting 2+ billion people in South Asia (Asutosh et al., 2025; Fiaz et al., 2025; Fanzo et al., 2024; Turner and Annamalai, 2012) and coral reef die-off eliminating protein sources for 150+ million in the Coral Triangle (Crona et al., 2015; Cruz-Trinidad et al., 2014; WWF, 2009). Mental health impacts emerge from displacement pressures (Torres and Casey, 2017; McMichael et al., 2012), with potential displacement of 13 million people in the US from sea level rise alone (Hauer et al., 2016), while healthcare infrastructure faces direct physical threats precisely when demand surges from cascading health emergencies that would exceed system capacity (NRDC, 2024).

Biodiversity and ecosystems

Earth system tipping points pose severe threats to global biodiversity through habitat destruction, ecosystem collapse and species extinction cascades, leading to abrupt and possibly irreversible shifts between alternative ecosystem states (Pecl et al., 2017; Urban, 2015). Evidence exists for tipping points in ecosystems including forest dieback, dryland desertification, lake eutrophication, coral reef die-off and fishery collapse, with several biomes such as the Amazon rainforest losing resilience and approaching key tipping thresholds. Recent analysis reveals a biodiversity paradox: increased biodiversity lowers collapse thresholds while enhancing restoration potential (Dakos et al., 2019). Stable ecosystems underpin all economic activity through providing natural resources, regulating climate and providing resilience against disasters, yet human pressures are increasing ecosystem tipping point risks (Marsden et al., 2024; Dasgupta, 2021; Folke et al., 2021; Dakos et al., 2019). Research suggests that tipping point events would create compounding ecological emergencies exceeding ecosystem adaptation capacity, potentially triggering irreversible losses of species and functions essential for planetary stability.

AMOC collapse represents a particularly severe example of how circulation changes trigger cascading biological impacts. AMOC collapse would reduce North Atlantic marine productivity by up to 30 per cent over the 21st century while decreasing fisheries species abundance by up to 17 per cent locally, fundamentally altering marine food web structure (Boot et al., 2025). The collapse creates phenological mismatches where ecosystem timing shifts faster than species adaptation capacity, particularly affecting the North Atlantic bloom timing and its dependent food webs. Temperature-driven biogeographical shifts cascade through multiple trophic levels with amplifying effects, while reduced ecosystem carbon sequestration capacity creates positive feedbacks that accelerate atmospheric CO_2 accumulation (Boot et al., 2024). Terrestrial systems face complex disruptions as altered precipitation patterns and temperature regimes drive vegetation state changes and species range contractions. Dynamic vegetation models demonstrate significant relationships between AMOC strength and ecosystem composition, suggesting widespread transitions under collapse scenarios. These changes enhance the ongoing biodiversity crisis by creating additional stresses on vulnerable species already facing habitat loss and climate change, with documented effects including amphibian population declines and contracted geographic ranges for plants and animals (Ureta et al., 2022; Velasco et al., 2021).

Terrestrial systems face disruption as altered precipitation patterns affect productivity zones, with shifts in the Intertropical Convergence Zone relocating prime productivity in equatorial rainforests. Amazon forest loss would eliminate critical habitat for over 25 per cent of terrestrial species while disrupting moisture recycling essential for regional ecosystem stability.

The Fourth Global Coral Bleaching Event reveals the severity of ecosystem simplification, where reefs that survive have a different community structure with much less diversity in coral species. The ‘reef to rubble’ phenomenon causes coral colonies to fragment and transition to rubble, representing ecosystem transformation to new states that are difficult to recover from (Kai L Kopecky et al., 2023; Kenyon, Doropoulos, et al., 2023). This simplification adversely impacts thousands of species that rely on complex three-dimensional reef architecture, fundamentally altering ecosystem services provided to over half a billion people globally.

Water resources

Tipping points threaten global water security through altered precipitation patterns, hydrological cycle disruption and freshwater system collapse, with water security encompassing scarcity, quality, hazards, access and governance challenges. AMOC collapse would trigger southward shifts of tropical precipitation zones and disrupt monsoon systems (DiNezio et al., 2025; Steinert et al., 2025; Ben-Yami et al., 2024; Ben-Yami et al., 2023; Good et al., 2022; Kug et al., 2022), with palaeoclimate evidence showing that past AMOC weakening led to abrupt Asian and African monsoon collapse (Mohtadi et al., 2014, 2016). This would create complex regional impacts, with substantial Sahel rainfall reductions affecting primary water sources for hundreds of millions in West Africa (Defrance et al., 2017, 2020), while South Asian monsoon weakening affects primary water sources for billions of people (Dagdeviren et al., 2021),

Forest cover loss affects hydrologic systems of major freshwater-producing regions, with critical thresholds identified after which hydrologic regimes shift rapidly (Domínguez-Tuda and Gutiérrez-Jurado, 2024; Yang et al., 2021). Amazon dieback would disrupt critical moisture recycling processes, with an estimated 30 per cent of Amazon rainfall originating from forest evapotranspiration, affecting water availability across South America through disrupted atmospheric moisture transport (Beveridge et al., 2024).

Mountain glacier retreat fundamentally alters regional hydrology, with glaciers contributing up to half of downstream discharge while buffering seasonal variability through enhanced melt during warm, dry years. Rapid deglaciation initially increases discharge until around 2080, followed by decreased total discharge as glacier volume diminishes, affecting both freshwater security and hydroelectric generation potential for the nearly 1.5 billion people living in glacier-influenced regions globally. Greater variability in timing and volume of freshwater delivery affects dominant circulation patterns in nearshore waters, influencing transport and delivery of materials and nutrients to offshore ecosystems.

Human interference through climate forcing, water withdrawal and land-use change has disturbed hydrological cycles, with examples including aquatic system collapse. Recent research suggests tipping point events would create unprecedented hydrological disruption (van Thienen et al., 2025) affecting agriculture, energy, urban supplies and ecosystems, with cascading effects on food security, public health and economic stability globally.

2.4.5 Regional impact assessment

This section examines how Earth system tipping points manifest as concrete risks across different world regions, translating global-scale biophysical changes into localized consequences that vary dramatically based on geographical location, exposure patterns and socioeconomic context. We analyze impacts across 27 regions using the IPCC SREX classification system, which provides an appropriate spatial scale for synthesizing the currently limited literature on tipping point consequences. For each region, we assess exposure to major tipping points including AMOC collapse, ice sheet loss, permafrost thaw, monsoon disruption, coral reef die-off, Amazon dieback and boreal forest shifts, examining how these translate into direct impacts across the nine risk currencies established in our framework. This regional analysis reveals the highly uneven distribution of tipping point risks globally and identifies which populations face the most severe consequences from Earth system instability.

Europe

Major tipping point exposures

Europe faces dramatic impacts from AMOC collapse, sea level rise affecting extensive coastlines, permafrost thaw in northern regions, boreal forest shifts and Arctic sea ice loss effects. The region's high latitude position makes it particularly vulnerable to circulation changes and ice sheet effects.

Subpolar gyre

Collapse of deep convection in the subpolar gyre (Labrador and Irminger Seas) represents a critical early stage in broader North Atlantic circulation breakdown, with the key distinction that deep convection can collapse much faster than the full AMOC system winds down (Sgubin et al., 2017). While AMOC collapse by definition includes the loss of deep convection, subpolar gyre collapse deserves specific focus because it can occur decades sooner than complete AMOC shutdown, creating immediate regional impacts. The rapid cooling of large surface ocean areas from halted deep convection directly impacts atmospheric circulation, strengthening winter storms and altering weather patterns across the North Atlantic region (Swingedouw et al., 2021; Sgubin et al., 2017). This creates a stepping-stone scenario where subpolar gyre collapse serves as both an early warning signal and a driver of accelerated AMOC weakening, making it a critical threshold for monitoring and risk assessment.

NEU (northern Europe) could face major impacts from subpolar gyre collapse through altered ocean temperatures and circulation patterns affecting regional climate. Changes in ocean heat transport could modify coastal temperatures and precipitation patterns, potentially affecting agriculture and energy systems. Marine ecosystems supporting major fisheries, including cod, herring and other commercially important species, could face fundamental shifts in distribution and productivity. Recent modelling studies project that the North Atlantic bloom—the phytoplankton foundation of the regional food web—faces potential collapse this century due to weakened deep winter convection, with surface chlorophyll levels halving and bloom timing shifting by over 30 days, fundamentally disrupting food web dynamics that support these commercially important fisheries (Kelly et al., 2025). The collapse could also affect storm tracks and intensity across the North Atlantic (Shaw et al., 2016; Woollings et al., 2012), potentially increasing extreme weather risks to infrastructure and coastal communities. Changes in subpolar gyre strength are linked to North Atlantic Oscillation variability, which controls the latitudinal position of storm tracks and wind strength in the North Atlantic region, with subpolar gyre variations potentially affecting the northward-shifted storm track and North Atlantic Current strength (Bhagtani et al., 2024, 2025; Koul et al., 2020; Cannaby and Hüsrevo-lu, 2009; Sarafanov, 2009). CEU (central Europe) may experience moderate impacts through teleconnections affecting Atlantic weather patterns that influence continental European climate. Changes in storm frequency and intensity originating from altered North Atlantic conditions could affect agriculture and water resources. MED (Mediterranean) would likely see limited direct impacts from subpolar gyre changes, though some effects on Atlantic-origin weather patterns reaching Iberia and western Mediterranean regions may occur.

AMOC collapse

AMOC collapse could cause cooling and drying (Bellomo and Mehling, 2024; Caesar et al., 2018; Jackson et al., 2015) that may fundamentally transform agricultural systems and energy demands across Europe. These impacts result from fundamental asymmetries in ocean heat transport where heat loss occurs over smaller northern areas compared to southern heat distribution, making Northern Hemisphere regions particularly vulnerable as net receivers of Atlantic heat transport (S. Drijfhout, 2015; S. S. Drijfhout, 2015). Sea-ice expansion plays a critical amplifying role, capping atmospheric heat release while reflecting solar radiation back to space, creating self-reinforcing cooling effects that are larger in colder baseline climates. These changes can produce measurable drops in global mean temperatures despite originating from regional circulation shifts, with cooling patterns evolving over decades as winter sea ice expands southward (van Westen and Baatsen, 2025; van Westen et al., 2024).

Northern Europe (NEU) would likely experience the most severe impacts, with 3-8°C cooling and dramatic shifts in precipitation patterns shown in modelling studies that could cause widespread cessation of arable farming in northern Europe. Northwest European winters would become substantially harsher, characterized by stronger winds, more frequent snow events and intensified cold extremes leading to more frequent stormy conditions (Meccia et al., 2024, 2025; van Westen and Baatsen, 2025; Howard et al., 2024; Woollings et al., 2012). Summer weather patterns may shift toward sunnier, less cloudy conditions driven by more frequent blocking high-pressure systems east of the British Isles, associated with cool northerly winds (Bellomo et al., 2023; Haarsma et al., 2015). Storm tracks would intensify and extend eastward, particularly over northern regions of western and central Europe, leading to higher and more frequent storm surges that enhance coastal flooding risks (Howard et al., 2024; Yang et al., 2020; Lehmann et al., 2014; Woollings et al., 2012).

Marine ecosystems from the northeast Atlantic would face fundamental restructuring as reduced deep convection decreases nutrient entrainment, leading to phytoplankton productivity declines of up to 30 per cent over the 21st century. Critical fisheries species could decline locally by up to 17 per cent, fundamentally altering food web structure and economic dependencies (Boot et al., 2025). The timing of the North Atlantic bloom may shift substantially, creating phenological mismatches where species higher in food webs cannot adapt quickly enough to changing seasonal patterns, potentially causing ecosystem function collapse.

In Britain, rainfall during the growing season could be reduced by 123mm (approximately 20 per cent) and land suitable for arable farming could drop from 32 per cent to 7 per cent, reducing agricultural output by £346 million annually (Ritchie et al., 2020). This represents a critical food security threat affecting millions across the region. Shortened growing seasons may cause crop failures across Scandinavia, while reduced precipitation (-0.5 to -2 mm/d) and altered hydrological cycles could stress water resources (Bellomo and Mehling, 2024; Bellomo et al., 2023; Ritchie et al., 2020; Lynch-Stieglitz, 2017) . Storm track changes would likely make existing infrastructure and built environment inadequate, potentially requiring massive increases in heating energy demand and affecting renewable energy security potential. Sea transport will be hampered by increased risk of frozen sea during winter (van Westen and Baatsen, 2025).

Central Europe (CEU) could face 2-4°C cooling, particularly in Atlantic-influenced western areas, experiencing similar but less severe storm intensification patterns, potentially leading to reduced agricultural productivity and altered crop zones affecting major agricultural regions like the North German Plain, creating significant food security challenges (Bellomo and Mehling, 2024; Bellomo et al., 2023; Jackson et al., 2015). Forest ecosystem stress and altered species distributions may occur alongside infrastructure and built environment adaptation needs for altered climate patterns, while biodiversity and ecosystems face unprecedented stress from rapid climate transitions.

Southern Europe and the Mediterranean (MED) could experience moderate cooling (1-2°C) in Atlantic-influenced areas (Bellomo and Mehling, 2024; Jackson et al., 2015). Altered precipitation patterns potentially affecting Mediterranean agriculture and reduced precipitation in western Mediterranean regions that may stress ecosystems and water resources, while the eastern Mediterranean would likely see minimal direct impacts from AMOC changes.

Sea level rise from ice sheet collapse

Ice sheet collapse would accelerate sea level rise rates substantially in coming decades, with an additional 0.7m by 2100 in IPCC AR6's high-impact storyline, while the full multi-meter rise (up to 7.4m from Greenland, 5.1m from West Antarctica) would unfold over centuries (Siahaan et al., 2022; Stokes et al., 2022; Payne et al., 2021; Golledge, 2020; Dutton et al., 2015; Bamber et al., 2009; Dowdeswell, 2006; Alley et al., 2005). Critically, AMOC collapse would compound these impacts by raising sea levels by up to 1m along some European coastlines through altered ocean circulation patterns (van Westen et al., 2024; Chafik et al., 2019; Chen et al., 2019; Bouttes et al., 2014; Körper et al., 2009; Levermann et al., 2005), creating compound flooding risks that exceed global mean projections. Regional variations in sea level change due to gravitational and rotational effects mean some areas face disproportionately higher impacts, with the combination of accelerated ice sheet contributions and circulation changes creating unprecedented coastal vulnerability in the near term. NEU could face critical threats to low-lying agricultural areas in the Netherlands and Denmark, with major port Rotterdam and coastal cities like Amsterdam and Copenhagen potentially requiring massive coastal protection investments or partial abandonment of low-lying areas. Research on coastal impacts suggests protection costs could exceed hundreds of billion of Euros for Europe (Hinkel et al., 2014, with potential displacement of 10+ million people from low-lying areas.

CEU may experience major impacts on North German plain agricultural areas and infrastructure, with Hamburg and other North Sea ports potentially threatened by multi-meter sea level rise (Siahaan et al., 2022; Stokes et al., 2022; Payne et al., 2021; Golledge, 2020; Dutton et al., 2015; Bamber et al., 2009; Dowdeswell, 2006; Alley et al., 2005). The Wadden Sea and coastal ecosystems could be fundamentally altered. MED would likely face critical threats to major coastal cities including Venice and Alexandria, with the Po Valley and Nile Delta agricultural areas potentially severely affected by saltwater intrusion. Research indicates these low-lying areas could face permanent inundation or increased flooding, potentially displacing millions and disrupting regional economies (Hsiao et al., 2021; Silveira et al., 2021; Mohd et al., 2018; Rueda et al., 2017; Vitousek, Patrick L Barnard, et al., 2017; Vitousek, Patrick L. Barnard, et al., 2017).

Glacier collapse

Retreating glaciers, such as those in Svalbard, could impact NEU, exposing previously ice-covered land, altering freshwater and coastal water regimes while amplifying local warming through feedbacks like ice-albedo and melt-elevation effects (Marshall, 2021). Retreating glaciers in Arctic fjords, such as Billefjorden in Svalbard, have led to increased areas of shallows, decreased salinity and elevated temperatures in inner basins (van der Kamp et al., 2025). These changes are partly due to the influx of Atlantic waters from the shelf, transforming the fjord environment towards conditions characteristic of boreal ecosystems (Drewnik et al., 2016). The retreat of glaciers further drives differentiation of benthic communities and other ecological shifts over small spatial scales, indicating that ice loss triggers complex, localized environmental changes (van der Kamp et al., 2025). Consequently, there is an increase in organic matter turnover, significantly impacting local marine life .

Beyond the major ice sheets, smaller Arctic glaciers are experiencing extreme losses that may signal early tipping points, often linked to sea ice decline. Notably, Svalbard glaciers lost ~60 billion tons of ice in 2024, exceeding the annual ice loss from the entire Greenland Ice Sheet (Schuler et al., 2025). Such rapid glacier retreat further transforms local ecosystems and poses challenges for regional communities reliant on glacial meltwater.

Permafrost thaw

Permafrost thaw in northern Scandinavia causes ground instability, though impacts in Northern Europe are more limited than in North Asia and North America due to fewer settlements, lower ground ice content and better infrastructure maintenance (Hjort et al., 2022). NEU would likely experience the most significant impacts simply because that's where the permafrost is located - primarily in northern Scandinavia. Infrastructure damage in northern Norway, Sweden and Finland from ground instability could require massive adaptation investments or community relocation (Ramage et al., 2021). Traditional livelihoods of Indigenous populations and reindeer herders face disruption from changing landscape stability. Permafrost thaw causes changing landscapes and ecosystem shifts, including wetland formation, altered tundra vegetation and disrupted habitats for migratory birds, caribou and other Arctic wildlife (Berteaux et al., 2017; Jones et al., 2015; Keuper et al., 2012; Post et al., 2009), while infrastructure including buildings, roads and energy networks (such as pipelines) in permafrost regions face similar threats from ground instability. CEU and MED would have no direct permafrost impacts, experiencing only global carbon feedback effects.

Map 1: Potential impacts of Earth system tipping points on Europe

NORTHERN EUROPE

SPG collapse

Changes to coastal temperatures and rainfall impacting agriculture and energy systems

Increasing storm intensity damages infrastructure and coastal communities

Fundamental shifts in productivity and distribution of fisheries

AMOC collapse

Harsher winters

Widespread cessation of arable farming

Dramatic cooling, with annual temperatures dropping by 4-10°C on average and average winter temperatures dropping by as 15°C.

Permafrost thaw, ice sheet and glacier collapse

In northern Scandinavia, ground instability leading to infrastructure damage, requiring massive adaptation investments or community relocation

Previously ice-covered land exposed, altering freshwater access.

CENTRAL EUROPE

SPG collapse

Changes in storm frequency and intensity affect agriculture and water resources.

AMOC collapse

Potentially 2-4°C cooling

Reduced agricultural productivity

MEDITERRANEAN

SPG collapse

Some effects on weather patterns

AMOC collapse

Reduced precipitation in western Mediterranean regions stress ecosystems and water resources

SPG	Subpolar Gyre Overturning
AMOC	Atlantic Meridional Overturning Circulation

Boreal forest shifts

NEU may experience critical impacts with major albedo changes documented and wildfire smoke health impacts (El Garroussi et al., 2024). Forest-agriculture transitions in Fennoscandia could occur with wildfire risks (Kelly et al., 2024; Rolstad et al., 2017), while watershed changes and fire impacts on water quality may affect forest capacity for forest growth, carbon uptake and sequestration as well as infrastructure. Critical wildfire risks to infrastructure and forest industry disruption could occur, with Fennoscandian boreal forest ecosystem shifts and northward treeline movement potentially affecting energy infrastructure and biomass energy.

CEU could face major impacts through smoke drift from northern fires affecting air quality and economic disruption from reduced timber and biomass energy supplies, while forest-agriculture transitions in northern regions may create new land use pressures.

Africa

Major tipping point exposures

Africa faces severe impacts from AMOC collapse and West African monsoon disruption altering precipitation patterns, sea level rise affecting extensive coastlines, Coral reef die-off and ecosystem changes from global warming feedbacks. The continent's high dependence on rain-fed agriculture makes it particularly vulnerable to precipitation changes.

Changes in North Atlantic circulation (SPG and AMOC collapse) and monsoon disruption

AMOC collapse would likely trigger a southward shift of the Intertropical Convergence Zone and weaken the West African monsoon system, potentially dramatically reducing precipitation across parts of the Sahel and West Africa (Defrance et al., 2017, 2020; Held et al., 2005). Collapse of deep convection in the subpolar gyre can also lead to significant weakening of the West African monsoon in several models (Swingedouw et al., 2021), creating an additional pathway through which North Atlantic circulation changes can affect the region beyond full AMOC collapse.

West Africa (WAF) could face the most severe impacts, with AMOC collapse potentially causing substantial Sahel rainfall reductions (Steinert et al., 2025; Defrance et al., 2017, 2020). The southward shift in tropical precipitation zones would create severe agriculture, ecosystem and livelihood disruptions affecting 400+ million people dependent on West African monsoon patterns (Sylla et al., 2018; Sultan and Gaetani, 2016). The West African monsoon would be disrupted with shorter wet and longer dry seasons and less overall rainfall, following the same global pattern affecting other Northern Hemisphere monsoon systems (Ben-Yami et al., 2024; Ben-Yami et al., 2023). The AMOC is strongly connected to precipitation over the Sahel, a region that has experienced at least five successful military coups since 2020, suggesting potential climate-political stability linkages (Ben-Yami et al., 2024; Kipo-Sunyehzi & Lambon, 2025; Larémont, 2021; Mulitza et al., 2008; Neupane & Cook, 2013; Peterson, 2024; Surazu, 2024; Taruvinga, 2023).

Extended dry periods would stress savanna ecosystems and agricultural systems, while irregular intense rainfall events would generate erosion and flooding that damages both natural habitats and human settlements. Primary water sources for hundreds of millions may be disrupted (Omotoso and Omotayo, 2024; Omotoso et al., 2023; Diallo et al., 2016), while Sahel ecosystem shifts between forest and grassland states could occur as precipitation patterns change fundamentally. Hydroelectric generation may be severely affected by precipitation variability, while dust storm frequency would likely increase, affecting air quality across the region.

East Africa (EAF) may face altered Indian Ocean circulation patterns related to AMOC collapse that could disrupt monsoon reliability and affect agricultural productivity across Ethiopia, Kenya and Tanzania. Highland agriculture for 200+ million people depends on monsoon rains (Muema et al., 2023; Thornton and Herrero, 2015; Thornton et al., 2010, 2014; Jones and Thornton, 2009; P K Thornton et al., 2009; Philip K. Thornton et al., 2009) that could be significantly disrupted and major river systems dependent on monsoon precipitation may face disruption (Nooni et al., 2025; Palmer et al., 2023; Richardson et al., 2022; Ficchì et al., 2021). Highland forest and grassland ecosystems could be severely affected and hydroelectric generation severely impacted. Southern Africa (SAF) would likely experience limited direct AMOC impacts, primarily through marginally elevated Southern Hemisphere warming and altered global circulation patterns that may affect regional agriculture and water resources through monsoon teleconnections.

Sea level rise from ice sheet collapse

Ice sheet collapse would accelerate sea level rise rates substantially beyond current projections with the potential for multi-meter rise over centuries (Siahaan et al., 2022; Stokes et al., 2022; Payne et al., 2021; Golledge, 2020; Dutton et al., 2015; Bamber et al., 2009; Dowdeswell, 2006; Alley et al., 2005) that could disproportionately affect low-lying coastal areas (Brown et al., 2018; Nicholls and Cazenave, 2010; Harvey and Nicholls, 2008), with additional impacts from increased storm surge and coastal erosion (Lenton et al., 2023). WAF may face critical threats with cities like Lagos, Accra and Dakar potentially severely threatened. Coastal agricultural areas and river deltas could be flooded, while the Niger Delta oil infrastructure may be severely threatened. The World Bank estimates that erosion, flooding and pollution already cause $3.8 billion in damages annually in just four West African countries (Benin, Côte d'Ivoire, Senegal and Togo), suggesting massive economic vulnerability to larger sea level rise (Croitoru et al., 2019).

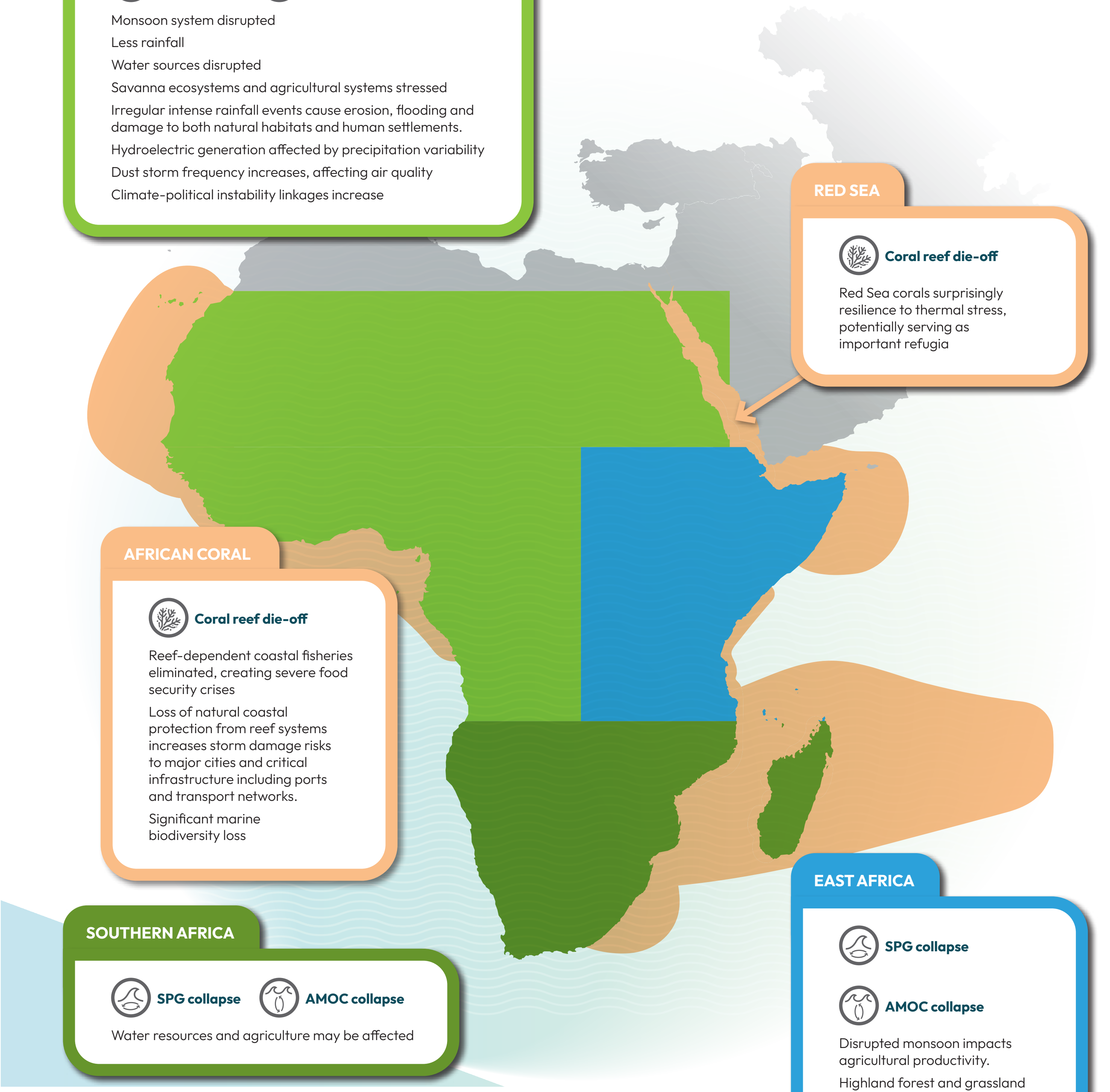
EAF could face major impacts on coastal agricultural areas, with ports like Dar es Salaam and Mombasa potentially threatened, disrupting transport infrastructure. Saltwater intrusion into coastal aquifers may affect water resources, while coastal and marine ecosystems could be altered. SAF may experience coastal agricultural area impacts, with cities like Cape Town and Durban potentially threatened by sea level rise, creating significant infrastructure and economic challenges.

Coral reef die-off

The Fourth Global Coral Bleaching Event, declared in April 2024, has affected 83.8 per cent of the world's coral reef area as of May 2025, with mass bleaching documented in at least 83 countries and territories - the most widespread bleaching event ever recorded (NOAA Coral Reef Watch, 2024, 2025; World Economic Forum, 2025; Goreau and Hayes, 2024; Reimer et al., 2024). This demonstrates that coral reefs have crossed the estimated 1.2°C tipping point threshold and are now in an overshoot state requiring urgent policy action to reduce stressor levels below critical thresholds (Pearce-Kelly et al., 2025).

Mass coral mortality events repeated more than twice per decade give insufficient time for recovery of impacted populations and ecological function (Hughes, Anderson, et al., 2018; Hughes, Kerry, et al., 2018), with repeated bleaching preventing recovery through failure of reproduction, dispersal, recruitment and growth. The potential for significant thermal refugia is increasingly doubtful (Pearce-Kelly et al., 2025; Dixon et al., 2022; Setter et al., 2022), as very few reef areas are predicted to remain below tipping thresholds of all key stressors. Reefs that survive will have different community structure with much less diversity in coral species (Hughes, Kerry, et al., 2018), as the 'reef to rubble' phenomenon causes coral colonies to fragment and transition to rubble (Kai L Kopecky et al., 2023; Kai L. Kopecky et al., 2023; Kenyon, Doropoulos, et al., 2023), representing ecosystem transformation to new states that are difficult to recover from. Recent observations during the latest global bleaching event show greater sensitivity in taxa previously thought resilient (Byrne et al., 2025).

Map 2: Potential impacts of Earth system tipping points on Africa



SAHEL AND WEST AFRICA

SPG collapse **AMOC collapse**

Monsoon system disrupted

Less rainfall

Water sources disrupted

Savanna ecosystems and agricultural systems stressed

Irregular intense rainfall events cause erosion, flooding and damage to both natural habitats and human settlements.

Hydroelectric generation affected by precipitation variability

Dust storm frequency increases, affecting air quality

Climate-political instability linkages increase

RED SEA

Coral reef die-off

Red Sea corals surprisingly resilience to thermal stress, potentially serving as important refugia

AFRICAN CORAL

Coral reef die-off

Reef-dependent coastal fisheries eliminated, creating severe food security crises

Loss of natural coastal protection from reef systems increases storm damage risks to major cities and critical infrastructure including ports and transport networks.

Significant marine biodiversity loss

SOUTHERN AFRICA

SPG collapse **AMOC collapse**

Water resources and agriculture may be affected

EAST AFRICA

SPG collapse

AMOC collapse

Disrupted monsoon impacts agricultural productivity.

Highland forest and grassland ecosystems severely affected

Hydroelectric generation severely impacted

SPG	Subpolar Gyre Overturning
AMOC	Atlantic Meridional Overturning Circulation

WAF, EAF and SAF would all face critical impacts from coral reef collapse, with coastal communities across these regions affected by the loss of reef fisheries that provide essential protein sources for millions (Obura et al., 2022; Hicks et al., 2019). Reef-dependent coastal fisheries would be eliminated, creating severe food security crises, while the loss of natural coastal protection from reef systems would increase storm damage risks to major cities and critical infrastructure including ports and transport networks. WAF's coral systems may collapse with significant biodiversity loss, while EAF and SAF would experience similar patterns of fishery collapse affecting coastal food security (Obura et al., 2022; Cinner et al., 2012). However, coral resilience varies significantly across African waters. While Atlantic and Indian Ocean coral systems face severe vulnerability under current warming trajectories, Red Sea corals have demonstrated surprising resilience to thermal stress, potentially serving as important refugia (Eladawy et al., 2022; Osman et al., 2018; Fine et al., 2013; van Hooidonk et al., 2013). This contrast between vulnerable and resilient coral populations highlights the critical importance of protecting climate-adapted reefs for future ecosystem recovery efforts across the region.

Asia

Major tipping point exposures

Asia faces impacts from monsoon disruption, sea level rise threatening densely populated coasts, permafrost thaw in northern regions, Coral reef die-off in tropical waters, boreal forest shifts and shifting precipitation patterns from global circulation changes.

AMOC collapse and monsoon disruption

AMOC collapse could disrupt global circulation patterns, creating a broad reorganization where the Southern Hemisphere becomes wetter while the Northern Hemisphere becomes drier, potentially affecting both the South Asian and East Asian monsoon systems through altered atmospheric circulation and ocean temperatures (Lenton et al., 2023). These changes reflect fundamental shifts in tropical precipitation zones, with the West African, Indian Summer and East Asian monsoons experiencing shorter wet seasons, longer dry periods and reduced overall rainfall (Ben-Yami et al., 2024; Ben-Yami et al., 2023). Paleoclimate evidence from the Okinawa Trough demonstrates that ITCZ migration significantly modulates East Asian monsoon systems, with southward ITCZ shifts correlating with weakened winter monsoon patterns, providing geological precedent for how AMOC-driven ITCZ changes can affect regional monsoon variability (Zheng et al., 2014).

Pacific circulation undergoes substantial modification as warming south and cooling north of the Equator alters El Niño-Southern Oscillation behavior. ENSO patterns shift eastward with warming signals becoming more geographically confined, while ENSO periods become more regular and predictable, fundamentally changing global weather variability patterns (Williamson et al., 2017)

South Asia (SAS) may face major impacts with South Asian monsoon weakening, potentially affecting regional temperatures and agriculture for 2+ billion people dependent on monsoon systems (Ben-Yami et al., 2024; Rehman et al., 2024; Chandio et al., 2023; Zhao et al., 2023; Wassenburg et al., 2021; Sandeep et al., 2020; Christensen et al., 2019; Amrith, 2016; Mohtadi et al., 2016; Turner and Annamalai, 2012; Lal et al., 2011). Primary water sources for billions of people may be disrupted (Dagdeviren et al., 2021; Amrith, 2016), while urban areas could be severely affected by monsoon variability. All major ecosystems depend on monsoon precipitation patterns and disruption would affect regional ecosystem productivity. Hydroelectric generation and cooling demand are potentially critically impacted, while altered circulation patterns linked to AMOC weakening would stress both terrestrial and marine systems across the region through temperature and precipitation regime changes.

East Asia (EAS) could see limited direct AMOC impacts, though some Pacific teleconnection effects may occur affecting monsoon patterns and agricultural productivity for 1.5+ billion people. Southeast Asia (SEA) may experience major impacts with altered monsoon circulation, potentially affecting regional temperatures and monsoon changes that could affect rice production and other agriculture, threatening food security for 600+ million people (Zhang et al., 2022; Loo et al., 2015; Buckley et al., 2014; Redfern et al., 2012; Wassmann et al., 2009). North Asia (NAS), West Asia (WAS), Central Asia (CAS) and the Tibetan Plateau (TIB) would likely experience limited direct impacts from AMOC collapse, primarily through teleconnections and altered global circulation patterns.

Sea level rise from ice sheet collapse

Long-term multi-meter sea level rise (Siahaan et al., 2022; Stokes et al., 2022; Payne et al., 2021; Golledge, 2020; Dutton et al., 2015; Bamber et al., 2009; Dowdeswell, 2006; Alley et al., 2005) could have severe impacts on Asian coastlines due to high population density in low-lying areas and extensive delta regions vulnerable to inundation (Nicholls and Kebede, 2012; Nicholls and Cazenave, 2010; Harvey and Nicholls, 2008; Nicholls and Tol, 2006). EAS may face critical threats with research indicating 78 million Chinese live in low-elevation cities vulnerable to sea level rise, while major cities, including Shanghai and other megacities could be severely threatened (WEF, 2025; Ao et al., 2024). The Yangtze Delta and coastal ecosystems may be lost, with coastal energy infrastructure potentially severely threatened.

SAS could experience critical impacts with research indicating that even a 0.5-meter rise would result in loss of 11 per cent of Bangladesh's land area, potentially displacing up to 15 million people and fouling drinking water due to salinity intrusion (Islam et al., 2025; WEF, 2025; Becker et al., 2020; Hossain et al., 2020; Shammi et al., 2019; Bose, 2013). The Ganges-Brahmaputra Delta, where 90 per cent of Bangladesh's rice production occurs, may be severely affected. Major cities, including Mumbai and Dhaka, could be severely threatened, while the Sundarbans and other delta ecosystems may be lost. SEA may face critical threats with the Mekong Delta (50 per cent of Vietnam's rice production) potentially severely affected and major cities, including Bangkok, Ho Chi Minh City and Jakarta could be threatened.

Coral reef die-off

SEA and the Coral Triangle region may face devastating impacts, as this area contains the highest marine biodiversity globally and supports over half a billion people for their livelihoods and over a quarter of marine species. Complete coral collapse could eliminate critical coastal protection and fisheries supporting 150+ million people in the region, with economic losses potentially exceeding $75 billion from tourism and fisheries collapse (Hughes et al., 2017). The simplification of reef structures will have adverse impacts on the thousands of species that rely on the complex three-dimensional structure of reefs, fundamentally altering the ecosystem services reefs currently provide.

EAS could face major impacts in southern regions with reef-dependent fisheries potentially lost in the South China Sea and loss of coastal protection for southern coastal cities. SAS may experience critical impacts with massive coastal populations dependent on reef fisheries for protein and loss of coastal protection that could increase storm surge risk for densely populated coasts. WAS could face critical impacts as Red Sea and Persian Gulf coral systems are among the most biodiverse globally, with reef-dependent fisheries potentially lost and major food security impacts for Gulf states.

Map 3: Potential impacts of Earth system tipping points on Asia

Sea level rise from ice sheet collapse

Severe threats of inundation in densely populated areas

Major cities severely threatened: Shanghai Bangkok, Ho Chi Minh City, and Jakarta

78 million Chinese live in low-elevation cities vulnerable to sea level rise

With just 0.5m sea level rise 11% of Bangladesh's land area lost, displacing up to 15 million people, and fouling drinking water due to salinity intrusion

Delta Ecosystems Lost: The Sundarbans, Yangtze and Mekong Deltas

Severe agricultural impacts: Ganges-Brahmaputra Delta produces 90% of Bangladesh's rice and Mekong Delta produces 50% of Vietnam's rice.

SOUTH ASIA

AMOC collapse

Monsoon weakens affecting regional temperatures and agriculture for 2+ billion people

Urban areas severely affected by monsoon variability

Hydroelectric generation and cooling demand critically impacted

SOUTH EAST ASIA

AMOC collapse

Altered monsoon circulation affects regional temperature

Rice production and other agriculture impacted, threatening food security for 600+ million people

THE CORAL TRIANGLE

Coral reef die-off

The Coral Triangle contains the highest marine biodiversity globally and supports over half a billion people for their livelihoods and over a quarter of marine species.

Collapse threatens critical coastal protection and fisheries supporting 150+ million people in the region, with economic losses potentially exceeding $75 billion from tourism and fisheries collapse.

SPG	Subpolar Gyre Overturning
AMOC	Atlantic Meridional Overturning Circulation

Boreal forest shifts

NAS could face critical impacts with albedo changes documented and with stronger warming in the boreal region in Russia than in the global mean (Schaphoff et al., 2016) and extensive wildfire smoke. Massive forest-agriculture potential may exist but wildfire risks and soil constraints could limit development (Vallotton and Unc, 2024; Eckdahl et al., 2023; Altdorff et al., 2021; Walker et al., 2019). Critical major watershed changes across Siberia may occur, with extensive wildfire risks to Siberian infrastructure and transportation networks. Massive Siberian boreal ecosystem transformation, affecting the world's largest terrestrial carbon storehouse, could have disproportionate global climate impacts (Fu et al., 2023; Bradshaw and Warkentin, 2015; Gauthier et al., 2015).

EAS may experience impacts with high-altitude or northeastern boreal forest changes and regional warming, while forest-agriculture transitions and watershed changes could occur in forested regions. SAS, SEA and WAS would likely experience limited direct impacts from boreal changes, primarily through global carbon feedback effects.

Permafrost thaw

NAS would likely experience the most critical impacts, with warming amplification documented (Schaphoff et al., 2016). Major hydrological changes across Siberia may include thermokarst lake formation and drainage, while extensive infrastructure damage across Siberian development could affect cities, roads and railways. Oil and gas pipeline infrastructure may be severely threatened, with extraction facilities potentially damaged.

CAS and TIB could face major impacts from high-altitude permafrost thaw, which is projected to degrade by up to 86 per cent across the Tibetan Plateau during 2020–2100, reducing surface water runoff and intensifying subsurface storage - thus exacerbating water shortages, particularly during drought seasons (T. Wang et al., 2023). Permafrost's role in regulating soil moisture and groundwater–surface water dynamics is critical to the hydrology of Asia's major river headwaters, affecting water availability for billions downstream (Gao et al., 2021). Additionally, thaw-driven changes in groundwater transit times alter dissolved organic carbon processing in headwater regions, impacting biogeochemistry and water quality (Sun et al., 2021). In the Yangtze source region, changes in freeze–thaw cycles are shifting seasonal runoff and sediment patterns, posing risks to water quality and river-dependent systems (Li et al., 2023). Mountain agriculture and pastoral activities are particularly vulnerable to these changes in soil stability and water availability. Permafrost thaw also poses broader environmental hazards: as the frozen ground loses stability, legacy industrial contaminants—including heavy metals and hydrocarbons—at thousands of Arctic sites may be released into ecosystems (Langer et al., 2023). SAS, SEA and WAS are likely to experience more limited direct impacts from permafrost thaw, though indirect consequences through hydrological changes and global feedbacks remain important.

Amazon dieback

Recent climate network analysis reveals significant teleconnections between Amazon rainforest changes and Asian climate systems, with the Amazon exhibiting strong negative correlations with Tibetan Plateau snow cover through a robust atmospheric pathway that propagates changes in approximately 15 days (Liu et al., 2023). The Amazon's role extends beyond regional food systems through atmospheric teleconnections that synchronize climate extremes globally, with precipitation-related indicators showing negative correlations (-0.54 to -0.20) between Amazon changes and the Tibetan Plateau, potentially affecting water resources for billions dependent on Asian river systems fed by Tibetan glaciers and snow. Amazon dieback creates cascading hydrological impacts through disrupted atmospheric moisture transport, with the identified teleconnection pathway suggesting that Amazon forest loss could affect snow cover and water storage in the "Third Pole," impacting water security for populations across South and East Asia dependent on glacier-fed river systems, while temperature-related indicators show correlations as high as 0.92 between the Amazon and Tibetan Plateau regions (Liu et al., 2023).

Mountain glaciers

Mountain glacier tipping dynamics will lead to glacial lake outburst flood (GLOF) hazards across South Asia (SAS), the Tibetan Plateau (TIB), and Central Asia (CAS), where accelerating ice loss destabilizes thousands of moraine-dammed lake systems. SAS contains over 15,000 glacial lakes with more than 2,000 classified as potentially dangerous due to rapid glacier retreat rates of 10-60 meters per year (Veh et al., 2020; Bajracharya and Mool, 2009), while TIB's 47,000+ glacial lakes represent the largest global concentration of GLOF risks, with GLOF frequency exhibiting a significant increasing trend since 1980 and intensified activity in southeastern Tibet (T. Zhang et al., 2023). CAS mountain ranges contain numerous unstable glacial lakes posing immediate threats to downstream communities (Petrov et al., 2017). Historical catastrophes including SAS's 2013 Kedarnath floods, the 2016 Gongbatongsha GLOF in TIB that destroyed hydropower infrastructure 40 km downstream, and CAS's 2002 Dasht lake outburst demonstrate how glacier system collapse can trigger civilizational-scale impacts (D. Zhang et al., 2023; Allen et al., 2016). Crossing glacier tipping thresholds creates irreversible GLOF risk increases as new lakes form faster than natural drainage systems can establish stable outlets, with approximately large swathes of land at risk from potential GLOFs across these regions, threatening water security for billions of people downstream and infrastructure investments worth hundreds of billions of dollars (T. Zhang et al., 2023; Immerzeel et al., 2020).

North America

Major tipping point exposures

North America faces cooling from AMOC collapse, permafrost thaw in northern regions, changing precipitation patterns affecting agriculture, sea level rise impacts on extensive coastlines, boreal forest ecosystem shifts and monsoon disruption.

AMOC collapse

AMOC collapse could cool the North Atlantic region while disrupting storm tracks and altering precipitation patterns across North America through changes in atmospheric circulation patterns (Bellomo and Mehling, 2024; Jackson et al., 2023; Woollings et al., 2012). The sea-ice amplification mechanisms and storm track intensification patterns described for Europe would similarly affect Eastern North America.

Eastern North America (ENA) may experience regional cooling (1-3°C) along the Atlantic coast with increased temperature variability that could affect agriculture and energy systems. Following the same storm intensification patterns seen in Europe, Eastern North America would experience altered storm tracks and increased coastal vulnerability. Accelerated coastal flooding may threaten Boston, New York, Philadelphia, Washington DC and Miami with 20-30cm additional sea level rise beyond the global mean documented along the eastern seaboard (Goddard et al., 2015; Ezer et al., 2013). The disrupted jet stream would create more frequent blocking patterns similar to those affecting Britain, leading to prolonged cold snaps and altered precipitation timing.

Marine ecosystems from Florida to Maine would face fundamental restructuring as a weakening of the AMOC alters water temperatures and nutrient distribution. Modelling studies suggest that AMOC disruption may collapse North Atlantic plankton stocks by more than 50 per cent, substantially lowering export productivity (Schmittner, 2005). The strongest decreases in marine biomass are found in the North Atlantic Ocean with decreases as large as 30 per cent over the 21st century, while species important for fisheries would decrease locally up to 17 per cent, affecting both ecosystem functioning and the services these ecosystems provide (Boot et al., 2025). These compound effects would overwhelm existing coastal defense infrastructure designed for historical storm patterns, while offshore wind patterns potentially changing and reduced cooling demand but increased heating demand.

Western North America (WNA) would likely experience minimal direct temperature impacts, with slight cooling in the Pacific Northwest, though indirect impacts through altered Pacific climate patterns may occur. Central North America (CNA) could face limited direct temperature impacts, with some cooling in the Great Lakes region, while altered precipitation patterns may affect Midwest agriculture and Great Lakes water levels could be potentially affected by regional climate changes. Modelling studies suggest that AMOC weakening and the associated southward displacement of the Intertropical Convergence Zone (ITCZ) may weaken the North American Monsoon system (Ma et al., 2024; Chemison et al., 2022; Parsons et al., 2014). Reduced monsoon rainfall would affect northern Mexico and the U.S. Southwest directly, while also altering teleconnections into the Great Plains. Such shifts could exacerbate drought risk in the Midwestern grain belt, compounding agricultural disruptions already expected from altered storm tracks and increased climate variability.

Alaska/N.W. Canada (ALA) may experience reduced Arctic warming due to decreased northward heat transport, with Arctic Ocean circulation changes that could affect sea ice formation and alter freshwater balance.

Subpolar gyre

Collapse of convection in the North Atlantic subpolar gyre would fundamentally alter regional oceanography with cascading effects on food security, economic stability and infrastructure resilience. The system is vulnerable to interactions with AMOC weakening, creating compound circulation failures. ENA could face major food security impacts through collapse of Atlantic fisheries and altered agricultural conditions from changed coastal climate. Critical infrastructure along the Atlantic seaboard may face increased extreme weather risks from altered storm patterns. CGI may experience severe economic impacts from fisheries collapse in the Grand Banks and other critical areas supporting regional economies. National security implications include resource conflicts over disrupted marine resources and potential displacement from affected coastal communities.

Permafrost thaw

ALA would likely experience amplified Arctic warming enhanced by global permafrost-carbon feedback and regional Arctic amplification (Ward Jones et al., 2022), with extensive infrastructure damage including buildings, roads and pipelines damaged by ground instability (Hjort et al., 2022), with documented loss of life (Gibson et al., 2021; Miner et al., 2021). Climate-driven expansion of northern agriculture must consider permafrost interactions and cultivation risks (Ward Jones et al., 2022). Traditional food systems face disruption as climate-driven changes affect the ability to sustain natural diets and store food, impacting the livelihood and health of Arctic communities, with ice cellars experiencing thermal instability under warming conditions (Maslakov et al., 2022). Ecosystem changes - such as shifts in wetland formation and species habitat shifts - could be possible (Jin et al., 2021; Chin et al., 2016). Emergent biogeochemical risks include the release of biological, chemical and radioactive materials sequestered in permafrost for tens to hundreds of thousands of years, potentially disrupting ecosystem function and endangering human health (Miner et al., 2021). Mercury releases from thawing permafrost could reach levels comparable to current global anthropogenic emissions by 2200, with fish mercury concentrations potentially exceeding EPA guidelines by 2050 under high emissions scenarios (Schaefer et al., 2020).

Eastern Canada/Greenland/Iceland (CGI) could face major impacts with regional warming amplification from carbon feedback and buildings and infrastructure in permafrost zones potentially severely damaged. Arctic coastal erosion is projected to increase dramatically, with erosion rates doubling to tripling by 2100, accelerating coastal retreat through the combined effects of permafrost thaw, sea-level rise and increased wave action (Nielsen et al., 2022). This coastal permafrost thaw contributes additional complications as coastal erosion releases 6.9-17.2 TgC annually by century's end, with the link between coastal permafrost thaw, sea-level rise and coastal erosion creating accelerating feedback loops (Creel et al., 2024; Z. Wang et al., 2023; Nielsen et al., 2022). WNA, CNA and ENA would likely experience limited direct impacts from permafrost thaw, primarily through global warming amplification from Arctic permafrost-carbon feedback effects.

Sea level rise from ice sheet collapse

Long-term multi-meter sea level rise from ice sheet collapse (Siahaan et al., 2022; Stokes et al., 2022; Payne et al., 2021; Golledge, 2020; Dutton et al., 2015; Bamber et al., 2009; Dowdeswell, 2006; Alley et al., 2005) could affect all coastal regions, with regional variations in impacts due to land subsidence, ocean currents and local factors (Lenton et al., 2023). ENA may face critical threats with major US coastal cities including Miami, New Orleans and New York potentially facing severe flooding from multi-meter sea level rise. Research indicates that in the United States, where almost 40 per cent of people live in coastal communities, 4.2 million people could face displacement from 3 feet of sea level rise, while up to 13.1 million could face displacement from 6 feet of permanent inundation by 2100 (Hauer et al., 2016). The Chesapeake Bay, Delaware Bay and Everglades could be lost, while coastal nuclear plants, refineries and LNG terminals may be at risk.

WNA could face critical threats with major coastal cities (Vancouver, Seattle, San Francisco, Los Angeles) potentially severely threatened. Coastal agricultural valleys (Central Valley, Fraser Valley) may be severely impacted by saltwater intrusion, while coastal wetland and estuary loss could occur and coastal nuclear plants and refineries may be at risk. CNA would likely experience limited direct impacts from sea level rise due to its inland location. ALA may face major impacts with coastal infrastructure threatened by sea level rise, while Arctic marine ecosystems could be fundamentally altered.

Boreal forest shifts

ALA may experience critical impacts from boreal forest shifts, with albedo changes potentially causing regional warming amplification and wildfire smoke health impacts. Major watershed changes and wildfire impacts on water quality and supply could occur, while extreme wildfire risk to infrastructure is already documented, including spruce beetle infrastructure damage (~0.5 million hectares affected since 2016). Massive ecosystem shifts from boreal to mixed forest/grassland may affect species habitat, with critical wildfire risks to power transmission and oil pipeline infrastructure creating energy disruption.

CGI could face major impacts with albedo changes and wildfire smoke impacts on air quality. Forest-agriculture transitions may occur with new agricultural potential but wildfire risks, while watershed changes from forest transitions and fire impacts on water systems could affect infrastructure. Critical boreal forest ecosystem shifts and northward treeline expansion may occur, with major wildfire risks to energy infrastructure and changes in biomass energy potential. WNA may experience major impacts with enhanced wildfire activity documented and smoke health impacts, while severe wildfire risks to infrastructure are already documented and critical mountain forest ecosystem shifts and species migrations could occur. CNA and ENA would likely experience limited direct boreal forest impacts, though ENA may face major impacts with southern boreal forest changes and enhanced fire activity affecting forest-agriculture transitions in northern regions.

Map 4: Potential impacts of Earth system tipping points on North America

ALASKA, CANADA, GREENLAND, ICELAND

Boreal forest shifts

Albedo changes potentially causes regional warming amplification and wildfire smoke health impacts

Watershed changes and wildfire impacts water quality and supply

Wildfire risk to infrastructure creating energy disruption

Health impacts from smoke inhalation associated with wildfire

CANADA, GREENLAND, ICELAND

SPG collapse

Regional oceanography fundamentally altered.

Interactions with AMOC weakening compound risks.

Major food security impacts through collapse of Atlantic fisheries and altered agricultural conditions from changed coastal climate

Critical infrastructure risks from increased extreme weather due to altered storm patterns.

Severe economic impacts from fisheries collapse.

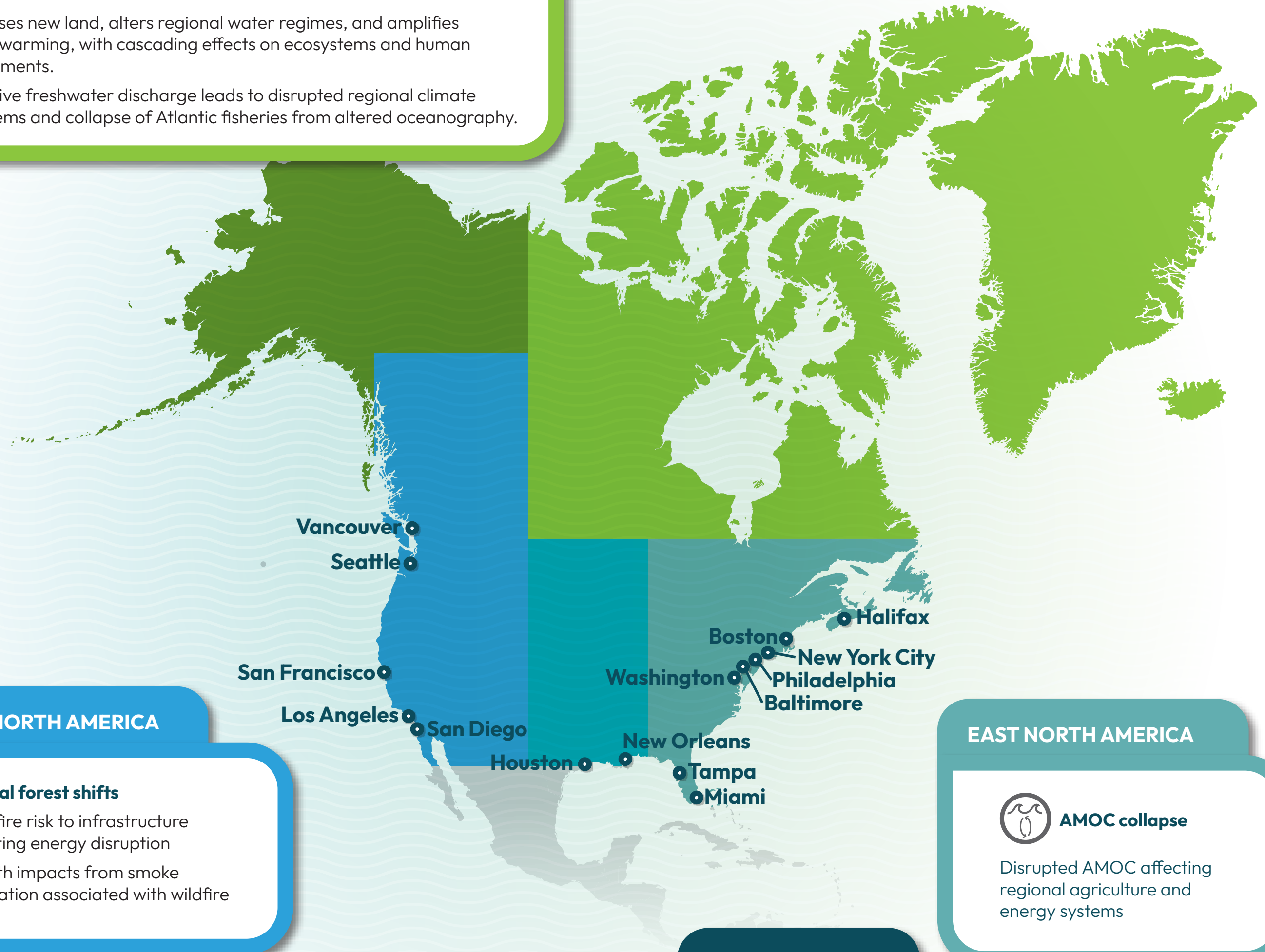
National security implications - conflicts over disrupted marine resources and potential displacement from affected coastal communities.

CANADA, GREENLAND, ICELAND

Ice sheet and glacier collapse

Exposes new land, alters regional water regimes, and amplifies local warming, with cascading effects on ecosystems and human settlements.

Massive freshwater discharge leads to disrupted regional climate systems and collapse of Atlantic fisheries from altered oceanography.



WEST NORTH AMERICA

Boreal forest shifts

Wildfire risk to infrastructure creating energy disruption

Health impacts from smoke inhalation associated with wildfire

EAST NORTH AMERICA

AMOC collapse

Disrupted AMOC affecting regional agriculture and energy systems

COASTAL CITIES

Ice sheet and glacier collapse

Threats to coastal cities and critical infrastructure from long-term multi-meter sea level rise

SPG	Subpolar Gyre Overturning
AMOC	Atlantic Meridional Overturning Circulation

- ● Alaska, Northwest Canada
- ● Canada, Greenland, Iceland
- ● West North America
- ● East North America
- ● Central North America

Ice sheet and glacier collapse

Beyond global sea level contribution, Greenland Ice Sheet collapse would create massive freshwater discharge fundamentally altering North Atlantic circulation. CGI could face critical impacts with disrupted regional climate systems and collapse of Atlantic fisheries from altered oceanography. ENA may experience major long-term threats to coastal cities and critical infrastructure from long-term multi-meter sea level rise, while immediate impacts could include disrupted AMOC affecting regional agriculture and energy systems. WNA and CNA would face primarily global sea level impacts on coastal infrastructure.

Ice sheet and glacier loss exposes new land, alters regional water regimes and amplifies local warming, with cascading effects on ecosystems and human settlements. Retreating glaciers, such as those in CGI, expose previously ice-covered land, altering freshwater and coastal water regimes while amplifying local warming through feedbacks like ice-albedo and melt-elevation effects (Marshall, 2021). Calving events from Greenland's marine-terminating glaciers release large icebergs into fjords and coastal waters, forming "armadas" that disrupt marine circulation (Moon et al., 2015), coastal habitats and local fisheries, while also representing a major component of ice mass loss. At the same time, the removal of ice mass causes isostatic rebound (Paxman et al., 2022), reshaping land surfaces and modifying terrestrial and freshwater systems, which has cascading effects on local communities and ecosystems.

WNA mountain glacier retreat creates GLOF and landslide risks as rapid warming pushes mountain ice systems beyond stability thresholds (Coe et al., 2017). Alaska's accelerating glacier retreat has created potentially dangerous glacial lakes, with the 2015 Taan Fjord event demonstrating how glacier destabilization can trigger tsunamis (Higman et al., 2018). Washington's Cascade Range glacier retreat creates new lake formations that could threaten Seattle's water supply infrastructure (Riedel et al., 2015), while California's Sierra Nevada exhibits similar patterns affecting water security for millions (Beltran-Peña et al., 2025). Mining infrastructure, hydroelectric facilities, and tourism operations face increasing vulnerability as glacier systems cross critical stability thresholds.

Central and South America

Major tipping point exposures

The region faces severe impacts from Amazon rainforest dieback, changing precipitation patterns from global circulation disruptions, sea level rise affecting extensive coastlines, Coral reef die-off, AMOC effects and monsoon changes. The Amazon region's role in global climate regulation makes its collapse particularly significant.

Amazon rainforest dieback

Amazon dieback relates to the disruption of close coupling between the land ecosystem and atmosphere, with the rainforest normally maintaining precipitation levels through rainfall recycling (Lenton et al., 2023). In the Amazon, around 30 per cent of the precipitating water has been evaporated within the region beforehand.

Amazon (AMZ) could face the most critical impacts with economic damages potentially between $957bn and $3,589bn over 30 years, mainly from changes in ecosystem services provision, compared to Gross Brazilian Amazon Product of approximately $150bn per year (Lapola et al., 2018). Amazon dieback would directly affect 30 million people living in the region, with Indigenous and traditional communities facing the most severe consequences as their livelihoods, cultural traditions and territorial integrity depend entirely on forest ecological stability. Since 2000, severe flood events now occur every four years instead of once every two decades, while prolonged droughts disrupt regional hydrological cycles and negatively impact food and water security (Jose A. Marengo et al., 2024; Jose Antonio Marengo et al., 2024; Souza et al., 2024).

Structural inequalities including poverty, ethnic marginalization, historical land dispossession and unequal access to adaptation resources compound these vulnerabilities. As traditional knowledge systems, ecosystems and forest-based livelihoods deteriorate, entire communities may lose their ability to sustain themselves, creating self-reinforcing cycles of socio-ecological vulnerability that drive forced displacement and migration (Quishpe et al., 2025; Pinho et al., 2015).

Regional warming from reduced evapotranspiration and increased fires may occur, while loss of precipitation recycling (25-35 per cent of rainfall) could alter hydrology (Sanchez-Martinez et al., 2025; Baker and Spracklen, 2022; Rocha et al., 2018; Zemp et al., 2017). Amazon deforestation creates contrasting seasonal precipitation effects: increased precipitation during wet seasons (+0.96 mm per month per percentage point forest loss) due to enhanced mesoscale circulation, but decreased precipitation during dry seasons due to reduced evapotranspiration, with effects weakening beyond 60 km from deforested regions (Qin et al., 2025). Deforestation also causes local temperature increases of 1-3°C, with effects extending to surrounding areas up to 60 km away (Butt et al., 2023). Wildfire risks may reduce river navigability, cause transportation disruption and potentially lead to biodiversity loss. Millions of Indigenous peoples and traditional communities could face collapse of forest-dependent livelihoods, while reduced hydroelectric potential and biomass energy disruption may occur alongside wildfire risks to infrastructure.

Southeast South America (SSA) faces the most severe downstream impacts as the La Plata basin receives approximately 24 per cent of its precipitation from Amazon moisture recycling (Beveridge et al., 2024), with cascading moisture recycling contributing 17-18 per cent to total precipitation over the La Plata basin (Z. Wang et al., 2023). Complete Amazon deforestation could reduce La Plata basin precipitation by 0.5 mm per day and decrease regional moisture transport by 22 per cent (Ruv Lemes et al., 2023). Amazon forest loss disrupts atmospheric moisture transport that provides the majority of precipitation to agricultural systems across Argentina, southern Brazil, Paraguay and Uruguay, creating catastrophic food security implications that extend far beyond the forest boundaries. With 40 per cent of the Amazon deforested, local annual precipitation would be reduced by 5–10 per cent in the Amazon basin, but cutting atmospheric moisture transport due to deforestation in climate-critical regions may induce a self-amplified drying process which would influence moisture arriving at the La Plata basin (Marengo et al., 2018).

Complete savannization combined with global warming would increase dry season length by 69 per cent and cause mean annual rainfall reduction of 44 per cent when averaged over the Amazon basin (Bottino et al., 2024). This near-complete dependence on Amazon moisture recycling makes SSA exceptionally vulnerable to agricultural collapse, water resource depletion and hydroelectric disruption.

West Coast South America (WSA) could face major impacts with altered precipitation patterns reaching Andean regions, as regions that depend on moisture recycled from the Amazon include the western flanks of the Andes Mountains (up to ~50 per cent of precipitation from Amazon moisture recycling) (Beveridge et al., 2024). The Amazon generates around half of its own rainfall by recycling moisture up to 6 times as air masses move from the Atlantic Ocean in the east across the basin to the west, with aerial rivers forming "flying rivers" that contribute to precipitation patterns within and beyond basin boundaries, particularly important for the tropical Andes and Western Amazon (Beveridge et al., 2024). Changed water availability from precipitation shifts may affect highland water resources that support millions across Peru, Ecuador and Colombia, with potential impacts on infrastructure and energy sectors.

Northeast Brazil (NEB) may experience impacts from Amazon precipitation changes, though the region faces multiple drought vulnerabilities. The semiarid lands of Northeast Brazil represent one of the most densely populated regions of the country, with rainfall variability together with land degradation creating vulnerability in rural areas, as most agriculture in this region is rainfed and deficient rainfall leads to severe drought impacts (Marengo et al., 2022) . The Central-Northeast region is among those most affected by multiple and widespread droughts, with drought characteristics varying significantly across Brazil (Gesualdo et al., 2024) . Amazon dieback may compound existing vulnerabilities in drought-prone regions already experiencing water scarcity, potentially affecting water infrastructure and hydroelectric potential, though the specific magnitude of Amazon moisture dependence for NEB requires further research.

Central America/Mexico (CAM) may face impacts through disrupted aerial rivers, as Amazon moisture transport affects precipitation patterns northward from the Amazon basin through atmospheric circulation pathways (Arraut et al., 2012).

AMOC collapse

AMOC collapse could alter global circulation patterns, affecting precipitation patterns across South America through changes in Atlantic circulation and atmospheric patterns (DiNezio et al., 2025; Steinert et al., 2025). The South American monsoon may intensify, particularly over southern Amazon regions (Ben-Yami et al., 2024; Ben-Yami et al., 2023). Central America/Mexico (CAM) may face major impacts with a southward shift of tropical rain belt potentially increasing heat stress and 10-30 per cent rainfall reduction during the growing season (Cerato et al., 2025) that could affect coffee, sugar and banana production (Varma and Bebber, 2019; Baez-Gonzalez et al., 2018; Ovalle-Rivera et al., 2015). Reduced wet season precipitation may affect water security for 50+ million people, while hurricane track changes could affect infrastructure planning and tropical forest stress from reduced precipitation may occur alongside mangrove systems affected by circulation changes.

AMZ could experience complex impacts with some forest areas potentially benefiting from increased precipitation while others may be stressed by flooding. Enhanced precipitation could benefit some agriculture but create flooding risks, while increased water availability may occur with altered seasonal patterns and flooding risks to infrastructure from enhanced precipitation (Gesualdo et al., 2024). NEB may face major impacts with altered precipitation patterns affecting drought-prone regions and increased drought risk in already water-stressed areas (Akabane et al., 2024; Nian et al., 2023), while water infrastructure could face stress and drought impacts on urban systems may occur.

SSA could see enhanced South American monsoon affecting heat patterns, with increased water availability in La Plata basin accompanied by flooding risks from enhanced precipitation (Chug et al., 2022; Parsons et al., 2014). However, La Plata basin precipitation is significantly influenced by Amazon moisture recycling through cascading moisture transport, with approximately 24-29 per cent of La Plata basin precipitation during the wet season originating from Amazon evapotranspiration (Zemp et al., 2014). This moisture recycling system involves evapotranspiration from Amazon forests that is transported southward and can be recycled multiple times along its trajectory before reaching the La Plata region (Chug et al., 2022). Enhanced vegetation growth may occur in some areas with altered flood plain ecosystems, while increased hydroelectric potential could exist alongside altered cooling/heating demands.

The South American monsoon would show opposite behavior to other monsoon systems, with rainfall increasing over the southern Amazon region in contrast to the drying experienced elsewhere (Ben Yami et al., 2024). This enhanced precipitation could benefit some agriculture but create flooding risks in areas not adapted to increased rainfall (Nian et al., 2023).

Shifts in the Intertropical Convergence Zone would shift the locations of prime productivity in the equatorial rainforests, as AMOC weakening affects tropical Atlantic sea-surface temperature patterns that influence the latitudinal position of the ITCZ and thus moisture inflow to South America (Boot et al., 2024; Ciemer et al., 2021). The altered precipitation patterns would affect both forest ecosystem composition and water availability, with complex implications for the millions of people dependent on Amazonian water and forest resources, as the region serves as a critical moisture source for continental precipitation through the Andes-Amazon-Atlantic pathway (DiNezio et al., 2025; Beveridge et al., 2024).

Sea level rise from ice sheet collapse

Long-term multi-meter sea level rise (Siahaan et al., 2022; Stokes et al., 2022; Payne et al., 2021; Golledge, 2020; Dutton et al., 2015; Bamber et al., 2009; Dowdeswell, 2006; Alley et al., 2005) could inundate coastal areas, with additional impacts from increased storm surge and saltwater intrusion into coastal aquifers and agricultural areas (Lenton et al., 2023). In CAM major cities (Veracruz, Cancun) and ports potentially may be severely threatened, while coastal agricultural plains could be flooded (Su et al., 2025; Schernewski et al., 2023; Tarolli et al., 2023; Bosserelle et al., 2022; Griggs and Reguero, 2021) and mangrove systems lost (Hülsen et al., 2025; Gilman et al., 2008). Major impact on coastal energy infrastructure may occur. A concrete example of energy infrastructure vulnerable to sea level rise in Central America is the Belize Coastal Road, which is a vital transportation link for energy distribution and is highly susceptible to inundation from even modest sea-level rise and associated storm surges, potentially disrupting power delivery to remote areas of the country (Nagy et al., 2019).

AMZ could experience major impacts on Amazon delta agricultural areas, with saltwater intrusion into the Amazon and Manaus deltas and the delta infrastructure potentially threatened. The critical Amazon delta ecosystem could be fundamentally altered, with major delta energy infrastructure at risk. NEB may face critical threats with major coastal cities (Recife, Salvador, Fortaleza) potentially severely threatened, while coastal agricultural areas could be flooded and coastal Atlantic forest remnants and mangroves lost.

WSA and SSA could face critical threats with major cities including Lima, Rio de Janeiro, Buenos Aires and Montevideo potentially facing flooding and saltwater intrusion (Su et al., 2025; Schernewski et al., 2023; Tarolli et al., 2023; Bosserelle et al., 2022; Griggs and Reguero, 2021) . Research indicates that 3 million people across Latin America and the Caribbean will be exposed to flooding from 0.43 meters of relative sea-level rise by 2100 under the RCP4.5 scenario, while over 4 million people will be exposed under the RCP8.5 scenario with 0.84 meters of sea level rise (Hauer et al., 2016; Reguero et al., 2015). Built capital valued at 334 billion USD is currently situated at elevations below the 100-year extreme sea level, with projections showing affected built capital could increase to 1,500–2,000 billion USD under future sea level rise scenarios (Reguero et al., 2015). Coastal agricultural areas may face saltwater intrusion affecting food production (Su et al., 2025; Tarolli et al., 2023).

Map 5: Potential impacts of Amazon dieback tipping point on South America

NORTHEAST BRAZIL (SEMIARID REGION)

Rainfall variability + land degradation = high drought vulnerability.

Amazon dieback may worsen water scarcity, drought impacts, and hydroelectric potential.

AMAZON BASIN

Rainforest recycles ~30% of rainfall; dieback disrupts precipitation, hydrology, and ecosystem services.

Economic damage: $957 bn–$3,589 bn over 30 years vs. ~$150 bn/year Gross Amazon Product.

30 million people affected, especially Indigenous and traditional communities.

Increased floods (every 4 yrs) and prolonged droughts since 2000.

Structural inequalities worsen socio-ecological vulnerability; forest-dependent livelihoods collapse.

Higher wildfire risk, reduced hydroelectric potential, and regional warming.

WEST COAST SOUTH AMERICA (ANDES & WESTERN AMAZON)

Amazon contributes ~50% of rainfall via “flying rivers.”

Altered precipitation impacts highland water resources, infrastructure, energy, and millions in Peru, Ecuador, Colombia.

SOUTHEAST SOUTH AMERICA (LA PLATA BASIN)

24% of precipitation depends on Amazon moisture; 17–18% from cascading moisture recycling.

Deforestation → reduced rainfall (5–10%) → agricultural collapse, water scarcity, hydroelectric disruption.

Highly vulnerable due to dependence on Amazon “flying rivers.”

Coral reef die-off

CAM could face critical impacts with the Caribbean (CAR) experiencing the most severe regional bleaching in history during 2023-2024, with Jamaica recording the highest sea surface temperature anomalies globally among reef systems (Goreau and Hayes, 2024). More than 90 per cent of hard corals bleached in some locations, with widespread mortality following. Heat stress in coastal communities from loss of reef fisheries income and loss of reef-dependent coastal fisheries affects food security for millions. Caribbean reefs generate approximately $8-10 billion annually through fisheries, tourism and shoreline protection, supporting over 15 per cent of GDP in several island nations (Pearce-Kelly et al., 2025). Critical loss of coastal protection from the Mesoamerican Reef system may increase hurricane damage, as healthy reefs significantly reduce wave energy (Guannel et al., 2016), providing essential coastal protection in this cyclone-exposed region. This second-largest barrier reef system globally potentially faces collapse with devastating impacts on the thousands of species that rely on complex three-dimensional reef architecture.

NEB may experience major impacts with coastal communities potentially affected by loss of reef fisheries and reef-dependent coastal fisheries lost, affecting protein sources. Major reduced coastal protection from reef systems could occur, with critical Brazilian reef systems collapse and endemic species loss as the only South Atlantic reef system. WSA and SSA have limited coral reef presence and so face minor impacts.

Mountain glacier

Tropical Andean glacier tipping creates acute GLOF risks as rapid ice mass loss destabilizes hundreds of moraine-dammed lakes (Somos-Valenzuela et al., 2016). Peru's Cordillera Blanca exemplifies how crossing glacier retreat thresholds triggers cascading lake instability (Emmer et al., 2020; Vilímek et al., 2005). Historical GLOF events such as the 1941 Huaraz disaster demonstrate how glacier system collapse can trigger society-scale impacts (Carey, 2005). Current glacier retreat rates of 30-50 meters annually are creating new unstable lakes while expanding existing ones beyond critical volume thresholds (Rabatel et al., 2013). The Quelccaya Ice Cap and other tropical glaciers face complete disappearance within decades, fundamentally altering regional hydrology and GLOF risk patterns (Thompson et al., 2013). Economic damages from major GLOF events can exceed GDP for affected regions, while upstream glacier tipping threatens water security for Lima's 10+ million residents (Bury et al., 2011).

Australasia

Major tipping point exposures

Australasia faces coral reef die-off around extensive coastlines, sea level rise impacts, changing precipitation patterns from altered global circulation, ecosystem shifts from multiple global changes and monsoon disruption effects.

Coral reef die-off

North Australia (NAU) could face critical impacts with the Great Barrier Reef experiencing catastrophic bleaching, with the Coral Sea region recording its warmest January-March temperatures in 400 years (Henley et al., 2024). The 'reef to rubble' phenomenon - where coral colonies fragment and transition to rubble (Kai L Kopecky et al., 2023; Kenyon, Doropoulos, et al., 2023; Kenyon, Harris, et al., 2023) - represents ecosystem transformation to new states that are difficult to recover from, with mass bleaching on the GBR becoming a biennial event (Byrne et al., 2025). Marine research indicates cascading effects on coastal protection and marine biodiversity may occur, with major Australian biodiversity loss as a World Heritage site could be lost. Critical reef tourism and fisheries represent major economic sectors at risk, with tourism revenue worth $6 billion annually and a major loss of coastal protection along Queensland coast.

South Australia/New Zealand (SAU) may face major impacts with coastal agricultural areas affected and coastal infrastructure threatened by long-term sea level rise, while coastal ecosystems could be altered, creating significant environmental and economic challenges.

Monsoon disruption and AMOC collapse

Changing global circulation patterns would alter precipitation patterns across Australia and New Zealand, potentially exacerbating existing aridity trends in interior Australia. For example, AMOC collapse would lead to wetter summers in northern Australia due to southward shifts in the Intertropical Convergence Zone and enhanced Indo-Australian monsoon systems, while simultaneously causing drier conditions year-round in New Zealand and southern Australia through altered storm tracks and weakened Southern Hemisphere westerlies (Du et al., 2025; Saini et al., 2025). Specifically, northern Papua New Guinea and Indonesia would receive less rainfall, while the Maritime Continent between 5°S and 6°N and southern Australian regions would display drier conditions throughout the year, with New Zealand experiencing reduced precipitation that could challenge agricultural productivity and hydropower generation (Saini et al., 2025).

NAU could face critical impacts with tropical agriculture critically dependent on monsoon precipitation and northern water resources critically dependent on monsoon (Du et al., 2025; Higgins et al., 2022), while urban areas could be severely affected by monsoon changes and tropical ecosystems critically dependent on monsoon patterns. Paleoclimate evidence indicates that Australian monsoon systems are sensitive to large-scale climate perturbations. For example, modelling of the 8.2 ka abrupt cooling event - caused by a weakening of the AMOC - suggests that northern Australia experienced shifts in precipitation due to a strengthened Indo-Australian summer monsoon and a southward shift of the Intertropical Convergence Zone (Du et al., 2025). Such responses indicate that both temperature and hydroclimate in northern Australia are strongly coupled to changes in global circulation patterns, highlighting the vulnerability of tropical agriculture, water resources and ecosystems to monsoon variability under both past and future climate perturbations. Increased rainfall in northern Australia could enhance agricultural productivity in regions that are currently underutilized due to water scarcity. However, the unpredictability of such changes poses challenges for long-term planning (Mai et al., 2025; Heidemann et al., 2023). Changes in precipitation patterns could strain existing infrastructure, especially in areas not designed to handle increased rainfall and can affect local ecosystems, potentially leading to shifts in biodiversity and the health of natural habitats (Heidemann et al., 2022; Marx et al., 2021).

Sea level rise from ice sheet collapse

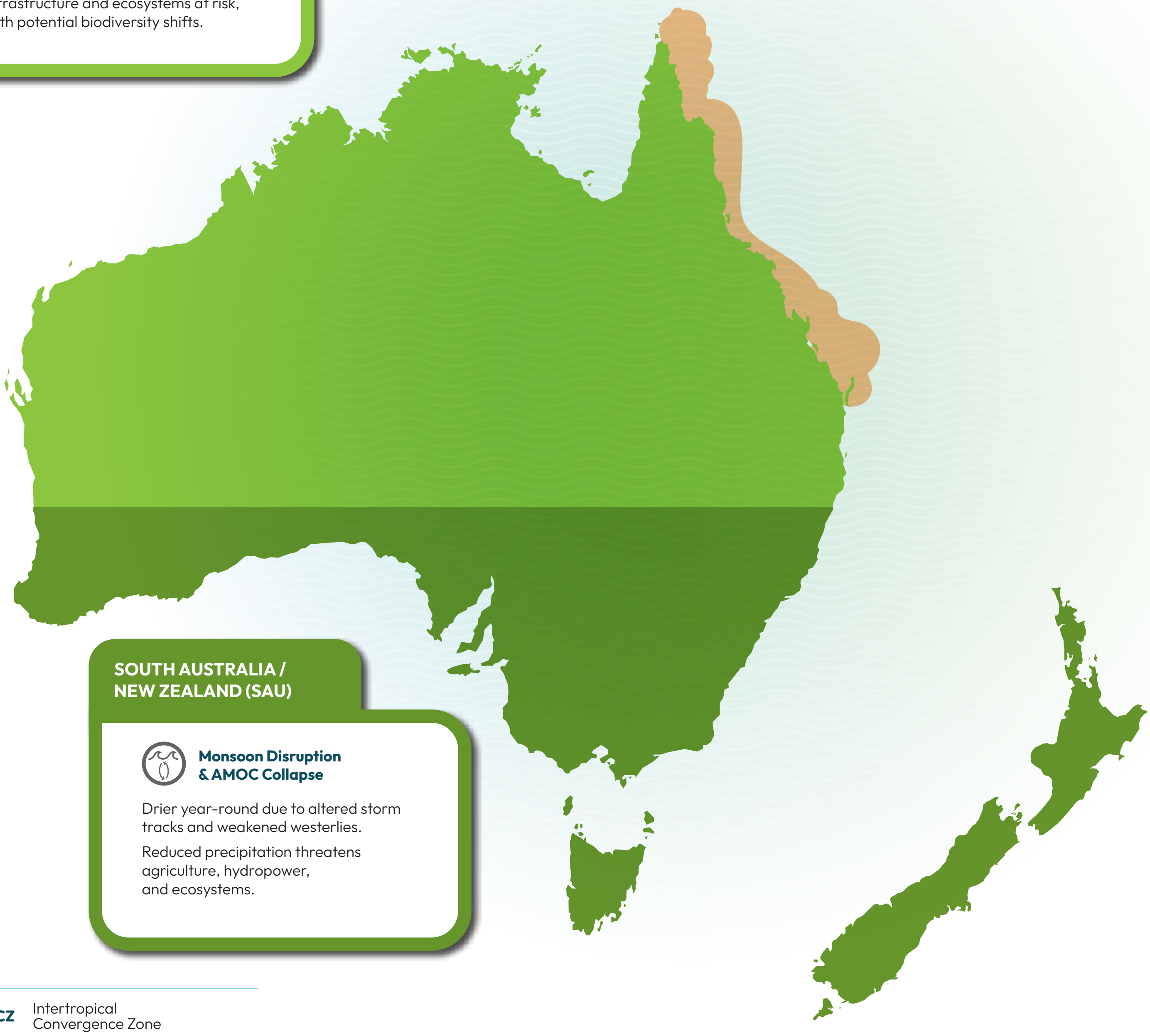
NAU and South Australia/New Zealand (SAU) may face major impacts with coastal agricultural areas affected and coastal infrastructure threatened by long-term sea level rise, while coastal ecosystems could be altered, creating significant environmental and economic challenges.

Small Island Developing States

Major tipping point exposures

Small Island Developing States (SIS) face existential threats from sea level rise from ice sheet collapse, Coral reef die-off eliminating critical coastal protection and fisheries and global warming effects amplified by Arctic feedbacks. These nations represent the most vulnerable populations globally to climate tipping points, with many facing complete uninhabitability (Cooper et al., 2025; Vousdoukas et al., 2023; Leal Filho et al., 2021).

Map 6: Potential impacts of Earth system tipping points on Australasia



NORTH AUSTRALIA (NAU)

Monsoon Disruption & AMOC Collapse

AMOC collapse → wetter summers from southward ITCZ shift and stronger Indo-Australian monsoon.

Tropical agriculture and northern water resources highly dependent on monsoon; urban areas and ecosystems vulnerable.

Precipitation changes unpredictable; infrastructure and ecosystems at risk, with potential biodiversity shifts.

GREAT BARRIER REEF

Coral Reef Die-Off

Great Barrier Reef facing catastrophic, biennial bleaching; "reef to rubble" transformation.

Major loss of biodiversity and coastal protection; $6 bn/yr tourism & fisheries at risk.

SOUTH AUSTRALIA / NEW ZEALAND (SAU)

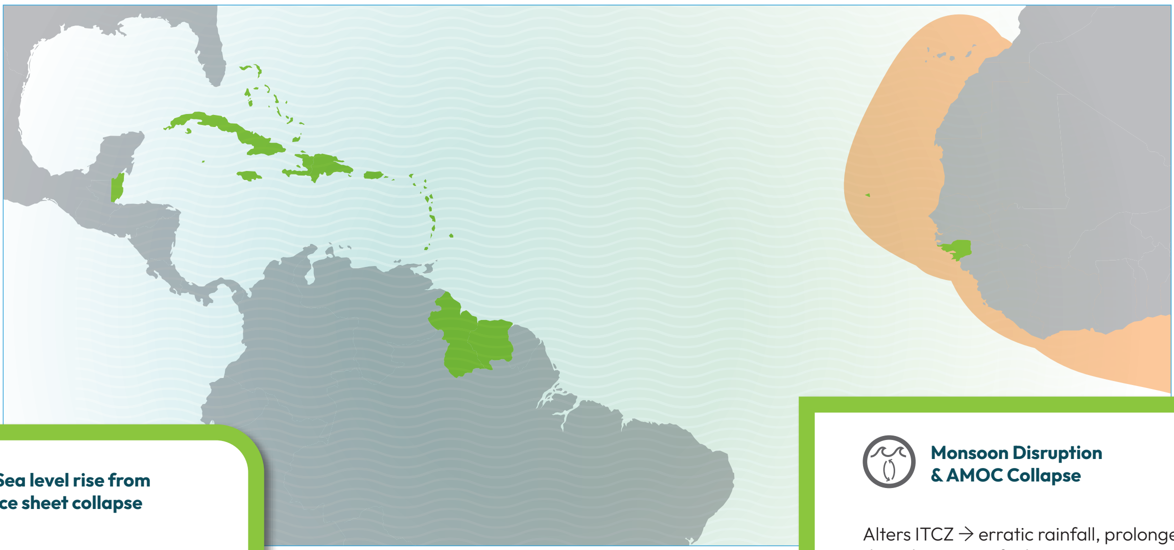
Monsoon Disruption & AMOC Collapse

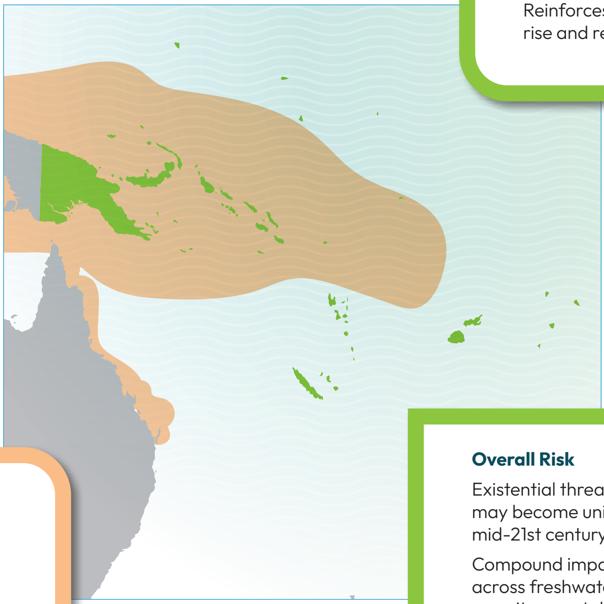
Drier year-round due to altered storm tracks and weakened westerlies.

Reduced precipitation threatens agriculture, hydropower, and ecosystems.

ITCZ	Intertropical Convergence Zone
SPG	Subpolar Gyre Overturning
AMOC	Atlantic Meridional Overturning Circulation

Map 7: Potential impacts of Earth system tipping points on Small Island Developing States





Sea level rise from ice sheet collapse

Multi-meter rise threatens complete inundation of low-lying islands and atolls.

Saltwater intrusion contaminates freshwater, soil salinization reduces agriculture.

Infrastructure, tourism, and fisheries at risk; economic losses may exceed 100% of GDP.

Potential complete displacement of populations → climate refugees and statehood challenges.

Monsoon Disruption & AMOC Collapse

Alters ITCZ → erratic rainfall, prolonged droughts, intensified storms.

Threatens freshwater, subsistence agriculture, and fisheries

Caribbean: fewer hurricanes but higher intensity; Pacific: more extreme drought–flood cycles.

Reinforces vulnerabilities from sea level rise and reef loss.

Coral reef die-off

Reef collapse eliminates coastal protection from storms and wave action.

Fisheries loss → severe food insecurity; reef tourism loss → economic collapse.

Cultural and biodiversity losses; reefs essential to island survival.

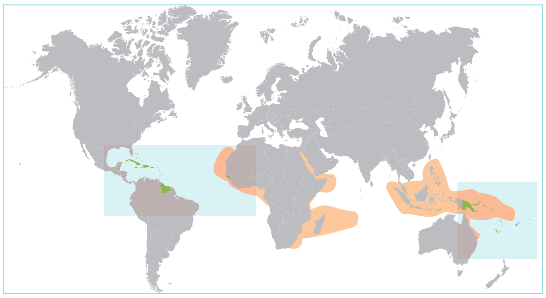
Overall Risk

Existential threat: some islands may become uninhabitable by mid-21st century.

Compound impacts across freshwater, food security, coastal protection, and economies.

ITCZ	Intertropical Convergence Zone
SPG	Subpolar Gyre Overturning
AMOC	Atlantic Meridional Overturning Circulation

● Small Island Developing States



Sea level rise from ice sheet collapse

Long-term multi-meter sea level rise from Greenland and West Antarctic Ice Sheet collapse poses existential threats to low-lying island nations (Lenton et al., 2023). Many coral atolls and low-lying islands could face complete inundation, with even 1-2 meter rise (reached in the late 21st Century in IPCC AR6's high-impact storyline) making numerous island nations uninhabitable. Research indicates that most atolls will be uninhabitable by the mid-21st century because of sea-level rise exacerbating wave-driven flooding (Storlazzi et al., 2018).

Some islands may become uninhabitable well before complete submersion due to saltwater intrusion into freshwater supplies (Gingerich et al., 2017; Terry and Falkland, 2010), with "overwash events generally result in salty ocean water seeping into the ground and contaminating the freshwater aquifer" (Storlazzi et al., 2018; Gingerich et al., 2017). Soil salinization from saltwater intrusion reduces the productivity of working lands and can prevent crops from growing, affecting agriculture on these vulnerable islands (Su et al., 2025; Shokri et al., 2024).

Critical threats include complete loss of agricultural land for many atolls, complete freshwater contamination from saltwater intrusion and complete infrastructure loss for many islands. Economic research indicates costs as a share of GDP could reach 100 per cent+ for many island nations, rendering them uninhabitable (Dietz and Koninx, 2022). Complete loss of territory would trigger unprecedented questions of statehood and require total population relocation, creating new categories of climate refugees. The economic impacts would be devastating, with complete loss of tourism infrastructure and fishing industries, while creating massive displacement requiring international resettlement programs.

Coral reef die-off

Small Island Developing States face critical impacts as entire populations of many islands are completely dependent on reef ecosystems for survival. Reef fisheries represent the primary protein source for many small island populations, while reefs provide essential coastal protection from storm surge and wave action.

Complete coral collapse could eliminate critical coastal protection, representing an existential threat to low-lying islands that depend on reefs as natural breakwaters. The loss of reef-based fisheries would create severe food security crises, while the collapse of reef tourism would eliminate major economic foundations for many island nations. Cultural and biodiversity losses would be devastating, as coral reefs represent fundamental elements of island cultures and contain unique marine biodiversity found nowhere else on Earth. Current overshoot conditions mean that unless global temperatures return below 1.2°C with minimal overshoot (IPCC, 2018), coral reefs on any meaningful scale will be effectively lost, creating unprecedented challenges for island nation survival.

AMOC collapse and monsoon disruption

SIS are vulnerable to global circulation shifts triggered by AMOC collapse and monsoon disruption, despite not lying directly in the core regions of these tipping elements (Bellomo and Mehling, 2024). AMOC weakening would shift the ITCZ southward, altering tropical rainfall across the Pacific and Indian Oceans (DiNezio et al., 2025; Steinert et al., 2025). For many SIS in the Pacific and Indian Ocean basins, this could drive more erratic rainfall regimes, prolonged droughts, and intensified storm seasons. These changes would directly threaten freshwater availability, subsistence agriculture, and fisheries, which are already stressed by sea-level rise and saltwater intrusion. Monsoon disruption could further destabilize rainfall patterns that sustain ocean–atmosphere interactions critical for cyclone activity and regional climate regulation (Ben-Yami et al., 2024; Sandeep et al., 2020). For Caribbean SIS, changes linked to AMOC weakening may reduce hurricane frequency but increase storm intensity, amplifying risks to coastal infrastructure and tourism economies (Thirumalai et al., 2024; Bhatia et al., 2018; Cai et al., 2014). In the Pacific, altered ENSO behavior under AMOC collapse could increase the frequency of extreme drought–flood cycles, placing additional pressure on freshwater and food systems.

2.4.6 Conclusion

Our assessment finds that crossing Earth system tipping points poses profound systemic risks across nine critical domains - including food security, energy infrastructure, and economic stability - threatening billions of people worldwide. Tipping points constitute a pressing national and global security concern, as cascading stresses on food, water, and health systems could drive mass mortality, large-scale displacement, and severe economic losses if climate change remains unchecked. Yet the evidence base remains limited, underscoring the urgent need for dedicated research into the societal consequences of tipping point cascades.

The risks are unevenly distributed across regions. Small Island Developing States face existential threats from sea-level rise and eventual uninhabitability; South and Southeast Asia's more than three billion people depend on highly vulnerable monsoon systems; and Arctic communities face wholesale ecosystem transformation. In contrast, developed regions are more likely to encounter challenges through infrastructure disruption and economic shocks. Critical risks include ice-sheet loss for small islands and East Asia, monsoon disruption for South and Southeast Asia and Central America, AMOC collapse and rainfall shifts for West Africa, permafrost thaw and boreal forest loss in North Asia, AMOC collapse for Northeast America and Northwest Europe, and Amazon rainforest dieback across South America.

These findings highlight stark inequalities in exposure and preparedness. The most acute vulnerabilities lie in small island states, West Africa, Central America, and the Amazon basin - regions with the least capacity to adapt yet facing some of the gravest risks. Without urgent action to limit warming and strengthen resilience, Earth system tipping points could overwhelm societies and economies worldwide. Meeting this challenge requires not only rapid emissions cuts but also major investment in research and preparedness to understand and manage cascading impacts. Effectively managing these risks is essential to safeguard global stability, security, and human well-being in the decades ahead.

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