The implications of overshooting 1.5°C on Earth system tipping elements - a review

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Abstract

Due to insufficient emission reductions in recent years, it is increasingly likely that global warming will exceed the 1.5 °C temperature limit in the coming decades. As a result, several Earth system tipping elements could, at least temporarily, have their tipping points surpassed, posing risks of large-scale and profound structural change. Tipping does not always occur immediately upon crossing such a critical threshold. If, in the following decades, global mean temperatures can be reduced below such long-term critical levels, tipping could still be avoided. An improved understanding is therefore needed of whether tipping remains avoidable, for which systems, and under what conditions. Here, we review how minimising the magnitude and duration of any temperature overshoot beyond 1.5°C is vital to minimising tipping risks. Limiting both the magnitude and duration of any overshoot beyond 1.5 °C is vital for reducing tipping risks. Tipping elements with fast response times, such as warm-water coral reefs, are especially vulnerable to overshoot. In contrast, those with slow response times, such as polar ice sheets, may be less sensitive to temporary overshoot. Potential interactions between tipping elements and additional human pressures, such as deforestation in the Amazon or pollution and disruption of coral reef habitats, may further lower tipping points, narrowing the range of overshoot trajectories that can still avoid it. The vulnerability of many tipping elements, even under shorter overshoot conditions, underscores that global warming must peak below 2 °C above pre-industrial levels, return to below 1.5 °C as quickly as possible (i.e., within this century), and to around 1 °C thereafter.

1. Introduction

Humanity is on track to soon cause global warming to exceed 1.5°C relative to pre-industrial levels (Friedlingstein et al., 2025) and current policies would take us towards 2.7°C of global warming (before accounting for any additional warming from causing possible tipping events or triggering so far unaccounted for climate-carbon cycle feedbacks (Steffen et al., 2018; Ripple et al., 2023, BioScience) later this century (Climate Action Tracker, 2024). To eventually limit warming levels at or below 1.5°C, it is now almost inevitable that there will be a period of temperature *overshoot* during which this warming target will be at least temporarily exceeded (Bustamante et al., 2023; Reisinger et al., 2025; Bevacqua et al., 2025). Temperature overshoot refers to pathways of global warming (averaged over a climatological period of 30 years) that first exceed a warming target (such as 1.5°C), followed by an eventual return to, or below, the warming target, as opposed to exceedance scenarios that permanently surpass a warming target. Therefore, temperature overshoots are often characterised by their peak warming, duration, and final stabilisation level (Schleussner et al., 2024; Wunderling et al., 2023; Schwinger et al., ESD, 2022). Two conceptual temperature overshoot pathways are illustrated in Figure 1a. Note that realistic scenarios that manage a return to 1.5°C by the end of the century have an upper limit of peak warming of about 1.8°C (Reisinger et al., 2025).

During temperature overshoots, there is an increased risk of exceeding *tipping points* (i.e. pathways in Figure 1a temporarily exceed an uncertainty range for a tipping point). Many elements of the climate system (see Table 1 and for a description of individual tipping elements see Section 4) are judged to have critical thresholds in global warming (tipping points) beyond which positive feedbacks can cause often irreversible and self-reinforcing change to a drastically different state with substantial negative impacts for human societies and the biosphere if exceeded for too long (Lenton et al., 2008; Armstrong McKay et al., 2022; Lenton et al., 2023). While temperature overshoot pathways have many negative consequences, assessing whether they exceed tipping points and cause tipping is crucial, due to the devastating impacts they bring.

Table 1: List of tipping elements along with their warming tipping point and tipping timescale estimates based on data from Lenton et al. (2023), and in case of no updates, from Armstrong McKay et al. (2022) (note for the tipping timescale if no minimum or maximum is given in the original source then this has been replaced by the given central estimate). Tipping elements are coloured according to cryosphere tipping elements in light blue, the biosphere in green, the ocean and atmosphere tipping elements in orange.

Tipping element	Warming tipping point (°C)			Tipping timescale (years)		
	Est.	Min	Max	Est.	Min	Max
Greenland Ice Sheet	1.5	0.8	3.0	10k	1k	15k
West Antarctic Ice Sheet	1.5	1.0	3.0	2k	500	13k
Marine Basins East Antarctica	3.0	2.0	6.0	2k	500	10k
Non-marine East Antarctica	7.5	6.0	10.0	10k	10k	10k
Mountain Glaciers	2.0	1.5	3.0	200	50	1k
Land Permafrost	1.5	1.0	2.3	200	100	300
Amazon Rainforest	3.5	2.0	6.0	100	50	200
Boreal Forest	4.0	1.4	5.0	100	50	100

Warm-Water Coral Reefs	1.2	1.0	1.5	10	10	10
West African Monsoon	2.8	2.0	3.5	50	10	500
North Atlantic Subpolar Gyre	1.8	1.1	3.8	10	5	50
Atlantic Meridional Overturning Circulation	4.0	1.4	8.0	50	15	300

When assessing risks of tipping from a temperature overshoot, considering the response timescale of the relevant system is important. Earth system tipping elements can be categorised by their response timescales to climate change: *slow* elements (e.g. ice sheets) have a delayed response over multi-centennial to millennial timescales much slower than the manifestation time of current climate change itself, while *fast* tipping elements (e.g., North Atlantic Subpolar Gyre, monsoons, or warm water coral reefs) respond on similar or faster annual to few centuries timescales (Lenton et al., 2024; Bochow et al., 2023; Ritchie et al., 2021; Swingedouw et al., 2021).

For a large and long temperature overshoot that exceeds a tipping point by a large amount and for a long time, there is a high risk of triggering tipping, even for slow elements (Figure 1b). However, a temporary crossing of a tipping point will not necessarily result in triggering the tipping of some inherently slow systems, if the temperature overshoot is small and short (Figure 1c). This is because such systems have substantial inertia and so are slow to respond to warming that has already occurred, as their response lags behind the forcing (i.e., anthropogenic greenhouse gas emissions).

Ideally, temperature exceedance of tipping points (even temporarily) should be avoided, but this may already be too late for some tipping elements (see Table 1). That is, the lower (and, in the case of coral reefs, central) uncertainty ranges of some Earth system tipping points are already exceeded (Figure 2). Further committed warming is inevitable and is almost certain to exceed 1.5°C in the near future, therefore exceeding the lower uncertainty ranges of even more tipping points (placed at around 1.5°C), and in the case of coral reefs exceeding the upper tipping point range, see Figure 2. Therefore, limiting the peak warming and duration of temperature overshoot is crucial for avoiding many key Earth system tipping elements from tipping (Ritchie et al., 2021). Hence, fundamental questions arise on what the limits for peak warming and overshoot duration are to avoid or limit the risk of tipping specific elements (Ritchie et al., 2021).

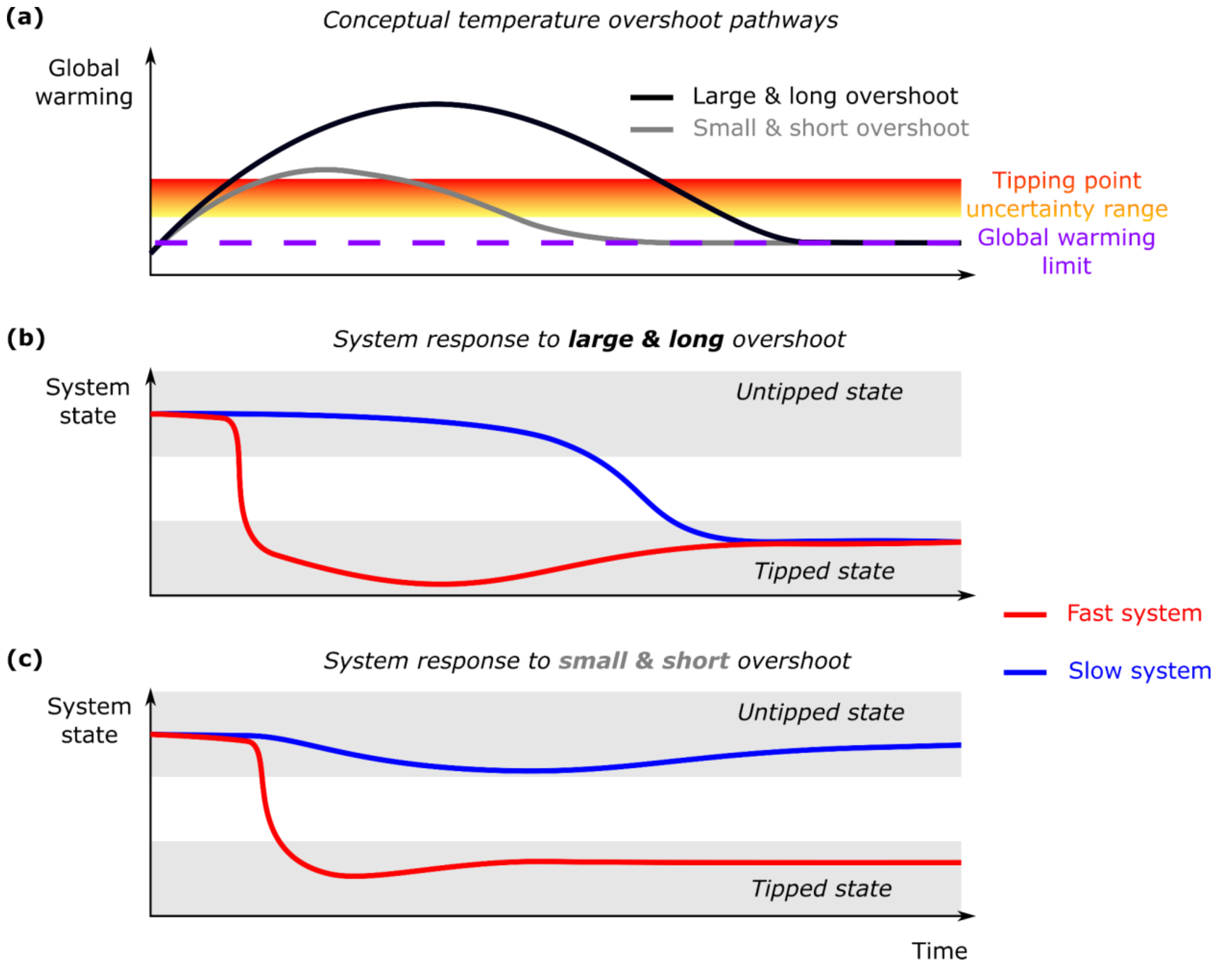

Figure 1: Schematic response of fast and slow systems with a common tipping point to different temperature overshoot pathways. (a) Two idealized temperature overshoot pathways that exceed a global warming target (purple dashed line), subsequently reach a level of peak warming, before returning and stabilising at the global warming target. These temperature 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 high peak and long overshoot duration (black), the other a low peak and short overshoot duration (grey). (b) For the large and long temperature overshoot, the fast system (red) tips very quickly after the tipping point is crossed, while for the slow system (blue), tipping is delayed although it still occurs. (c) For the small and short temperature overshoot, the fast system (red) again tips, but tipping is avoided for the slow system (blue) despite also temporarily exceeding its tipping point, due to its inherent slow timescale. Please note that the shown temperature trajectories only cover the case where the loss of a tipping element (i.e. tipping in the first place) is avoided. Instead, a recovery of an element after tipping is not shown as this would happen at even lower temperatures.

2. Handling uncertainties relevant for tipping elements during and after temperature overshoots

Considering the potentially severe and irreversible consequences from triggering tipping events requires a framework for assessing and acting under uncertainty. Due to the limited predictability of the precise tipping points (Ben-Yami et al., 2024), a probabilistic risk assessment approach becomes essential. Similar methods to those used in insurance and actuarial industries can help quantify risks. Such approaches have 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 (Deutloff et al., 2025; Möller et al., 2024; Abrams et al., 2023; Wunderling et al., 2023). Within this risk framework, we can systematically address different types of uncertainty.

2.1 Uncertainties in global temperature trajectories

Understanding the characteristics of temperature overshoot pathways is crucial for assessing tipping risks and informing mitigation strategies that can minimise these dangerous consequences of climate change (Figure 2). Understanding the peak and duration of potential global temperature overshoots requires an examination of the relationship between greenhouse gas concentrations, emissions pathways, and the resulting warming. Deriving an emissions pathway perspective considers the full chain from greenhouse gas emissions to resulting temperature changes (Meinshausen et al., 2024). While the concept of temperature overshoot scenarios is straightforward, projecting actual temperature trajectories from emissions involves dealing with substantial uncertainties. These uncertainties - stemming from several sources such as climate sensitivity (how much warming results from a given increase in greenhouse gases), carbon cycle feedbacks (how natural systems respond to warming), and the efficacy of mitigation measures - can be summarized as follows:

Uncertainties in climate sensitivity and resulting peak warming levels. The Transient Climate Response to cumulative carbon Emissions (TCRE) describes how much warming results from a given amount of cumulative CO_2 emissions (Allen et al., 2009; Matthews et al., 2009; Tachiiri et al., 2019; Meehl et al., 2020; Jones & Friedlingstein, 2020; Nijsse et al., 2020; Winkler et al., 2024). However, TCRE estimates vary considerably across models, with the IPCC AR6 likely range (17th–83rd percentile range) spanning 1.0°C to 2.3°C per 1000 GtC (IPCC AR6 WGI, Chapter 5, Canadell et al., 2021). This uncertainty implies that even with scenarios that have identical cumulative CO_2 emissions, peak warming projections can differ substantially. Additionally, non-CO_2 forcings and carbon cycle feedbacks such as permafrost thaw and forest changes can further extend this uncertainty range. Land and ocean carbon sinks have absorbed approximately 56% of anthropogenic emissions over 1960-2023, with the remaining portion retained in the atmosphere (Friedlingstein et al., 2025). While the future of these carbon sinks remains uncertain, there is growing evidence of a long-term weakening of land sinks (e.g. for the Amazon rainforest; Gatti et al., 2021; Ke et al., 2024), whereas ocean carbon sinks, while also weakening long-term, are comparatively stable across Earth System Models (Tokarska et al., 2019; Schwinger et al., ESD, 2022; Koven et al., 2023; Sanderson et al., 2024).

Uncertainties in temperature stabilization and reversal. Even if emissions reach net-zero and are maintained at that level - known as the Zero Emissions Commitment (ZEC) (Jones et al., 2019; MacDougall et al., 2020; Corner et al., 2023), considerable uncertainty remains over how global temperatures would subsequently evolve. Some Earth System Models show continued warming after emissions cease, while others indicate a plateau or gradual cooling. These divergent responses primarily reflect differences in how models represent ocean heat and carbon uptake and the interplay of several positive and negative feedback processes within the Earth system that could modify global warming. Prominent examples for positive climate feedbacks (meaning they amplify warming) are ice-albedo feedback, permafrost thaw or desertification (Ripple et al., 2023, One Earth; Lenton et al., 2023). Additionally, many tipping elements themselves possess self-reinforcing feedbacks through their disintegration, such as the large ice sheets or forest systems (e.g. Armstrong McKay et al., 2022). Such feedbacks do not only affect both TCRE during the warming ramp-up and subsequently whether stabilization will occur after net-zero is reached, but they also strongly condition the reversibility of global temperatures following overshoot pathways. When emissions become net negative, the temperature reversal is determined by ZEC (here as committed warming after positive emissions) and TCRE (here reversed TCRE that quantifies temperature response during carbon removal). This response is further modified by (yet uncertain) corrections due to the asymmetry in temperature response to net positive and net negative emissions (Zickfeld et al., 2016; 2021; Koven et al., 2023; Sanderson et al., 2024). In principle, reducing atmospheric greenhouse gas concentrations should cool the climate, yet these feedback-driven processes and hysteresis effects can delay or even prevent a return to previous climate states, particularly where tipping points are crossed. Together with current inadequate progress in emissions reductions, which increases the risk of overshoot (Climate Action Tracker, 2024; World Metrological Organisation, 2025; Forster et al., 2025), these uncertainties raise fundamental challenges for the feasibility of returning to internationally agreed temperature targets once they have been exceeded.

2.2 Implications for projected temperature overshoots and tipping

The characteristics of temperature overshoots are strongly influenced by the timing of emission reductions and carbon removals. Delayed action increases both the peak warming and the duration of the temperature overshoot, exacerbating tipping risks. Scenarios with higher peak temperatures also tend to have longer durations above temperature targets, creating compounding risks for tipping elements.

Pathways that temporarily exceed 1.5°C with a 50% likelihood of returning to this warming level by 2100 exhibit a temperature overshoot of 0.1-0.3°C in the best estimate (Kikstra et al., 2022). The IPCC categorizes temperature overshoot scenarios as either "limited overshoot" (C1), which refers to exceeding the specified limit by up to about 0.1°C, or "high overshoot" (C2), which refers to exceeding it by more than 0.1°C and up to 0.3°C (IPCC AR6 WGIII-SPM, 2022; Schleussner et al., 2024). Limited temperature overshoot pathways typically display exceedance of median temperature projections for up to a few decades before returning to below 1.5°C by or before the year 2100 (IPCC SR1.5-SPM, 2018). However, the uncertainty ranges around these projections are substantial, with much higher warming peaks possible due to stronger than expected climate sensitivity and Earth system feedbacks (Schleussner et al., 2024; Kaufhold et al., 2025; Reisinger & Geden, 2023; Myhre et al., 2025).

There has not been a thorough assessment of overshooting 2.0°C as there has been for 1.5°C. However, the scenario *SSP5-3.4-over* offers some insight into temperature pathways and the response of the carbon cycle in a pathway overshooting 2.0°C (Melnikova et al., 2021). Under this scenario, models show peak warming between 2.4°C and 4.1°C occurring between the 2040s and 2070s, after which temperatures decrease (due to carbon removal) and stabilize between 2-3°C by 2300, with temperatures remaining as high as ~3°C at the end of the 21st century. The rate of temperature decrease varies largely across models from steep to almost non-existent. Furthermore, most models show a decrease in TCRE during the cooling phase due to decreasing natural carbon sinks (Melnikova et al., 2021).

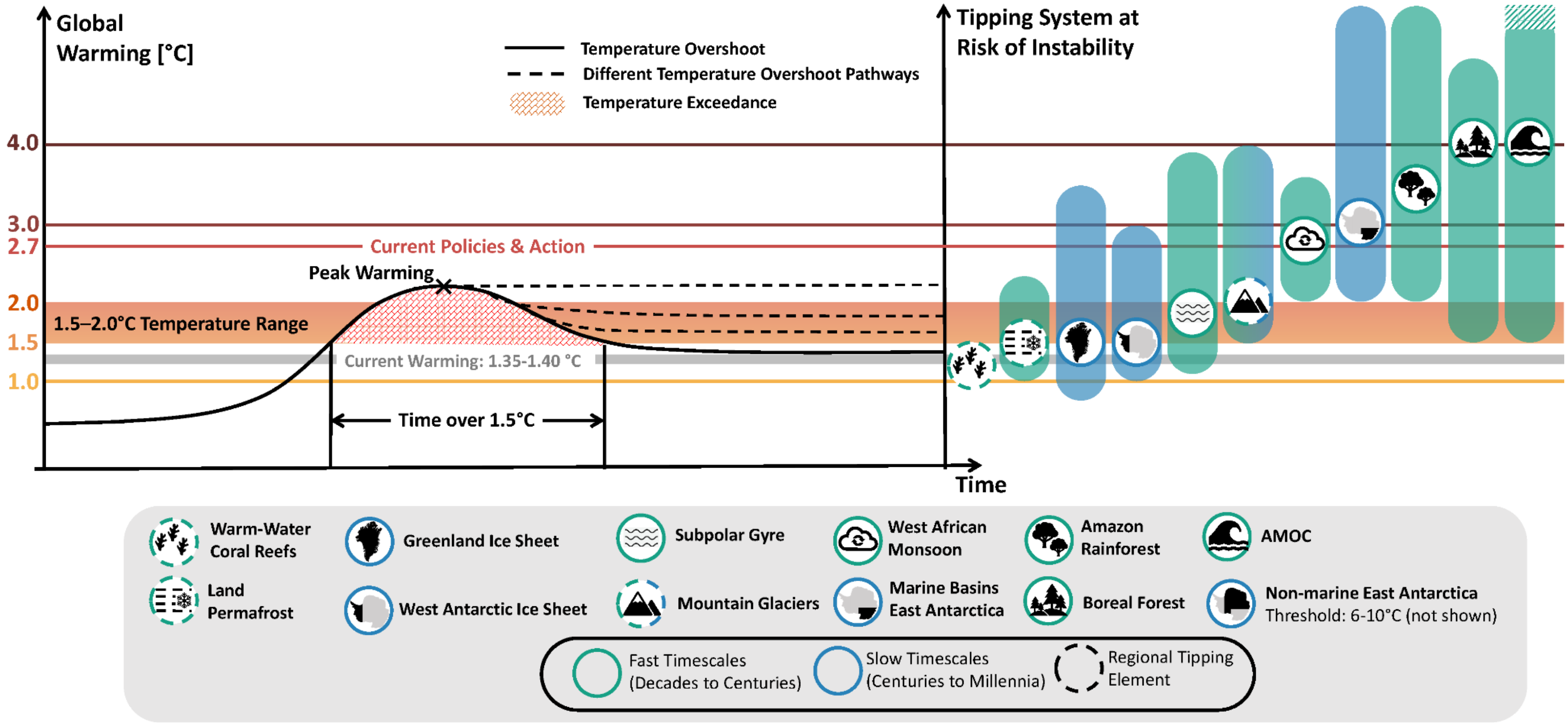
Global Warming [°C]
Temperature Overshoot
Different Temperature Overshoot Pathways
Temperature Exceedance
4.0
3.0
2.7
Current Policies & Action
Peak Warming
2.0
1.5–2.0°C Temperature Range
1.5
Current Warming: 1.35-1.40 °C
1.0
Time over 1.5°C
Time
Tipping System at Risk of Instability
Warm-Water Coral Reefs
Greenland Ice Sheet
Subpolar Gyre
West African Monsoon
Amazon Rainforest
AMOC
Land Permafrost
West Antarctic Ice Sheet
Mountain Glaciers
Marine Basins East Antarctica
Boreal Forest
Non-marine East Antarctica Threshold: 6-10°C (not shown)
Fast Timescales (Decades to Centuries)
Slow Timescales (Centuries to Millennia)
Regional Tipping Element

Figure 2: Overshooting 1.5°C risks crossing Earth system tipping points. Illustrative temperature overshoot pathways, 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 temperature overshoot pathway at least temporarily crosses several Earth system tipping points: whether tipping occurs depends on the peak warming, time spent beyond the tipping point and the element's response timescale. Icons denote tipping elements (global tipping elements are shown with a solid edge; regional tipping elements are shown with a dashed edge; local tipping elements 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 2.7°C (Climate Action Tracker, 2024), which is far from the upper limit of 1.8°C where a return to 1.5°C by 2100 appears feasible (Reisinger et al., 2025).

2.3 Tipping element uncertainty

Risk assessments must account for uncertainties in tipping points, system timescales, and coupled interactions. Central estimates for tipping points and timescales vary considerably across tipping elements (Armstrong McKay et al. (2022), Lenton et al. (2023)). The tipping point uncertainty range for each element also differs from very small values for the warm-water coral reefs (tipping point between 1.0-1.5°C, uncertainty: 0.5°C) to large uncertainty ranges in the case of the AMOC (tipping point between 1.4-8.0°C, uncertainty: 6.6°C), see Figure 2. Likewise, the tipping timescale uncertainties can vary by up to two orders of magnitude for single elements. Both uncertainties will have profound impacts on a tipping element's risk of tipping during and after an overshoot (Lux-Gottschalk & Ritchie, 2025). Further, tipping elements such as the Atlantic Meridional Overturning Circulation (AMOC) or the large ice sheets, are not isolated subsystems but form a coupled system, whereby the number of stable states and tipping points can exceed the number of tipping elements. Not all interactions are fully understood, and there is large uncertainty in their strengths but also in their physical pathways in general (Wunderling et al., 2024; Falkena & von der Heydt, 2024), and the impact of sub-system timescales on the response to forcing (Bastiaansen et al., 2023). Interactions between elements can change effective tipping points (Wunderling et al., 2023), and destabilising interactions introduce the risk of possible cascading transitions (Wunderling et al., 2024; Klose et al., 2021; Dekker et al., 2018), which could be triggered if only the lowest tipping point is crossed (Rosser et al., 2024).

2.4 Structural uncertainties and alternative tipping mechanisms beyond saddle-node bifurcations

Studies of tipping during and after overshoot have mostly focused on the crossing of a smooth saddle-node bifurcation starting from an equilibrium state of the system (Ritchie et al., 2019; Ritchie et al. 2021; Wunderling et al., 2023), but the real Earth system is often more complicated. The initial states of relevant systems may not be simple equilibrium states (Lohmann & Ditlevsen, 2021; Lohmann et al., J. Phys. Complex., 2024), opening up the possibility of other forms of tipping (Thompson et al., 1994; Alkhayuon et al., 2019; Alkhayuon et al., 2021; Ashwin & Newman., 2021; Budd and Kuske 2024). For example, if the tipping element has periodic behaviour (e.g. monsoon systems such as in West Africa), the given phase of the period at the time an overshoot starts may determine if the system tips or not

(Alkhayuon et al., 2018). Therefore, the possibility of structural uncertainty further complicates the estimation of a peak warming and overshoot duration that avoids tipping.

Tipping can occur via other mechanisms such as rate-induced tipping, which is caused by an external forcing changing too quickly (Ritchie et al., 2023). As one example, the AMOC, a tipping element with a tipping point between 1.4°C and 8.0°C (Armstrong McKay et al., 2022), has been shown to exhibit rate-induced tipping before a tipping point has been crossed both conceptually (Alkhayuon et al., 2019; Chapman et al., 2024) and in complex ocean models (Lohmann & Ditlevsen, 2021; Lohmann et al., Sci. Adv., 2024). Rate-induced tipping complicates the commitment from overshoot scenarios, and in some cases may make them more dangerous. For example, some fast overshoots can be more dangerous than slower ones (O'Keeffe & Wieczorek, 2020), as shown to be the case for a box-model of the AMOC. Thus, the risk of tipping does not necessarily continually increase with the duration of the overshoot (Ritchie et al., 2023). Similar behavior might occur if a tipping element possesses multiple stable states (e.g. ice sheets, ocean circulation currents, vegetation patterns) that do not correspond to a full collapse of the system (Robinson et al., 2012; Garbe et al., 2020; Bastiaansen et al., 2022; Bochow et al., 2023; Lohmann et al., Sci. Adv., 2024), which could be reached for different overshoot profiles.

Structural uncertainty propagates further once interactions between tipping elements are considered (Wunderling et al., 2024). Returning to the AMOC example, conceptual modelling already indicates that a tipping in the cryosphere can lead to rate-induced tipping in the AMOC (Lohmann et al., 2021; Sinet et al., 2024; Klose et al., 2024). There is thus a necessity to consider rate-induced tipping and other alternative scenarios in tipping cascade models to understand the full impact of various overshoot scenarios.

2.5 Modelling approaches to temperature overshoots and implications for tipping points

It is important to utilise the full modelling hierarchy when analysing the impact of temperature overshoots for tipping points. Conceptual models have the advantage of minimal computational cost, even for many stochastic realisations and long runs (Dijkstra, 2024). Therefore, it is possible to qualitatively investigate tipping mechanisms for overshoot scenarios using conceptual models (e.g. Lux-Gottschalk & Ritchie, 2025; Chapman et al., 2024; Rosser et al., 2024). Conceptual climate models generally describe sub-systems of the Earth's climate and are limited in the scale and processes they model (Dijkstra, 2013). Hence, conceptual models cannot provide a quantitative assessment for tipping risks during and after temperature overshoot. However, they can support the understanding of tipping behavior in more complex models (Dijkstra, 2024). Increasing scale leads to intermediate complexity models of the ocean/atmosphere, while increasing both scale and processes results in Earth System Models of Intermediate Complexity (EMICs), and eventually complex Earth System Models (ESMs).

Comprehensive ESMs typically approximate solutions to the fundamental laws that govern the behaviour of the atmosphere, ocean, land, sea ice, land ice, vegetation, and other components on a three-dimensional finite grid. While this allows for the resolution of a high number of processes, this makes it more difficult to diagnose the mechanisms causing the behaviour (e.g. tipping) observed in these complex models. Previous generations of ESMs were often limited to a horizontal resolution of 50-100 km (Eyring et al., 2016); however, the next generation is expected to allow for coupled sub-20 km simulations (Roberts et al., 2025). Even at this higher resolution, many important processes are still not explicitly resolved but are instead parameterised. Additionally, computational costs remain high, permitting a limited number of simulations on a 100-200 year timescale, making it challenging to investigate overshoot scenarios under consideration of all relevant uncertainties (see section above) especially in the context of crossing tipping points of slow tipping elements, which require long simulation runs. Furthermore, there have been discussions regarding the tuning process and the general ability of ESMs to represent tipping elements (Valdes et al., 2011, Hourdin et al., 2017). As models increase in complexity, they become more costly to run and challenging to explain output behaviour (IPCC AR5 WGI, Chapter 9, Flato et al., 2013). Conversely, as the number of processes and feedbacks increases, models produce a more realistic representation of overshoots.

However, there is a fourth tool that is computationally efficient and can reproduce the behaviour of more complex climate models, providing a rapid translation of emissions into probabilistic estimates of changes to the physical climate system (Nicholls et al., 2020), or explore the uncertainty associated with selected climate variables (Beusch et al., 2021): These are so-called *Emulators*. Physical emulation can be performed by simple parameterisations or statistical methods, where the emulator behaviour is tuned to reproduce the response of a given model ensemble. Consequently, emulators can only resolve and show the impacts of non-linear and self-amplifying feedbacks if they have been accurately tuned against modelling approaches that include these processes. To assess the probability of tipping for emission pathways, conceptual tipping models (e.g. Wunderling et al., 2021) can be used in conjunction with climate emulators (Möller et al., 2024; Abrams et al., 2023; Deutloff et al., 2023). Such approaches however do not resolve direct temperature feedbacks from destabilising tipping elements (Möller et al., 2024). Existing climate emulators are not fully tuned for overshoot scenarios, with large uncertainties about the response of the climate system.

These difficulties are increased by the challenges of detecting tipping points. Many systems experience *critical slowing down* before reaching a tipping point, indications of which have been observed in a range of tipping elements including the AMOC (Boers, 2021; Ditlevsen & Ditlevsen, 2023) and the Amazon rainforest (Boulton et al., 2022; Bochow & Boers, 2023). There is no comparable empirical technique to indicate the exceedance of any tipping point prior to the transition to a new state. Nonetheless, modelling suggests that some tipping points may have already been crossed, however, the impacts of their crossing are not yet realised (i.e. the element is not yet tipped). Even further, it may be difficult or impossible to recognize before substantial impacts begin to unfold. According to current best estimates in the literature (Armstrong McKay et al., 2022; Lenton et al., 2023), it is possible that the tipping points of the Greenland Ice Sheet, West Antarctic Ice Sheet, North Atlantic Subpolar Gyre convection, warm water coral reefs, and boreal permafrost are below the current warming level (Lenton et al 2023, Forster et al., 2025, Stokes et al. 2025). However, only the warm water coral reefs are assessed to have a central tipping point estimate below 1.5°C, where 1.5°C corresponds to the coral reefs upper tipping point (Lenton et al., 2023).

2.6 Approaches to handling uncertainties

Reducing uncertainty in future forcing scenarios and tipping element characteristics is essential for estimating the response of individual tipping elements (Ritchie et al., 2019). Given the role of uncertainty in temporarily crossing tipping points, tipping risks of selected emission pathways need to be evaluated probabilistically (Möller et al., 2024). Using a simple conceptual climate model, Lux-Gottschalk & Ritchie (2025) identify confidence levels for the location of the boundary that separates tipping from not tipping based on the peak overshoot and overshoot duration. They present a proof of concept, using Bayesian inference on how data could be used to better constrain uncertain tipping characteristics and hence also the tipping boundary. From investigations of the impact of uncertainties in conceptual climate models (Rosser et al., 2024), conclusions can be drawn on which model parameters have the biggest impact on tipping dynamics and thus need to be better constrained in more complex climate models.

Data-driven methods to better constrain the current proximity of tipping points have also been attempted. One avenue is to exploit critical slowing down as an early-warning signal of an approaching tipping point (Boers & Rypdal, 2021; Boers, 2021; Ditlevsen & Ditlevsen, 2023; Ben-Yami et al., 2023). Another avenue that has recently gained attention involves using deep learning and AI-methods to predict both the occurrence and timing of tipping points (Huang et al., 2024; Zhuge et al., 2025). However, in the context of overshoots, extrapolating early warning signals to predict a tipping event can provide false conclusions due to assumptions on the future forcing trajectory (Ashwin et al., 2025; Ben-Yami et al., 2024). Additionally, early warning signals can fail when a system is not in equilibrium, such as for slow tipping elements with long internal timescales (e.g. ice sheets). Instead, new methods need to be developed to determine when an element has crossed its tipping point but not yet tipped (Gottwald & Gugole, 2020). This would enable first order approximations for the chances of a return to the previous state (Ritchie et al., 2019). Another method is to infer the strength of the underlying physical mechanisms from observations, thereby adjusting biases in ESMs, leading to better estimates of the tipping point, a so-called *observation-based constraint* (e.g. Liu et al., 2017, Sgubin et al. 2017; Portmann et al., 2025).

3. Risk of triggering tipping during and after temperature overshoot

Multiple tipping elements of the Earth system could have their tipping point below 2°C of global warming, and some below 1.5°C (Lenton et al., 2023; Armstrong-McKay et al., 2022; see Figure 2). Consequently, even under the most optimistic emission scenarios of stabilising warming at 1.5°C without any overshoot, it is considered *as likely as not* (33-66% probability) that three Earth system elements will tip (see Figure 3a based on Lenton et al., 2023 or Armstrong-McKay et al., 2022). One of these elements will be the warm water coral reefs, which are *virtually certain* (>99% probability) to tip, given the upper range of their tipping point is 1.5°C (Lenton et al 2023; Figure 2). Other candidates that are vulnerable to tipping include the North Atlantic Subpolar Gyre, land permafrost, and the Greenland and West Antarctic ice sheets. It may be any combination of these elements, but it is considered *very unlikely* (<10% probability) for all of them to tip. However, delayed climate action and stabilising global warming at 2°C (without an overshoot) would change the probability of five elements tipping from *very unlikely* to *as likely as not*. Mountain glaciers, boreal forests and the AMOC are the additional elements that risk being tipped under this scenario. Stabilising global warming at 3°C would *likely* (>66% probability) cause eight elements 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. Here is an example: assume that a particular tipping element will have a 1% probability of tipping if warming remains 100 years, with a 0.1°C peak exceedance, beyond the tipping point. The theory suggests that if the peak exceedance of the same tipping point was instead 0.2°C then the exceedance duration of the tipping point would need to be limited to 25 years to maintain the same 1% tipping risk. Utilising this theory, we here assess the tipping risk for overshoots of the 1.5°C target (see Figure 3b).

Limiting the temperature overshoot beyond 1.5°C to a duration of 100 years could substantially reduce the number of elements that undergo tipping (compare Figure 3b to 3a). For a peak warming of 2°C, the number of elements 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 elements *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 not considered to be feasible (Schleussner et al., 2024).

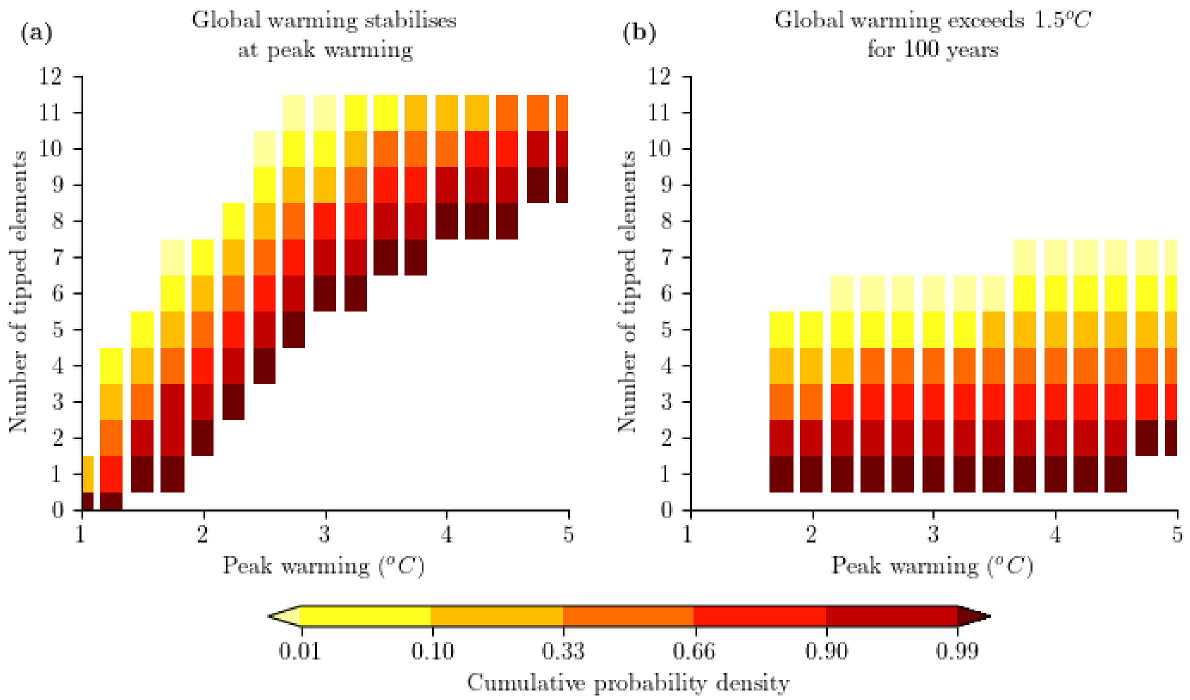

Figure 3. Tipping risk for Earth system tipping elements with and without temperature overshoot. (a) Cumulative number of tipped elements if global warming stabilises at different peak levels without return, and (b) cumulative number of tipped elements for different peak warming levels in an overshoot scenario lasting for 100 years and stabilising at 1.5°C. Colour is used to represent the cumulative probability density of the number of tipped elements using the IPCC likelihood scale (IPCC AR6 WGI-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 elements 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).

Figure 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 elements with fast timescales and a low warming tipping point (North Atlantic Subpolar Gyre and warm-water coral reefs) are the most susceptible to tipping even for short overshoot durations. In contrast, elements 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 that seeks to limit the devastating long-term consequences of committing to ~10 metres of sea-level rise from tipping these elements, 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).

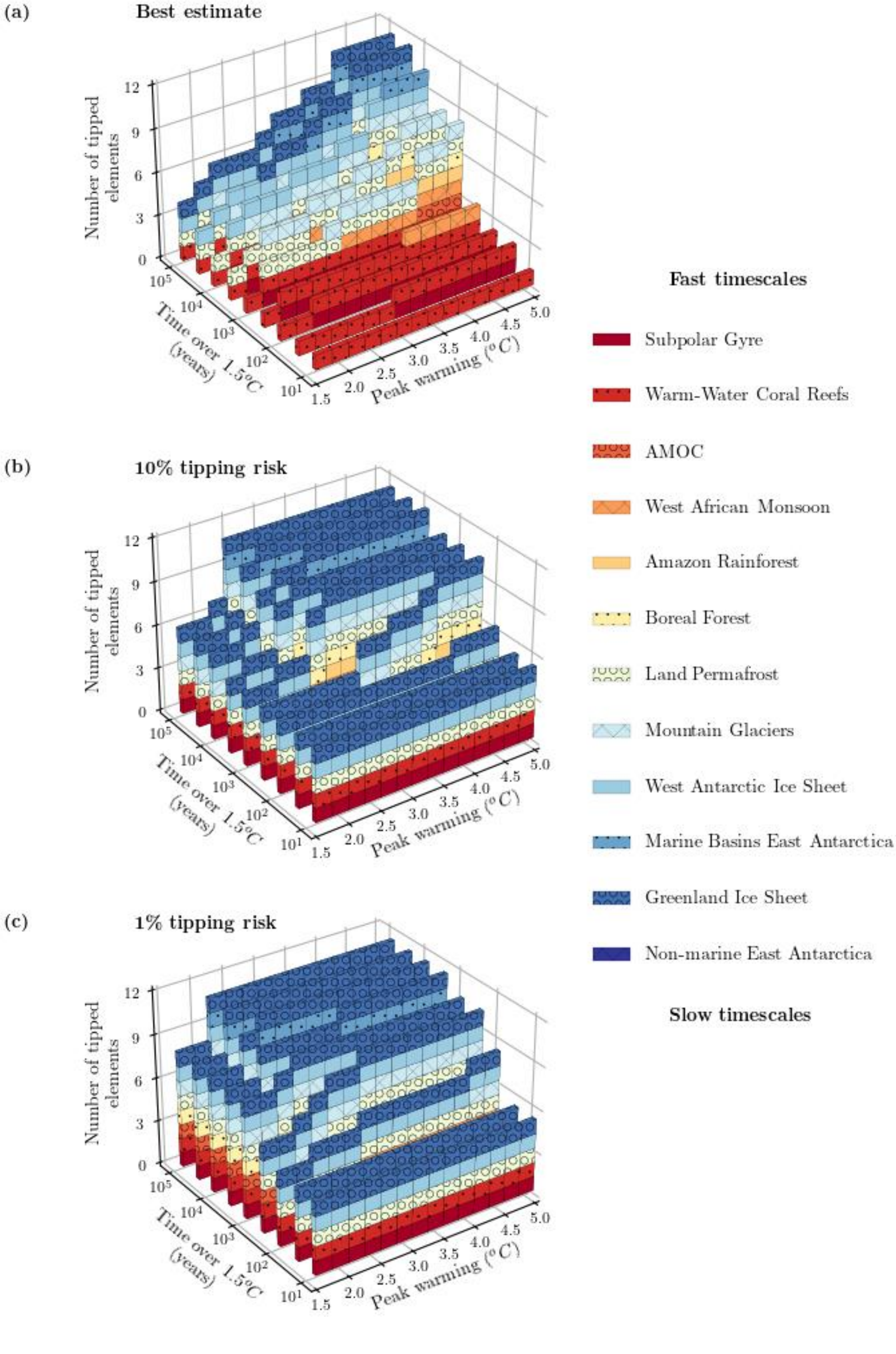
(a)
Best estimate
(b)
10% tipping risk
(c)
1% tipping risk
Number of tipped elements
0
3
6
9
12
Time over 1.5°C (years)
10^1
10^2
10^3
10^4
10^5
Peak warming (°C)
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
Fast timescales
Subpolar Gyre
Warm-Water Coral Reefs
AMOC
West African Monsoon
Amazon Rainforest
Boreal Forest
Land Permafrost
Mountain Glaciers
West Antarctic Ice Sheet
Marine Basins East Antarctica
Greenland Ice Sheet
Non-marine East Antarctica
Slow timescales

Figure 4: Tipping risk for overshoots characterised by peak warming and time over 1.5°C. (a) Best estimate for the cumulative number of tipped elements for overshoots characterised by their peak warming and time over 1.5°C. (b) and (c) are the same as (a) but now an element is only included if its tipping risk exceeds 10% and 1% probability, respectively. The same global and regional tipping elements are considered as in Figure 2. Each element is coloured and marked as given in the labels to the right side of the panels. Colours are selected such that red colours represent fast, and blue colours represent slow tipping timescales. Figure adapted from Ritchie et al. (2025) to account for the latest updates and different levels of tipping risk.

4. Implications of temperature overshoot for individual tipping elements

A temperature overshoot will have varying implications for the different tipping elements of the Earth system. Here we provide a brief summary for all elements considered in the previous sections, except for the terrestrial (non-marine) parts of the East Antarctic Ice Sheet, and the West African monsoon.

Greenland Ice Sheet (GrIS): The Greenland ice sheet is generally assessed as a slow tipping element where a complete disappearance would occur on the time scale of centuries to millennia (Robinson et al., 2012; Solgaard & Langen, 2012; Pattyn et al., 2018; Bochow et al., 2023; Höning et al., 2023; Petrini et al., 2025). Different modelling studies show that an exceedance of the tipping point does not necessarily imply a complete tipping of the Greenland Ice Sheet but reversing the forcing can result in, at least, a partial regrowth of the ice sheet (Ridley et al., 2010; Gregory et al., 2020; Bochow et al., 2023; Höning et al., 2023; Höning et al., 2024). However, for some overshoot scenarios, a regrowth might not be possible as atmosphere-ice sheet interactions such as the surface mass balance-elevation feedback may impede reversibility (Gregory et al., 2020; Pattyn et al., 2018; Bochow et al., 2023; Höning et al., 2024). Additionally, there is substantial uncertainty about the tipping point global warming level (Noël et al., 2021; Petrini et al., 2025), which makes it difficult to assess an overshoot duration that would prevent a tipping of the Greenland Ice Sheet. In any case, an exceedance of the tipping point implies substantial melt and therefore sea level rise, depending on the overshoot peak temperature and duration (e.g., Rückamp et al., 2018; Bauer et al., 2023).

West Antarctic Ice Sheet (WAIS): The response of the Antarctic Ice Sheet—the largest source of potential long-term sea-level rise—to global warming overshoot scenarios remains poorly constrained, with only a few modelling studies available (Mengel et al., 2018; Bauer et al., 2023). As a “slow” tipping element, the full consequences of past and ongoing warming may take centuries or longer to unfold (Clark et al., 2016; Klose et al., 2024). Nevertheless, Antarctica is losing mass and contributing to sea-level rise already today, with losses projected to accelerate even if global temperatures were stabilized at current levels (Reese et al., 2023). Even for a stable climate with current temperatures, a partial WAIS collapse may already be unavoidable (Reese et al., 2023; van den Akker et al., 2025; Chandler et al., 2025; Stokes et al., 2025), though its onset could range from centuries to millennia. Overshooting global warming targets, even temporarily, increases the risk of transgressing tipping points in Antarctica. The West Antarctic Ice Sheet, in particular, is highly vulnerable due to its marine-based configuration (meaning that the ice sheet rests on bedrock submerged below the sea level), making it susceptible to runaway retreat through marine ice sheet instability (Garbe et al., 2020). Ice-shelf disintegration driven by overshoot-induced warming could further accelerate ice loss, compounding global sea-level rise. Some models suggest this could trigger an even more dangerous instability cascade within the ice sheet itself (DeConto et al., 2021), though the precise mechanisms remain debated.

Marine Basins East Antarctica: The marine basins of East Antarctica hold ice equivalent to about 19.2 metres of potential sea-level rise and have been identified as a 'global core' climate tipping element (Lenton et al., 2023). Model simulations suggest that warming tipping points vary strongly in each basin: Recovery Basin at 1-3°C ocean warming, Wilkes Basin at 2-4°C atmospheric warming, and Aurora Basin at 5-8°C warming (Garbe et al., 2020; Golledge et al., 2017). Paleoclimate data reveals that past warm periods with global temperatures 1-2°C above pre-industrial levels led to significant ice retreat, especially in the Wilkes Basin (Blackburn et al., 2020). If tipping points for these basins are crossed, self-reinforcing feedbacks such as marine ice sheet instability, reduced ice shelf buttressing, and basal thawing, which together can trigger irreversible ice retreat and long-term sea-level rise (Garbe et al. 2020; Abram et al. 2025). In the scenario of a temperature overshoot exceeding these tipping points even temporarily, the marine basins could undergo self-sustaining retreat with substantial ice loss, committing these basins to long-term mass loss and sea-level rise, despite subsequent climate cooling efforts. Such retreat would unfold over time scales ranging from centuries to millennia, with irreversible impacts due to hysteresis, which would require cooling far below pre-industrial levels to be reversed (Garbe et al., 2020; Mengel & Levermann, 2014).

Mountain Glaciers: Mountain glaciers have been identified as a potential tipping element (e.g. Armstrong-McKay et al., 2022), though the response of mountain glaciers to global warming and potential overshoot are not uniform globally and depend on region and the individual glaciers' sensitivity to temperature change. Like the polar ice sheets, mountain glaciers do not respond immediately to changes in climate, but rather the committed volume loss due to warming manifests over decades to centuries following the change in temperature forcing (Zekollari et al., 2025). Few studies have investigated the response of mountain glaciers to overshoot and thus there remains considerable uncertainty in the timing and rate of mountain glacier mass loss and potential recovery. Despite their typically-linear response to warming (Rounce et al., 2023), the few available studies demonstrate that slowly-responding glaciers will still undergo additional long-lasting glacier mass loss with overshoot than if temperatures were stabilised to the same level without a period of overshoot (Schuster et al., 2025). Fast-responding glaciers, such as those in steeper regions (Zekollari et al., 2020), may exhibit partial regrowth following overshoot.

Atlantic Meridional Overturning Circulation (AMOC): A collapse of the AMOC has been observed in models across the hierarchy, from conceptual models (Stommel, 1961) to state-of-the-art Earth System Models (Van Westen et al., 2024; Romanou et al., 2023) and is usually taking more than a century to occur. The main positive feedback leading to this tipping behaviour is related to the northward salt advection (Stommel, 1961, Van Westen et al., 2024). AMOC's response to overshoot scenarios can be thoroughly understood in conceptual models (e.g. Alkhayuon et al., 2019; Chapman et al., 2024) and explored in ESMs using extreme freshwater or temperature forcing profiles (e.g. Jackson et al., 2023; Hawkins et al., 2011). However, the tipping point for the AMOC has the largest uncertainty range of all tipping elements (Lenton et al., 2023; Armstrong-McKay et al., 2022) and therefore determining overshoot profiles that avoid tipping the AMOC is challenging. This is due to the large uncertainty in AMOC projections, with reduction going from 3 to 72% in 2100 mainly depending on the CMIP6 model considered. As such, coordinated experiments are useful to assess the AMOC dynamics (and notably importance and strength of the salt advection feedback) in various models, in response to the same surface perturbations (contrary to emission scenarios where surface forcing of the AMOC can be very different among models). In this respect, the TIPMIP initiative (Winkelmann et al., 2025) is welcome to better understand differences in models. Improvements in the understanding of key oceanic processes that influence the AMOC like eddies (Hirschi et al., 2020) and salt fluxes (Faure Ragani & Dijkstra, 2025), combined with the observational-constraints framework (Portmann et al., 2025), allows to reduce uncertainty concerning its tipping point and characteristics to better assess tipping risk related to overshooting scenarios.

North Atlantic Subpolar Gyre convection (SPG): The SPG is a subset of the larger-scale AMOC, focusing on the subpolar gyre region, south of Iceland. This specific circulation has been shown to have tipping behaviour and bistability regimes in conceptual models (Born & Stocker, 2014), EMICs (Levermann and Born, 2007) as well as CMIP models (Sgubin et al., 2017; Swingedouw et al., 2021). The tipping point might be related to a critical surface salinity beyond which stratification might become too strong to allow any convection before the formation of sea ice (Swingedouw et al., 2020; Wood et al., 2024). The time scale of a deep convection collapse in the SPG is about one decade, making this tipping element faster than an AMOC collapse. As such, it might be very sensitive even to short-term overshoot. The response of the SPG strongly depends on the model considered, so the implications of an overshoot on the risk of collapse have not been properly assessed up to now. However, some models do show a collapse of the deep convection in the SPG for low-emission scenarios like SSP1-2.6, raising concerns for neighbouring regions like the UK and western Europe (Sgubin et al., 2019). To improve estimates of the proximity to a deep convection collapse in the SPG linked with potential global temperature overshoots, improvements in deep convection processes and the spread of freshwater from the borders of the SPG (related to Greenland melting for instance) to the centre might be crucial to improve (e.g. Swingedouw et al., 2022).

Amazon Rainforest: The potential of climate change to cause an Amazon rainforest tipping from a closed-canopy, humid tropical forest system to a more open, drier, and savanna-like ecosystem remains an iconic risk associated with rising atmospheric greenhouse gases (Flores et al., 2024; Brando et al., 2025, Melnikova et al. 2025). This leads to regional climate change and water stress to the forest system, first identified by Friend et al. (1997) and Cox et al. (2000) but also in subsequent literature (Cox et al., 2004; Malhi et al., 2009; Nobre et al., 2016; Parry et al., 2022; Flores et al., 2024). In addition to climate change alone, direct deforestation and forest degradation (e.g. from fires) also pressure the Amazon rainforest. When combined, these pressures interact, reducing the overall resilience and lowering the tipping point, potentially anticipating tipping from one adverse influence alone (Boers et al., 2017; Lovejoy & Nobre, 2019; Bochow & Boers, 2023; Flores et al., 2024). This implies that all efforts are needed for the prevention of Amazon rainforest tipping, potentially including whether deliberate reforestation could adjust the adjust the Amazon rainforest's tipping point, or create inertial effects, such that the forest would be more resilient to any imposed decadal or century-timescale temperature overshoot. Ritchie et al (2021) estimate that the Amazon rainforest may be resilient if exceedance of its warming tipping point was limited to only a few decades. However, as of yet, a dedicated study on temporary exceedance of the Amazon rainforest tipping point is still lacking. Frequent extreme droughts, such as in the years of 2005, 2010, 2015/2016 and 2023/2024 (Marengo et al., 2024; Espinoza et al., 2024; Jiménez-Muñoz et al., 2016; Lewis et al., 2011), may provide empirical evidence of how forests may respond in the future. Trees can withstand drier conditions for a certain period of time, but there are limits to adaptation (Wunderling et al., 2022). Better ecological understanding will reveal if a temperature overshoot pathway associated with a temporary dry period in the Amazon rainforest can be withstood or not. Initial studies suggest that once a temperature overshoot period ceases, regional rainfall patterns are expected to experience lasting changes through atmosphere–vegetation feedbacks, as reduced forest cover weakens evapotranspiration and moisture recycling, leading to either higher or lower rainfall levels depending on the region (Kim et al., 2022; Oh et al., 2022; Schleussner et al., 2024).

Boreal Forests: Boreal forests, one of the largest terrestrial biomes on Earth, store about a third of the global terrestrial carbon above and below ground (Bradshaw & Warkentin, 2015) and destabilization could result in additional global warming due to the release of carbon dioxide (Armstrong McKay et al., 2022). The biome does not exhibit a gradual decline in tree cover towards the ecological limits, but demonstrates high susceptibility to abrupt shifts between stable but competing forest, grassland-steppe, and shrubland states with differing effects on surface albedo and disturbance regimes (Scheffer et al., 2012, Gauthier et al. 2015). Two primary tipping processes influence boreal forest dynamics and the associated carbon sequestration rates. Firstly, southern dieback is driven by warming-induced drought stress, coupled with increased fire frequency, lower pest resilience, and limited seed availability, which constrains regrowth, leading to rapid shifts in forest composition and density, and facilitating the expansion of steppe or temperate forests at regional to sub-continental spatial scales (Rao et al., 2023). On the other hand, northern forest expansion into tundra areas is expected due to longer and warmer growing seasons and would reduce winter surface albedo, potentially reinforcing warming effects. Recent evidence suggests that this shift is much slower than the southern steppe transition but that improved growing conditions have increased the productivity in the northern boreal forests (Berner & Goetz, 2022, Rotbarth et al., 2023). Therefore, for a temperature overshoot, the risk of boreal forest dieback in the south is greater than boreal forest expansion in the north (assuming the same tipping point). While boreal forest loss is generally reversible on centennial timescales, nonlinear biome shift at the southern margin, to woodland or treeless states, alter the ecosystem state at regional to sub-continental spatial scales. A temperature overshoot could in turn lead to the loss of ecosystem-protected and -modified permafrost, which exhibits a strong coupling between forest cover and active layer dynamics, particularly in terms of water availability (Stuenzi et al., 2022). The associated permafrost thaw and ground ice melt is not reversible within centennial timescales.

Warm-Water Coral Reefs: Warm-water coral reefs, which play a critical role in supporting marine biodiversity and human livelihoods, are among the most vulnerable ecosystems to anthropogenic driven climate change, with a tipping point for collapse closely tied to rising global temperatures and CO_2 concentrations. Collapse is defined as having insufficient live cover (typically <10%) and diversity of hard corals to support the wide diversity of species and ecological interactions typical of a coral reef (Lenton et al 2023). Stressors such as rising sea surface temperatures (i.e. more severe and frequent marine heatwaves), ocean acidification, overfishing and pollution are the primary drivers of potentially irreversible transformations (Pearce-Kelly et al., 2025). The likelihood of reaching these tipping points is high, as many reefs already experience conditions beyond their thermal tolerance (IPCC AR6 WGII-SPM, 2022; Klein et al., 2024; Cooley et al., 2023; Lenton et al., 2023; Goreau & Hayes, 2024, Muñiz-Castillo et al., 2019; Reimer et al., 2024; Byrne et al., 2025). A global mean surface temperature increase of 1.2°C above pre-industrial levels (range 1–1.5°C) and atmospheric CO_2 concentrations exceeding 350 ppm are recognized as key tipping points for mass bleaching events and coral reef collapse that would lead to biodiversity and ecosystem services loss (Hansen et al., 2013; Veron et al., 2009; IPCC AR6 WGII-SPM, 2022; Lenton et al., 2023; Pearce-Kelly et al., 2025). Previous generally acknowledged estimates for temperature driven coral reef loss is 70–90% loss at 1.5°C warming and 99% loss at 2°C (Frieler et al., 2013; Schleussner et al., 2016; Hoegh-Guldberg et al., 2018; Díaz et al., 2019; Souter et al., 2021; Armstrong-McKay et al., 2022; Reimer et al. 2024). Finer-scale modelling projects a 100 % loss at 2.0 °C (Dixon et al., 2022; Kalmus et al., 2022). Moreover, co-occurring stressors (Setter et al., 2022), such as ocean acidification, pollution, storms and disease, together with cascading Earth system and ecological impacts, may further lower these tipping points, accelerating ecosystem collapse (Pearce-Kelly et al. 2025). Corals have very fast response timescales (mortality may play out over weeks to months for thermal stress, or years for chronic threats such as disease and pollution, but prolonged failure to recover over a decade or more is necessary to qualify as collapsed), suggesting anything other than the briefest overshoot period is likely to cause irreversible damage. Recovery from such tipping events is (partially) possible (Anderson, 2025; Devlin, 2022; Donner & Carilli, 2019) but challenging due to slowed coral recruitment and calcification rates following repeated disturbances. Ongoing mass coral mortality events increasingly compromise recovery potential of corals. This creates hysteresis, where reefs fail to recover even if environmental conditions improve. Hence, when emission-driven temperature overshoot is considered, lower target temperatures with a temporary overshoot can mean little difference in the coral survival compared to stabilization scenarios at higher temperatures (Tachiiri et al., 2019).

Land Permafrost: Overshooting temperature targets presents a substantial risk to permafrost stability and its climate impacts due to its potential to release vast amounts of greenhouse gases from the large quantities of carbon in the form of frozen soil organic matter (Schuur et al,, 2022) in an almost irreversible manner. While permafrost thaw is characterized by multiple regional-scale tipping processes, including abrupt thermokarst lake formation and slope slumping, these processes do not aggregate to a single globally coherent tipping point (Nitzbon et al., 2024). Therefore, permafrost is likely not a tipping element on a global scale. This means that, in contrast to other tipping elements, permafrost thaw commences with every increment of global warming and therefore there is no maximal warming limit up to which climate change impacts are minimal to permafrost (Nitzbon et al., 2024). The severity of permafrost degradation under overshoot depends on both the peak and duration of the overshoot, i.e. cumulative heat exposure (Gasser et al., 2018; Schleussner et al., 2024). Even if an overshoot is temporary, heat can penetrate deep into the soil, causing continued permafrost degradation. While some may refreeze if temperatures decline after the warming peak, much of the carbon loss is likely irreversible due to the slow formation timescales of permafrost. Even if temperature levels eventually decline, sustained microbial decomposition of previously frozen organic matter causes continued carbon emissions over centennial to millennial timescales and reinforces warming through a self-perpetuating, although relatively weak, positive feedback loop (Schwinger et al., ESD, 2022; de Vrese et al., 2021; Ji et al., 2025). Furthermore, permafrost thaw does not occur uniformly, as some areas experience localized abrupt thaw, leading to rapid carbon loss and landscape destabilization, i.e., degradation of ice-rich permafrost, and subsequent rapid ground subsidence and the formation of thermokarst landscapes (Turetsky et al., 2020; Park et al., 2025). Temperature overshoot enhances the risk of causing localised abrupt thaw. Overshooting temperature targets 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., NComms, 2022; Park et al., 2025), potentially accelerating global climate change.

5. Additional pressures on tipping elements

In addition to direct global warming impacts, further pressures such as direct anthropogenic interference, tipping element interactions and Earth system feedbacks may threaten the stability of tipping elements, and the feasibility of realising/maintaining stabilisation target levels. This means that warming tipping points may effectively be lower than their reported value in the recent literature (e.g., Lenton et al., 2023; Armstrong McKay et al., 2022) where they are studied in isolation, consequently reducing the allowable peak and duration for a temperature overshoot that does not cause tipping.

Additional anthropogenic pressures: Biosphere tipping elements suffer from additional anthropogenic interference such as deforestation in the Amazon forest, or overfishing, ocean acidification and pollution in warm-water coral reefs, further reducing its resilience. Comparable pressures are evident in the ocean: industrial shipping noise, plastic loading, and deep-sea mining increasingly disrupt marine ecosystems; in the cryosphere: soot and black carbon deposition on snow and ice accelerate melting, while infrastructure development in permafrost regions destabilizes ground systems and releases greenhouse gases; and in the atmosphere: emissions of aerosols and short-lived climate forcers (like methane and tropospheric ozone) alter radiative forcing patterns and regional monsoon dynamics. Combined with global warming, these additional pressures may cause these tipping elements to have their tipping point at effectively lower temperatures than would be the case for global warming pressure alone (e.g. Hughes et al., 2018; Lovejoy & Nobre, 2018; Setter et al., 2022; Lenton et al., 2023, Pearce-Kelly et al., 2025). Or, in turn, opportunities for improved management and local agency offer to limit these pressures and provide increased resilience within these biosphere/ecological tipping elements.

Interactions between tipping elements: Most direct interactions between tipping elements are assessed as destabilising (Wunderling et al., 2024; Lenton et al., 2023). Therefore, interactions between tipping elements exert additional pressure on the resilience of tipping elements and become relevant at 1.5°C of global warming or higher. This means that increasing temperatures can trigger a first element into tipping that in turn effectively lowers the warming tipping point for subsequent tipping elements via direct physical interactions (Wunderling et al., 2021). The AMOC sits centrally in a network of tipping elements and is therefore often viewed as a mediator of a possible cascade of tipping events (Wunderling et al., 2021). For instance, a destabilisation of the Greenland ice sheet could cause a collapse of the AMOC, that could then impact the Amazon rainforest or monsoon systems. In such an accelerating cascade of tipping elements (Ritchie et al., 2025), an overshoot that may only temporarily cross the Greenland ice sheet's tipping point and not cause tipping (due to its slow timescale), may still be sufficient to cause tipping of the AMOC as a result of its faster timescale (Klose et.al., 2024). Conversely, due to the relatively fast timescales of the AMOC, a slowdown could stabilise the slower responding Greenland ice sheet and lead to a mutual stabilisation of both tipping elements (Pöppelmeier & Stocker, 2025). Alternatively, melting from the Antarctic ice sheets could have a stabilising effect on the AMOC (Knight & Condron, 2025; Sinet et al., 2025; Sinet et al., 2023).

Earth system feedbacks: Further, there may be Earth system feedbacks that alter the risk for triggering tipping elements. Many tipping elements would cause feedbacks that increase global warming levels if they tip (Armstrong McKay et al., 2022; Ripple et al., One Earth, 2023; Lenton et al., 2023; 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. Further positive climate feedbacks include cloud feedbacks (Bjordal et al., 2020; Ceppi & Nowack, 2021) or the permafrost carbon feedback (MacDougall et al., 2020; Steinert & Sanderson, 2025). However, there are also few but potentially strong negative feedbacks on global temperatures (e.g. 0.5°C cooling due to AMOC tipping) (Armstrong

McKay et al., 2022). Therefore, the overall effect of temperature feedbacks of disintegrated tipping elements on tipping risks remains uncertain and requires improved constraints of their feedback mechanisms, direction and magnitude (Bdolach et al., 2025). Furthermore, 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 CO_2-increase and global warming (Friedlingstein et al., 2025). There is now growing evidence of a long-term weakening of land carbon sinks (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., ESD, 2022; Koven et al., 2023; Sanderson et al., 2024).

6. Implications of climate tipping risks for mitigation ambition during and after temperature overshoot

Considering these findings, the prospects of temperature overshoot must inform climate mitigation ambition in the near and longer term. Given the potential of initiating tipping processes during overshoot, and the severe risks tipping events present to societies, the ambition reflected in greenhouse gas emission reductions should aim to minimise tipping risks by limiting the peak and duration of temperature overshoot, and bringing temperatures back down to levels well below 1.5°C.

A race to net-zero CO_2: Limiting overshoot requires mitigation strategies that minimize the global peak temperature, keeping it as close to 1.5°C as possible, and returning to below 1.5°C as soon as possible (Palter et al. 2018; Wunderling et al., 2023; Schleussner et al., 2024). Peak temperature and return time are interdependent - the higher the peak, the longer the overshoot duration likely becomes. Minimizing the global peak temperature (McKenna et al., 2021) requires immediate peaking of global greenhouse gas emissions and stringent emission reductions thereafter towards global net zero CO_2 emissions by 2050 (IPCC AR6 WGIII-SPM, 2022).

Limiting Overshoot Duration: Crucially, aiming for warming reversal from peak levels above 1.5°C requires to achieve not only net zero CO_2, but substantial net negative CO_2 emissions - where anthropogenic carbon dioxide removals (CDR) exceed remaining emissions. CDR refers to a set of methods aimed at actively extracting CO_2 from the atmosphere and storing it in terrestrial, geological, or ocean reservoirs. There is an immediate need to invest in and bring to scale sustainable methods of CDR as a complement to - not a substitute for - mitigation to enable future temperature reduction. Achieving net zero greenhouse gas emissions as of Article 4.1 of the Paris Agreement requires CDR deployment to achieve net-negative CO_2 emissions to balance out residual non-CO_2 emissions and may therefore lead to a long-term temperature decline (Fuglestvedt et al., 2018; Schleussner et al., 2022). Achieving a faster temperature decline may require going even beyond net-zero greenhouse gases.

Current assessments indicate that CDR rates in overshoot 1.5°C scenarios range from 7 to 10 $GtCO_2$/yr (Smith et al., 2024). With a current rate of CDR of 2 $GtCO_2$/yr from conventional methods such as Afforestation, Forestry and Other Land Use, massive upscaling will be required to achieve the removal rate required to return warming to below 1.5°C by 2100 (Smith et al., 2024). These removals would need to be in tandem with reductions in CO_2 emissions to near zero. Even higher rates of CDR would be needed to reduce temperatures below the most sensitive tipping points (at around 1°C warming). Even if CO_2 removal rates required to restore temperature to 1.5°C after various levels of overshoot prove to be technically feasible, large upscaling of CDR is subject to various sustainability and feasibility constraints, including political preferences and social acceptability (Smith et al., 2024; Schleussner et al., 2024).

The reversibility of global temperatures remains uncertain, and substantially greater CDR deployment to achieve net-negative CO_2 emissions might be required should Earth system feedbacks exceed current expectations (Schleussner et al., 2024, Kaufhold et al., 2025). Furthermore, the potential reversibility of global mean temperature does not mean that the impacts of climate change can be reversed. While some impacts may be reversible with lowering global mean temperature, others such as sea level rise, loss of ecosystem functionality, increased risks of species extinction, and glacier and permafrost loss are not reversible on timescales of decades to millennia (Tokarska & Zickfeld, 2015; Ehlert & Zickfeld, 2018; Drouet al., 2021; Bauer et al., 2023). Further, even if temperature can be reversed on a global scale, there will likely be substantial impacts on regional-to-local scales as consequence of the overshoot (Pfleiderer et al., 2024; Schleussner et al., 2024; Steinert et al., 2025). These factors together highlight the need for climate governance to evolve to collectively manage global emissions and temperature pathways rather than focus only on achieving the long-term temperature goal. This pathway focus has direct implementation potential in the ambition cycle of the Paris Agreement, e.g., with explicit considerations in Nationally Determined Contributions, the Global Stocktake, and the Enhanced Transparency Framework.

Long-term Temperature Stabilization: The Paris Agreement temperature goal sets upper limits for global mean temperature increase above pre-industrial levels in light of the ultimate Objective of the Climate Convention to avoid 'dangerous anthropogenic interference' (UNFCCC, 1992). The Paris Agreement climate objectives are designed to achieve long-term temperature decline and do not specify a 'safe' level of global temperature stabilisation (Schleussner et al. 2022). Emerging science on tipping points risks indicates that temperature levels well below 1.5°C, potentially around 1°C above pre-industrial levels, would be required to limit tipping point risks in the long-run (Breyer et al., 2023; Rockström et al., 2023; Möller et al., 2024; Gupta et al., 2024). Considering this emerging evidence, the current temperature goal may require amendments e.g., in a future Periodic Review process under the United Nations Framework Convention on Climate Change (UNFCCC).

7. Conclusion

Recent assessments indicate that current global carbon emissions remain at high levels, making at least a temporary overshoot of the 1.5 °C target increasingly likely. Combined with evidence that some tipping points may already have been crossed, this trajectory heightens the risk that additional Earth system tipping elements could be pushed beyond their tipping points. This calls for a comprehensive risk assessment approach to quantify tipping likelihoods for various temperature overshoot pathways and for changes in climate governance to limit the risks related to Earth tipping processes.

Five, and possibly up to eight, tipping elements of the Earth system may reach their tipping point below 2°C of global warming, with some tipping points potentially exceeded below 1.5°C (see Figure 2). The risk of tipping for individual elements is found to increase for larger and longer overshoots. Minimizing the peak of an overshoot is crucial, but arguably minimizing the duration of an overshoot is of even greater importance. However, these characteristics are interrelated - invariably a higher peak temperature will result in a longer overshoot duration. Therefore, limiting peak global warming to as close to 1.5°C as possible will contribute to ensuring that the overshoot duration is limited too. This will help to avoid as many tipping points as possible from being exceeded, particularly those associated with fast elements (e.g. North Atlantic Subpolar Gyre), where it will be difficult to prevent tipping once the tipping point is exceeded, even if overshoot duration is comparatively short. Keeping the overshoot duration as short as possible and then pursuing efforts to reduce warming to levels of 1°C and below, will aid in preventing slow elements (e.g. polar ice sheets) from tipping in the long term despite some maybe already having reached their tipping points (in terms of level of warming).

Further research is needed to better understand the reversibility of elements if they were to tip. This includes determining how much further global warming must be reduced, compared to the level that triggered tipping in the first instance, to restore an element to its original state. The magnitude and timescale of such hysteresis effects, and how they differ across Earth system tipping elements, are still poorly constrained. Further, rate-induced tipping requires considerably more research: while rapidly reducing temperatures after an overshoot could shorten the period of high tipping risk, fast changes in forcing may destabilize systems that are sensitive to the rate of change rather than just absolute level. Exploring these interactions systematically across different temperature pathways is crucial for anticipating unintended consequences of both overshoot and rapid-reversal scenarios. More generally, reducing key uncertainties on tipping points, the strength and interactions of Earth system feedbacks, and the value of climate sensitivity remains fundamental for narrowing the range of possible futures and for designing strategies that minimize tipping risks.

Achieving the rapid reversal in warming needed to prevent many tipping elements from tipping, requires substantial net negative emissions. The longer CO_2 emission reductions are delayed, the larger net negative emissions must be. Additionally, the larger the overshoot, the larger the need for negative emissions and the implications of those for our planet's critical biophysical systems. Potential 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 CDR (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 to amplify global warming (e.g., Deutloff et al., 2025) or the weakening of land carbon sinks under climate change. Therefore, urgent climate action to minimise tipping risks is required, also considering additional anthropogenic pressures, interactions between tipping elements as well as uncertainties in tipping points and system timescales. This means that peak overshoot temperature (below 2.0°C), overshoot duration (below 1.5°C by the end of this century), and long-term warming stabilisation (at or below 1.0°C) must be limited to sufficiently low levels to prevent Earth system elements from tipping in the short and long term.

Acknowledgements and financial support

This review article has been carried out within the framework of the Global Tipping Points Report 2025. P.D.L.R. acknowledges support from the European Union's Horizon Europe research and innovation programme under grant agreement No. 101137601 (ClimTip): Funded by the European Union. This is ClimTip contribution #X. P.D.L.R., C.H., T.M.L. and D. S. also acknowledge support by the UK Advanced Research and Invention Agency (ARIA) via the project "AdvanTip" and D.S. via the project "SORTED". N.W. is grateful for funding support from the Center for Critical Computational Studies and the Klaus Tschira Foundation (under the grant agreement ID 25545). N.J.S has been supported by the Research Council of Norway through the project NAVIGATE (Grant 352142). D.S. acknowledges support from the European Union's Horizon Europe research and innovation programme under grant agreement No. 101137673 (TipESM) funded by the European Union. J.F.A. acknowledges support from the PREDICT project which has received funding from the European Space Agency (ESA) under ESA Contract No. 4000146344/24/I-LR. J.F.A. also acknowledges support from the Earth Commission, which is hosted by Future Earth. C.Q. acknowledges support from the Australian Research Council under Discovery Early Career Researcher Award project number DE250101025. K.L-G. acknowledges the Irène Curie fellowship of the Eindhoven University of Technology. T.M. acknowledges financial support by the Luxembourgish Fond National de la Recherche (FNR) (under the AFR PhD grant 18824314). N.B. acknowledges support from the Research Council of Norway (project number 314570).

Competing interests

The authors declare no competing financial interests.

Data and Code availability

The data and the code can be accessed here once the paper is accepted for publication: https://github.com/PaulRitchie89/Overshoots_review

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