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Global warming overshoots increase risks of climate tipping cascades in a network model

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Current policies and actions make it very likely to, at least temporarily, overshoot the Paris climate targets of 1.5–$<$2.0°C above pre-industrial levels. If this global warming range is exceeded, potential tipping elements such as the Greenland Ice Sheet or Amazon rainforest may be at increasing risk of crossing critical thresholds. This raises the question how much this risk is amplified by increasing overshoot magnitude and duration. Here, we investigate the danger for tipping under a range of temperature overshoot scenarios using a stylised network model of four interacting climate tipping elements. Our model analysis reveals that temporary overshoots can increase tipping risks by up to 72% compared to non-overshoot scenarios, even when the long-term equilibrium temperature stabilises within the Paris range. Our results suggest that avoiding high-end climate risks are only possible for low temperature overshoots and if long-term temperatures stabilise at or below today's levels of global warming.

It has long been proposed that important continental-scale subsystems of the Earth's climate system possess nonlinear behaviour[1,2]. The defining property of these tipping elements are their self-perpetuating feedbacks once a critical threshold is transgressed[3] such as the melt-elevation feedback for the Greenland Ice Sheet[4] or the moisture recycling feedback for the Amazon rainforest[5]. The global mean surface temperature has been identified as the driving parameter for the state of the climate tipping elements[6,7,1], which include, among others, systems like the large ice sheets on Greenland and Antarctica, the Atlantic Meridional Overturning Circulation (AMOC), and the Amazon rainforest[8,9,10,11].

Besides further amplifying anthropogenic global warming[3], the disintegration of such climate tipping elements individually would have large consequences for the biosphere and human societies, including large-scale sea-level rise or biome collapses. Since the first mapping of climate tipping elements in 2008[1] the scientific focus has increased, with a 2019 warning that nine of the 15 known climate tipping elements are showing signs of instability[12], followed by a listing of all known climate tipping elements with expert judgements of tipping point confidence levels in the IPCC AR6 WG1[13]. While the uncertainty for crossing tipping points is still stated as medium to high, the IPCC concludes that crossing them triggering potentially abrupt changes cannot be excluded from projected future global warming trajectories[13]. As this science has advanced over the last two decades, potential temperature thresholds have been corrected downwards several times[12]. The most recent scientific assessment places the critical threshold temperatures of triggering tipping points at 1–5°C, with moderate risks already at 1.5–2°C for several systems, like the Greenland and West Antarctic Ice Sheets[6]. In this sense, tipping elements research provides even further scientific support to hold global mean surface temperatures within the Paris range of well below 2°C, while at the same time emphasising that tipping point risks cannot be ruled out even at this lower temperature range[6,7]. There is thus a triple dilemma emerging here. First, insufficient policies and actions mean that the world is following a trajectory well-beyond

2°C by the end of this century[14]. Second, essentially all IPCC scenarios that hold the 1.5°C line include a period of several decades of temperature overshoot[15,16,13]. And third, although given the large uncertainties among the different assessments[13,17], research cannot exclude the crossing of tipping point thresholds already at low temperature rise[6]. Therefore, more knowledge is urgently needed on which overshoots still allow for low tipping risks[18,19,20].

Hence, it is essential to assess temperature overshoots and long-term temperature stabilisation levels that can lead to irreversible changes in the climate system. While the impacts of overshoots have been investigated from a mathematical point of view and for individual climate tipping elements[21,18,22], they interact across scales in space and time, creating risks for additional feedback dynamics[12,23,24,25]. Interactions may increase tipping risks by triggering cascades, when a transition of one element triggers transitions of connected tipping elements[26]. Therefore in this work, we combine interactions between climate tipping elements and temperature overshoots in a stylised network model. We designed (stylised) our model to be able to perform tipping risk assessments, but it should not be used to make predictions. We systematically assess the risk for tipping and identify a high climate risk zone, considering remaining uncertainties in the properties of the tipping elements and different global warming overshoot scenarios if Paris temperature targets are not met without overshoots.

Modelling approach

Following Wunderling et al. (2021)[26], we use a stylised network model of four coupled ordinary differential equations designed for the analysis of risk assessments, which couples four climate tipping elements (see Methods): the Greenland Ice Sheet, West Antarctic Ice Sheet, AMOC, and Amazon rainforest (Fig. 1c). We assume that each of the four elements is a climate tipping element, exhibiting a critical transition at its respective critical temperature threshold (see Methods, Eq. 1)[6,27]. Even though there is considerable uncertainty in complex climate models whether and at which global warming level the exact tipping point is located[13,17], evidence from models of varying complexity, data based approaches and paleo-climate observations are consistent with considerable risks for nonlinearities among them[6] (SI chapter 1). On the other hand, there are negative feedbacks, such as the Planck feedback, CO_2-fertilisation, ocean solubility of CO_2, and ocean heat uptake that stabilise the climate system[13,28,29]. Those negative feedbacks, generally well represented already in climate models (as compared to the tipping elements explored in this paper), might modify the tipping properties of some tipping elements. For example, the positive ice-albedo feedback despite competition with the negative Planck feedback has been shown to induce two stable large-scale Earth system states, a snowball Earth and a warm state[30,31]. On the smaller scale of climate tipping elements, the Planck feedback would be large if the global mean temperature increase from disintegrating climate tipping elements is large because the Planck feedback operates on the global mean temperature. At least for the large ice sheets on Greenland and West Antarctica, however, this effect may be limited since their complete disappearance would lead to a global warming of less than 0.2°C in total[32]. On the other side, although the Amazon rainforest is stated to lose resilience[33], the formation of spatial patterns[34,35] and climate change may not affect all parts of the Amazon rainforest equally[36] and could prevent a single system-wide tipping event.

Nevertheless, we argue that sufficient evidence exists for climate tipping points to justify a risk analysis approach based on the precautionary principle. It is important to quantify tipping risks because the likelihood of tipping points existing is nonzero, and if they exist, they present high climate risks for the biosphere and human societies[6,12]. This has been re-emphasised in a recent study remarking that current risk assessments of high-end climate change scenarios (including tipping elements) are dangerously underexplored[37,38]. Simplified representations of more complex phenomena is a useful modelling approach in this context for capturing broad-scale patterns and risks.

Since the four tipping elements are not individual subsystems, we conceptualise the interactions as linear couplings in our model (Eq. 1). Each of these interactions has a driving physical mechanism behind it (Fig. 1c), which was coarsely quantified by a formalised expert elicitation[25]. While these interaction estimates were coarse, newer literature confirms and substantiates them[26,39,40,41], enabling us to assess cascading tipping risks at a certain level of global warming. For further details on the exact nature of the interactions see Fig. 1c and Wunderling et al. (2021)[26].

Overall, our network model is able to capture the main dynamics of these four interacting tipping elements, and is therefore able to propagate important uncertainties in the input parameters. It is designed to assess the risk for critical transitions, but can as such not be used for predictions, nor to assess whether tipping points exist or not, but their existence is an a-priori assumption in this work. Important model uncertainties include critical temperature thresholds, interaction strengths and interaction network structures, as well as typical transition time scales of individual tipping elements (see Methods and Tab. S1). Here, the transition time scale is the time that is needed for a transition from the baseline to the transitioned regime for an individual (non-interacting) climate tipping element as compiled in recent literature (cf. Fig. 1)[6]. The low computational complexity of our approach allows to sample the parameter space by means of a very large-scale Monte Carlo ensemble, including approximately 4.455 million individual ensemble members in total. For the construction of the ensemble, but also for the boundary values of the parameters uncertainties (based on the latest literature review[6]), see Methods. Lastly, there is not only uncertainty in model parameters, but also in the assumed (fold-bifurcation) structure of the tipping elements themselves due to negative feedbacks, at different strengths, modifying the bifurcation structure. This uncertainty can be taken into account by altering the prefactors of the cubic and linear terms of Eq. 1. Therefore, it would be possible to probe scenarios where some of the tipping elements are weak (or not) nonlinear systems. However, since exact values for these prefactors cannot be straightforwardly derived from existing data, such a sensitivity assessment is beyond the scope of this work. More importantly, our present study focuses on the high-end risk case where all considered climate subsystems possess tipping points.

In our numerical experiments, the four tipping element network is exposed to different global warming overshoot scenarios characterised by peak temperature, overshoot duration, and the final convergence temperature reached in long-term equilibrium (Fig. 1a). All these important properties of the overshoot trajectory determine the potential of a tipping event. The stylised temperature overshoot trajectories applied to the four interacting climate tipping elements, were primarily designed to capture typical temperature profiles generated by Earth System Model simulations for low to medium emission scenarios[42]. Moreover, the formulation of the trajectories allows for flexibility in how society manages the transition from current warming to the convergence temperature, which can therefore lead to overshoot trajectories[18]. To this end, our ensemble spans all combinations of (i) peak temperatures $T_{\text{Peak}} = 2.0, 2.5, ..., 6.0$°C (maximally reached temperature), (ii) convergence temperatures $T_{\text{Conv}} = 0.0, 0.5, ..., 2.0$°C (final stabilisation temperature), and (iii) convergence times $t_{\text{Conv}} = 100, 200, ..., 1000$ years (time to reach T_{Conv}), allowing us to quantify the respective risk and time scale for tipping events. Note that the limit case of $T_{\text{Peak}} = T_{\text{Conv}} = 2.0$°C is simulated as constant temperature. In this paper, we will focus on peak temperatures up to 4.0°C, where 4.0°C represents an upper temperature limit we investigate, based on *policies and targets* following COP26 and the climate-action-tracker[14]. High-end warming scenarios with peak temperatures of 4.5–6.0°C are added in the Extended Data figure material, which allow computing a comprehensive risk analysis. Fig. 1a presents an exemplary timeline of an overshoot trajectory that peaks at 2.5°C warming and converges to a 2.0°C convergence temperature after 400 years. The impact on the four studied interacting tipping elements is shown in Fig. 1b (for further examples see Extended Data Fig. 1). In the remainder of this work, the impact of a certain relevant parameter combination (T_{Peak}, T_{Conv}, t_{Conv}) on the risk of an element tipping is given by the fraction of all simulation runs that result in the transitioned regime, averaged over all other parameters and uncertainties. We define the tipping of an element as the tipping process being completed, i.e. when the tipping element reaches the transitioned regime (cf. Fig. 1b). We first evaluate the tipping risk with respect to the overshoot peak temperature, convergence temperature and convergence time, and identify risk maps for a high climate risk zone. After that, we determine the mechanisms and reasons for tipping events.

The effects of overshoot peak temperature

Focusing on the role of overshoot peak temperature, we find that the risk for the emergence of at least one tipping event increases with rising peak temperature. Averaged over all ensemble members, around one-third (36.5±5.0%) of all simulations show a tipping event or cascade at a peak temperature of 2.0°C, while it is close to three-quarters (74.3±1.4%) of all simulations at 4.0°C peak temperature (Fig. 2a). However, the dependence on the peak temperature is unevenly distributed among the four different climate tipping elements (Fig. 2b). The tipping risk for tipping elements with high inertia (slow tipping elements: Greenland and West Antarctic Ice Sheets) remains relatively constant over an increasing peak temperature because their reaction time (500–13,000 years) is slow against the duration of the overshoot trajectory ($t_{\text{Conv}} = 100 - 1,000$ years). Therefore, the tipping risk for the Greenland Ice Sheet remains relatively constant between 14.0±5.7% ($T_{\text{Peak}} = 2.0$°C) and 16.0±3.5% ($T_{\text{Peak}} = 4.0$°C, Fig. 2b). In contrast, for tipping elements with low inertia (fast tipping elements: AMOC and Amazon rainforest) there is a strong tipping risk increase, comparing 24.7±3.7% ($T_{\text{Peak}} = 2.0$°C) with 50.8±4.4% ($T_{\text{Peak}} = 4.0$°C, Fig. 2b) for the AMOC. On the other hand, the tipping risk for the slow tipping elements increases for increasing convergence times (Extended Data Fig. 3), whereas the tipping risk for the fast tipping elements only increases slightly for increasing convergence times above 200 years. This subsequent increase can largely be attributed to cascading effects, where typically the Greenland Ice Sheet tipping has initiated tipping on the faster elements. Fig. 2 shows the equilibrium results after 50,000 simulation years, which demonstrate the long-term commitment due to transgressed tipping thresholds. While this provides an important insight into potential locked-in change, some tipping risks are already realised after 100–1,000 years. On these shorter time scales, especially the AMOC and the Amazon rainforest show a strong dependence on the peak temperature (Extended Data Fig. 2).

Risk maps for identifying a high climate risk zone

For final convergence temperatures comparable with today's levels of warming (approx. $T_{\text{Conv}} = 1.0°\text{C}$), we find that the expected number of tipped elements is at least $< \# >_{\text{tipped,min}} = 0.29$ (Fig. 3a). This minimal number of tipped elements is evaluated for the most optimistic case of this study (lowest-left parameter combination in Fig. 3), where the peak temperature reaches 2.0°C above pre-industrial and the convergence time is 100 years. The tipping risk that at least one tipping element transitions to its alternative state (related to $< \# >_{\text{tipped,min}} = 0.29$) is 15% (Fig. 3d). Stabilising global warming at the lower (upper) limit of the Paris range at 1.5°C (2.0°C) above pre-industrial levels, increases the number of minimally tipped elements (to 1.19 and 1.89, Fig. 3b, c).

We define a *high climate risk zone* as the region, where the likelihood for no tipping event is smaller than 66%, or the risk that one or more elements tip is higher than 33%. We compute this risk and find a marked increase for increasing convergence temperatures (compare Fig. 3d, e, f). For convergence temperatures of 1.5°C and above, our results indicate that the high climate risk zone spans the entire state space for final convergence temperatures of 1.5–2.0°C. Only if final convergence temperatures are limited to, or better below, today's levels of global warming, while peak temperatures are below 3.0°C, the tipping risks remain below 33% (Fig. 3d). In parallel, the equipotential lines shift strongly from higher peak temperatures and convergence times to lower ones with increasing convergence temperature. This leads to a lower likelihood of low-risk scenarios without tipping elements transitioning to their alternative state. In the worst case of a convergence temperature of 2.0°C (Fig. 3f), the tipping risk for at least one tipping event to occur is on the order of above 90% if peak temperatures of 4.0°C are not prevented. The devastating negative consequences of such a scenario with high likelihood of triggering tipping events would entail significant sea level rise, biosphere degradation or considerable North Atlantic temperature drops.

Therefore, this would entail an *unsafe overshoot* regime. On the other hand, strictly lowering the final convergence temperature to or below today's levels of global warming while limiting peak overshoot temperatures to 3.0°C and convergence times in parallel significantly reduces the risk of tipping events (Extended Data Fig. 4 and Fig. 3d). In the most optimistic scenario, tipping risks are kept below 5%.

Tipping mechanisms under warming overshoots

The risk for tipping events increases with higher peak temperatures, higher convergence temperatures, and longer convergence times. However, the mechanism causing a tipping event in our model is twofold: (i) The element tips due to the final temperature T_{Conv} being higher than its critical temperature threshold. We call this *baseline tipping* because the final baseline (T_{Conv}) is already higher than the critical temperature (e.g. Fig. 1a,b for the Greenland Ice Sheet). (ii) The element tips due to the temperature overshoot trajectory, which temporarily transgresses its critical temperature threshold. We call this *overshoot tipping* (e.g. Extended Data Fig. 1c for AMOC). In both cases, baseline or overshoot tipping, the first tipped element can draw along other elements in a cascade such that the size of the cascade is not necessarily restricted to one.

Our results show that the risk for tipping events in scenarios converging within the limits of the Paris climate target, ranges from 57.8% to 91.4% (Fig. 4). For small peak temperatures ($T_{\text{Peak}} = 2.5°\text{C}$), overshoot tipping only accounts for as little as 9% of all tipping events but for higher peak temperature levels ($T_{\text{Peak}} = 4.0°\text{C}$) this number can increase to as much as 42% (bar charts in Fig. 3). Specifically, the risk of tipping increases between 10–72% in these scenarios for overshooting before stabilising at the convergence temperature as compared to non-overshoot scenarios. Note that in the special case, where the peak temperature equals the convergence temperature ($T_{\text{Peak}} = T_{\text{Conv}} = 2.0°\text{C}$), overshoot tipping events do not occur.

The number of expected tipping events increases from short to long time scales as tested in our experiments, where we separated tipping events realised after 100 (short-term tipping), 1,000 (mid-term tipping) and 50,000 simulation years (equilibrium tipping, pie charts in Fig. 4). For higher peak temperatures, we additionally observe a larger portion of tipping events realised within 100 and 1,000 years. These short-term events are dominantly caused by the fast tipping elements (AMOC and Amazon rainforest), but mid-term events are additionally also partially caused by a tipping West Antarctic Ice Sheet (Extended Data Fig. 2). Together our results indicate that, in order to avoid tipping events within the Paris range, not only the peak temperature must be limited but also the final convergence temperature has to fall significantly below 1.5°C in the long run (Figs. 3 and Extended Data Fig. 7). To further hedge tipping risks, the time to reach the convergence temperature must also be small (i.e. $t_{\text{Conv}} \lesssim 200$ yrs, cf. Extended Data Fig. 4c,d). However, current *policies and action* would lead to 2.0–3.6°C (mean: 2.7°C), and present *pledges and targets* to 1.7–2.6°C (mean: 2.1°C) above pre-industrial, based on the COP26-update published in November 2021 as expected temperatures in 2100 (see climateactiontracker and vertical axis in Fig. 4c)[14]. As noted above, these temperatures would lead to significant tipping risks if they were interpreted as peak temperatures. If they would be convergence temperatures, tipping very likely is unavoidable. Additionally, high-end scenario simulations with very high peak temperatures between 4.5–6.0°C reveal that the risk to observe tipping becomes virtually certain (>95% for $T_{\text{Peak}} \gtrsim 5.5$°C). At these scenarios, it is likely (>40%) that the first tipping event would occur within 100 years, typically the Amazon rainforest or AMOC (Extended Data Fig. 8).

Furthermore, we investigate the effects of interactions between the tipping elements on the risk of (cascading) transitions in overshoot scenarios (SI chapter 2 and Fig. S1). Our results show that increasing the interaction strength from 0.0 (no interaction) to 0.3 increases the average number of tipped elements strongly (by 49.3±2.1%) at a convergence temperature of 2.0°C. A further increase of the interaction strength from 0.3, only leads to a marginal additional tipping risk (of 12.1±0.5%, Fig. S1e).

Discussion

In summary, we find that in our stylised network model the high climate risk zone characterised by large tipping risks (>33%) can only be avoided if several aspects are met in parallel due to the different time scales involved. These aspects are limited overshoot peak temperatures, limited convergence times, and most importantly limited convergence temperatures (due to baseline tipping) to a level of, or better, below the current level of global warming (1.2°C)[14]. Our model analysis shows that the overshoot peak temperature should be constrained based on fast tipping elements (Fig. 2b), whereas slow tipping elements largely determine the upper limit for convergence times (Extended Data Fig. 3). The convergence temperature needs to be limited to avoid baseline tipping, and lower levels of it will also assist in avoiding overshoot tipping (Fig. 4). Therefore, the combination of the slow Greenland Ice Sheet having a low temperature threshold and the faster elements (AMOC, Amazon rainforest) having at least partially higher thresholds (Tab. S1), facilitates the possibility of a small overshoot without causing tipping events and thus further cascades. Ritchie et al. (2021)[18] came to similar conclusions for individual tipping elements but we find, for a sufficient interaction strength ($\gtrsim$0.2), a marked increase in the expected number of tipped elements in equilibrium due to the possibility of emerging tipping cascades (Fig. S1). Taken together, safe and unsafe temporary overshoot trajectories can clearly be separated.

The choices of our stylised global warming overshoot scenarios are motivated by current knowledge, summarising short and long-term effects. The shape of the short-term overshoot trajectories captures the temperature profiles from different Earth system model simulations[42], but is still of conceptualised nature (Eq. 2). To allow for a direct comparison to the baseline critical temperatures, we keep the temperature trajectories at constant levels in the long run. While this is supported by ZECMIP (Zero Emissions Commitment Model Intercomparison Project) for the near- to intermediate future for decades to centuries[43,44], it is unclear how carbon sinks and sources behave for the more distant future. On time scales of centuries to millennia, it seems more likely than not that a slight downward trend of global mean temperatures will be entered[44,45,46]. Still, large uncertainties remain and make future research necessary as has for instance been proposed by using a novel framework of model experiments for zero emission simulations[47]. Overall, it is questionable whether naturally decreasing temperatures would be sufficient to bring global mean temperatures after an overshoot back down to safe levels without additional artificial carbon removal from the atmosphere[46].

Our employed stylised network model does not directly capture physical processes or the spatial extent of tipping elements (e.g. important for spatial heterogeneity), and can as such not be used as a model for predictions, but has been designed as a risk assessment tool for some of the potentially most nonlinear and societally harmful elements in the Earth system. Thus, a benefit of low complexity models such as ours is that they allow for very large-scale Monte Carlo ensemble simulations, which can take into account relevant uncertainties, e.g., in interaction structure, strength and critical temperature thresholds. Still, future research should also be targeted at building more complex models around coupled nonlinear phenomena and climate tipping elements, either by combining simple physics-based models and combining those models with observational data[48,49,50,51], or by employing Earth System Models of either intermediate or high complexity. In the latter case, tipping elements could be spatially resolved, which might refine or modify some of the results gained here[35]. Moreover, data-based approaches or machine learning should be considered, with which it might be possible to reconstruct actual interaction strength values[17,52]. Recently, it has also been proposed to combine these two research strands to what has been framed “neural” Earth system models[53]. Also, uncertainty in the assumed fold-bifurcation structure should be taken into account in future work to probe how results are affected if some of the tipping elements were less nonlinear, e.g. due to spatial pattern formation or negative feedbacks[28,34,35]. Most importantly, this would decrease the abruptness of change expected in the model, or may increase the time for complete disintegration of the respective (tipping) element. Thus, the convergence time for safe overshoots would likely be larger.

Even in the absence of climate tipping points, future climate change will cause significant economic, ecological and societal damage, however, the need for climate action becomes even more urgent if (interacting) climate tipping elements would undergo a critical transition during an overshoot[54,55,56]. Critically, to reduce the risk and prevent the negative impacts of interacting climate tipping elements on human societies and biosphere integrity, it is of utmost importance to ensure that temperature overshoot trajectories are limited in both magnitude and duration, while stabilising global warming at, or better, below the Paris agreement’s targets. Furthermore, also many of the low global mean temperature scenarios, limiting warming to well-below 2°C above pre-industrial levels, are forced to include an overshoot period over 1.5°C[57,58]. Our paper highlights the importance to investigate further the risks of triggering non-linear changes also during these lower and shorter overshoots in future work. Although our results motivate that a future climate trajectory without or with limited temperature overshoots would be preferable, current results from the COP conferences and their pledges and targets indicate that at least temporary overshoots over the Paris range seem likely[14,59]. This would not only be problematic because of natural risks exerted by the potential of disintegrating climate tipping elements, but also economic damages would be smaller in case of a non-overshoot scenario[59,60].

Data availability. The data on overshoot trajectories and time series of the 4.455 million individual ensemble members are, due to the very high storage requirements, available from N.W. upon reasonable request. The code that led to these results is freely available (see code availability statement).

Code availability. The code leading to the overshoot trajectories and tipping risk assessments is available within the python modelling package *pycascades* at `https://pypi.org/project/pycascades/`, together with a model description paper[61]. The version of pycascades of the results of this manuscript is stored together with a readme, code of the figure files and intermediate evaluation scripts under the doi: . In case of questions, requests or required assistance, please contact N.W..

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Author contributions

R.W., J.R. and J.F.D. conceived the study. N.W. designed the study, performed the simulations and led the writing of the manuscript with input from all authors. N.W., S.L. and B.S. prepared the figures with input from R.W., J.R. and J.F.D.. J.F.D. led the supervision of this study.

Competing interests

The authors declare no competing interests.

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Methods

Interacting climate tipping elements model. We use the stylised network model designed for risk analysis of four interacting tipping elements detailed in Wunderling et al. (2021)[26]. Each tipping element is described by the following differential equation

$$\frac{dx_i}{dt} = \left[-x_i^3 + x_i + \sqrt{\frac{4}{27}} \cdot \frac{\Delta\mathrm{GMT}(t)}{T_{\text{crit, i}}} + d \cdot \sum_{\substack{j \\ j \neq i}} \frac{s_{ij}}{10} \left(x_j + 1 \right) \right] \frac{1}{\tau_i}. \tag{1}$$

Here, x_i describes the state of the respective tipping element $i = \mathrm{GIS},\ \mathrm{AMOC},\ \mathrm{WAIS},\ \mathrm{AMAZ}$ (GIS: Greenland Ice Sheet, AMOC: Atlantic Meridional Overturning Circulation, WAIS: West Antaractic Ice Sheet, AMAZ: Amazon rainforest). This differential equation possesses two different stable states: a baseline regime around $x_i \approx -1.0$ and a transitioned regime around $x_i \approx +1.0$. $\Delta\mathrm{GMT}(t)$ denotes the global mean surface temperature increase above pre-industrial levels (as compared to the 1850–1900 level). This term is time dependent because of the time dependence of the overshoot trajectory, which serves as our input: $\Delta\mathrm{GMT}(t) =$ overshoot trajectory(t). The mathematical form of the overshoot trajectory is given below in the methods section: *temperature overshoot trajectories*. $T_{\text{crit, i}}$ denotes the critical temperatures for the four tipping elements. The link strength values s_{ij} are taken from an expert elicitation[25], and each represent a physical mechanism (see Fig. 1c and Tab. S1). While these link strength values are quantified, the absolute importance of the interaction is not known for many of the interactions. Therefore, we introduce the interaction strength parameter d, which is varied between 0.0 and 1.0, where $d = 0.0$ means no interaction between the tipping elements and $d = 1.0$ means that interactions are approximately as important as the individual dynamics. With that we can probe a large range of possible interactions strengths among the tipping elements.

Lastly, the time scale-parameter τ_i denotes the transition time of a particular tipping element. Of course, the four stylised differential equations above (Eq. 1) are a strong simplification of the more complex tipping elements. However, they represent a summary of the main stability patterns, as has been argued in literature before[26,27]. For more details on the mathematics in this model, please be referred to Wunderling et al. (2021)[26]. As initial conditions at $t = 0$, the states of the four climate tipping elements are set to $x_i = -1.0$ (the completely untipped, baseline regime), and the parameters for T_{crit}, s_{ij}, τ_{i} are chosen from their respective limits (see Methods: *parameter uncertainties* and Tab. S1).

Parameter uncertainties. There are uncertainties in several parameters of the model (Eq. 1 and Tab. S1): (i) In the critical temperature regimes $T_{\text{crit, i}}$, which are taken from the recently refined literature values[6]. (ii) The interactions between the climate tipping elements all represent physical mechanisms behind each pair of tipping elements. For instance a melting Greenland Ice Sheet induces a freshwater input into the North Atlantic and, by that, weakens the AMOC, while a weakening AMOC would reduce the warming over Greenland (Fig. 1). There is a considerable uncertainty of the link strength parameters s_{ij}, which are included in our uncertainty analysis, and their values are taken from an expert elicitation on interacting climate tipping elements[25]. The same values for interaction strengths have been used in earlier research on tipping cascades[26]. (iii) The upper and lower bounds for transition times for the four tipping elements are again taken from recent literature[6]. It is important to note that the timescales for tipping vary from decades, over centuries up to millennia depending on the respective tipping element. While the Amazon rainforest and the AMOC tip on shorter timescales (decades to centuries), the Greenland and West Antarctic Ice Sheets take longer to disintegrate (multiple centuries to millennia). These, on at least two orders of magnitude, different transition times have important effects on the dynamics of tipping, and as to whether a specific tipping event occurs or not. These effects are discussed in the main text.

Propagation of uncertainties via a Monte Carlo ensemble. Since there are considerable uncertainties in the critical temperature regimes, interaction strengths and structure, as well as in the transition time scales, we set up a large-scale Monte Carlo ensemble to adequately propagate the uncertainties in these parameters. The uncertainty range of the parameter uncertainties are given in Tab. S1. For each combination of peak temperature ($T_{\text{Peak}} = 2.0, 2.5, ..., 6.0$°C), convergence temperature ($T_{\text{Conv}} = 0.0, 0.5, ..., 2.0$°C), convergence time ($t_{\text{Conv}} = 100, 200, ..., 1000$ years) and interaction strength ($d = 0.0, 0.1, ..., 1.0$), we draw 100 realisations from a continuous uniform distribution using a latin hypercube algorithm[62] over the uncertainties in critical temperatures, link strengths and transition times. This leads to $9 \cdot 5 \cdot 10 \cdot 11 \cdot 100 = 495,000$ ensemble members, which are looped over the 9 possible different network structures ([i] a positive link between WAIS→AMOC and a positive link between AMOC→AMAZ, [ii] a zero link between WAIS→AMOC and a positive link between AMOC→AMAZ, ..., [ix] a negative link between WAIS→AMOC and a negative link between AMOC→AMAZ). With this procedure, we obtain approximately 4.455 million ensemble members in total. By drawing from a continuous uniform distribution for all tipping elements, we slightly overestimate the overall uncertainties and perform a maximum uncertainty assessment. Therefore, our errors are conservative. After 100 years, 1,000 years and in equilibrium (here: 50,000 years), we branch off the results for each of our 4.455 million ensemble members such that we can assess our results at these three different timings.

Temperature overshoot trajectories. In this study, we have used stylised temperature overshoot trajectories based on overshoot trajectories that capture temperature profiles generated by Earth System Model simulations for a low to medium emissions scenario[42]:

$$\Delta\text{GMT}(t) = T_0 + \gamma t - \left[1 - \text{e}^{-(\mu_0+\mu_1 t)t}\right]\left[\gamma t - (T_{\text{Conv}} - T_0)\right]. \tag{2}$$

In this equation, the temperature overshoot trajectory $\Delta\text{GMT}(t)$ is determined via five parameters: (i) T_0 is the approximate current level of global warming, i.e. the point at which the trajectories start at $t = 0$. We have chosen $T_0 = 1.0°\text{C}$ above pre-industrial levels. (ii) T_{Conv} is the final convergence temperature, for which we have chosen an ensemble approach comprising $T_{\text{Conv}} = 0.0, 0.5, 1.0, 1.5, 2.0°\text{C}$ above pre-industrial. (iii) The parameter γ is chosen such that the global warming rate matches the recent past. The exponential decay term describes the development away from the linearly increasing trend (set by γ) bent towards the stabilisation level (set by T_{Conv}), specified by the parameters (iv) μ_0 and (v) μ_1. In our ensemble, we construct a temperature overshoot trajectory with a specific peak temperature T_{Peak} and convergence time t_{Conv} by iteratively altering the parameters γ, μ_0 and μ_1 until it matches the desired peak temperature and convergence time. Exemplary overshoot trajectories can be found in Extended Data Fig. 1, where the chosen parameters correspond to Fig. 1a. The chosen parameter values to get $T_{\text{Peak}} = 2.5°\text{C}$ and $t_{\text{Conv}} = 400$ years are: $\gamma = 0.0963°\text{C}\,\text{yr}^{-1}$, $\mu_0 = 1.5 \cdot 10^{-3}\,\text{yr}^{-1}$, and $\mu_1 = 1.83 \cdot 10^{-4}\,\text{yr}^{-2}$. The convergence temperature is set to $T_{\text{Conv}} = 2.0°\text{C}$. The accuracy we require for our scenarios is $\Delta T_{\text{Peak}} < 0.025°\text{C}$ and $\Delta t_{\text{Conv}} < 0.5$ years, where the convergence time is determined as the time when the temperature overshoot curve has reached the convergence temperature to an accuracy of 0.01°C.

Notes on maps. This paper makes use of perceptually uniform colour maps developed by F. Crameri[63]. The underlying world map of Fig. 1 has been created by cartopy[64].

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599 **Figure legends.**

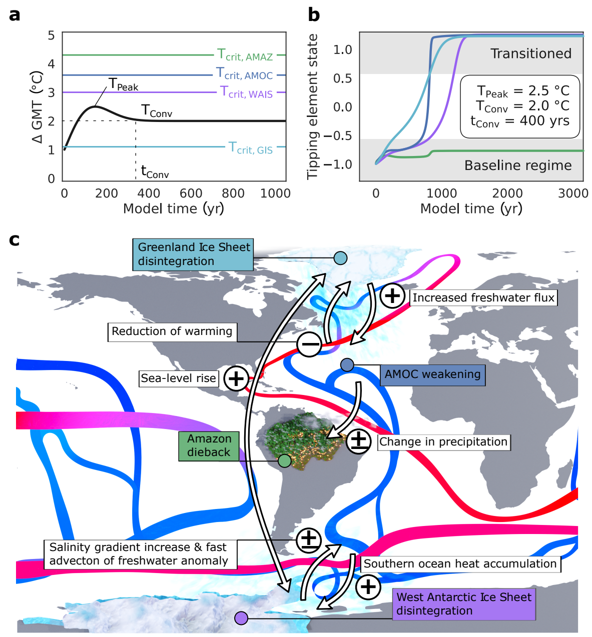


Fig. 1 | Interacting climate tipping elements. a, Exemplary global warming overshoot scenario with a peak temperature of $T_{\text{Peak}} = 2.5°\text{C}$, a convergence temperature of $T_{\text{Conv}} = 2.0°\text{C}$ above pre-industrial, and a time to convergence to 2.0°C of $t_{\text{Conv}} = 400$ years. This scenario is applied to a set of four interacting climate tipping elements with an exemplary draw of critical thresholds from their full uncertainty ranges (Tab. S1). **b,** The effect of the overshoot trajectory shown in panel a: the Greenland Ice Sheet, the West Antarctic Ice Sheet and the AMOC tip. The grey shaded areas depict the two possible states, either not tipped (baseline regime) or tipped state (transitioned). **c,** Map of the four interacting climate tipping elements. Each arrow represents a physical interaction mechanism between a pair of tipping elements, which can either be destabilising (denoted as +), stabilising (denoted as −), or unclear (denoted as +/−).

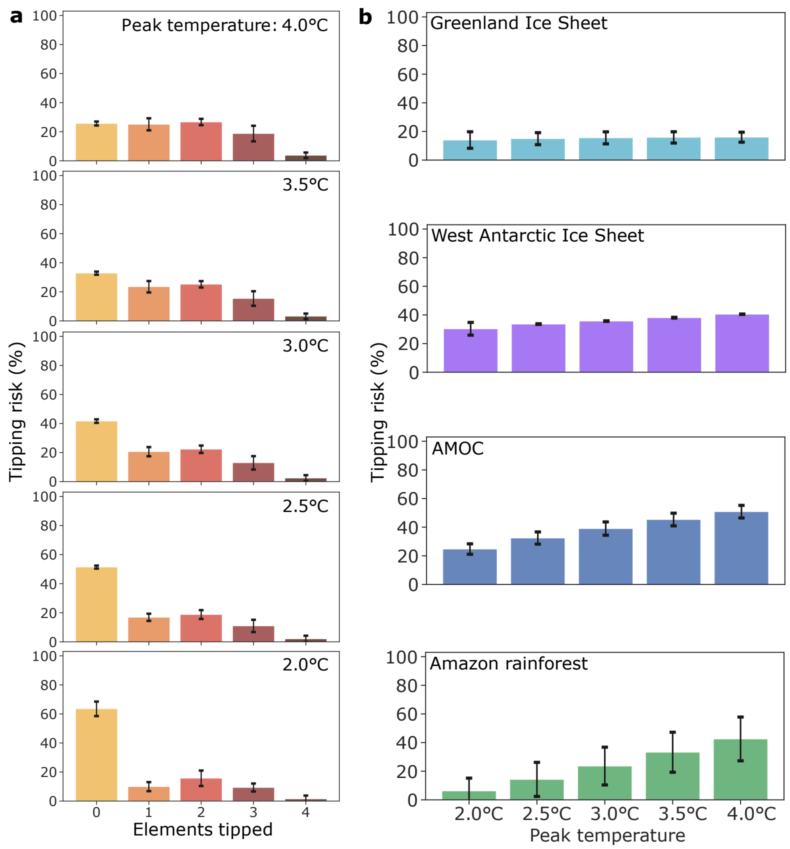


Fig. 2 | Effect of overshoot peak temperature. **a,** Number of tipped elements crossing tipping points due to additional forcing at overshoot peak temperatures of 2.0–4.0°C above pre-industrial levels. **b,** Risk for the individual climate tipping elements of transitioning into the undesired state crossing tipping points at overshoot peak temperatures of 2.0–4.0°C. We depict the average of the equilibrium run (long-term tipping after 50,000 simulation years) over the entire ensemble as the bar height and the error bars show the standard deviation. High-end overshoot peak temperatures up to 6.0°C above pre-industrial levels and transition times (after 100 yrs, 1,000 yrs, and in equilibrium), are shown in Extended Data Fig. 2.

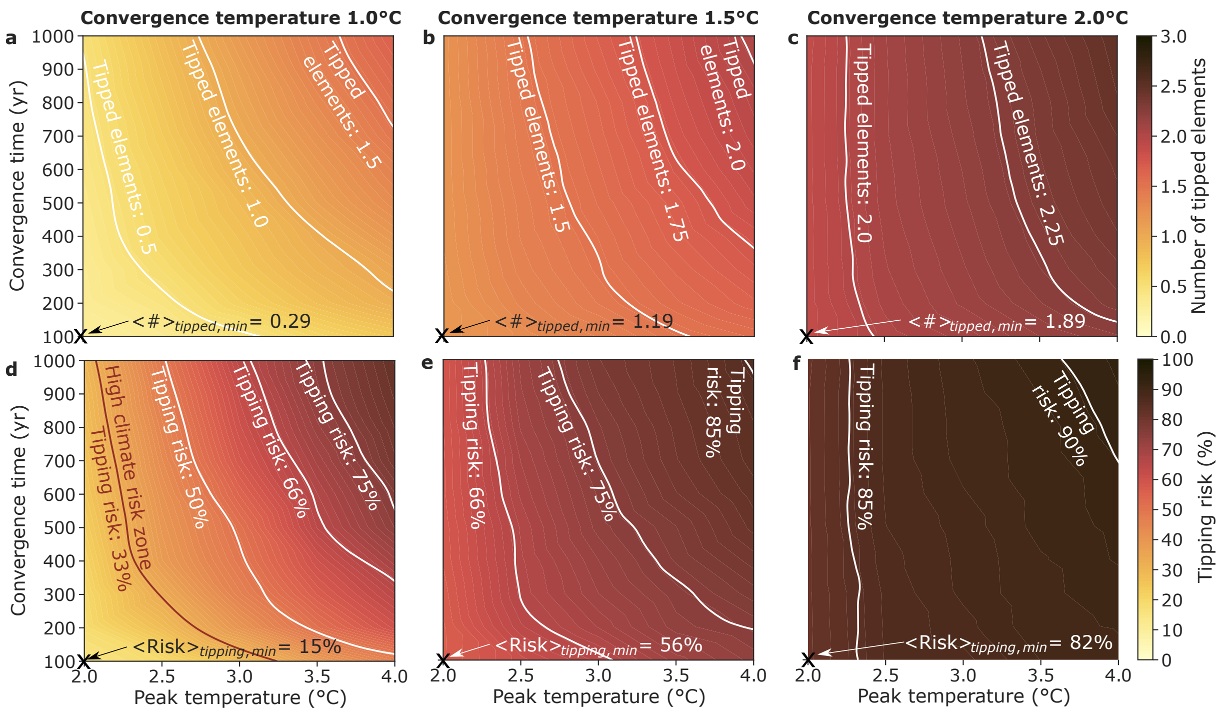


Fig. 3 | Expected number and risk of tipping events at different convergence temperatures. a, Number of tipped elements averaged over the entire ensemble for all investigated convergence times t_{Conv} and peak temperatures T_{Peak} at a convergence temperature of $T_{\text{Conv}} = 1.0°\text{C}$ above pre-industrial levels. The white lines show the conditions at which 0.5, 1.0, and 1.5 elements are tipped on average. $< \# >_{\text{tipped, min}}$ is the average number of tipped elements at $t_{\text{Conv}} = 100$ years and $T_{\text{Peak}} = 2.0°\text{C}$. **b, c,** Same as in **a**, but for convergence temperatures of 1.5°C and 2.0°C, respectively. **d,** The risk that at least one tipping element transitions to its alternative state in equilibiurm (after 50,000 simulation years) for a convergence temperature of 1.0°C. The equipotential line in red indicates the *high climate risk zone* (tipping risk is equal to 33%). $<\text{Risk}>_{\text{tipping , min}}$ is the average risk of at least one element being tipped at $t_{\text{Conv}} = 100$ years and $T_{\text{Peak}} = 2.0°\text{C}$. **e, f,** Same as for **d**, but for convergence temperatures of 1.5°C and 2.0°C, respectively. The simulations for $T_{\text{Conv}} = 0.0°\text{C}$ (return to pre-industrial temperatures) and $T_{\text{Conv}} = 0.5°\text{C}$ can be found in Extended Data Fig. 4. High-end scenarios with T_{Peak} =4.0–6.0°C are added in Extended Data Figs. 5, 6.

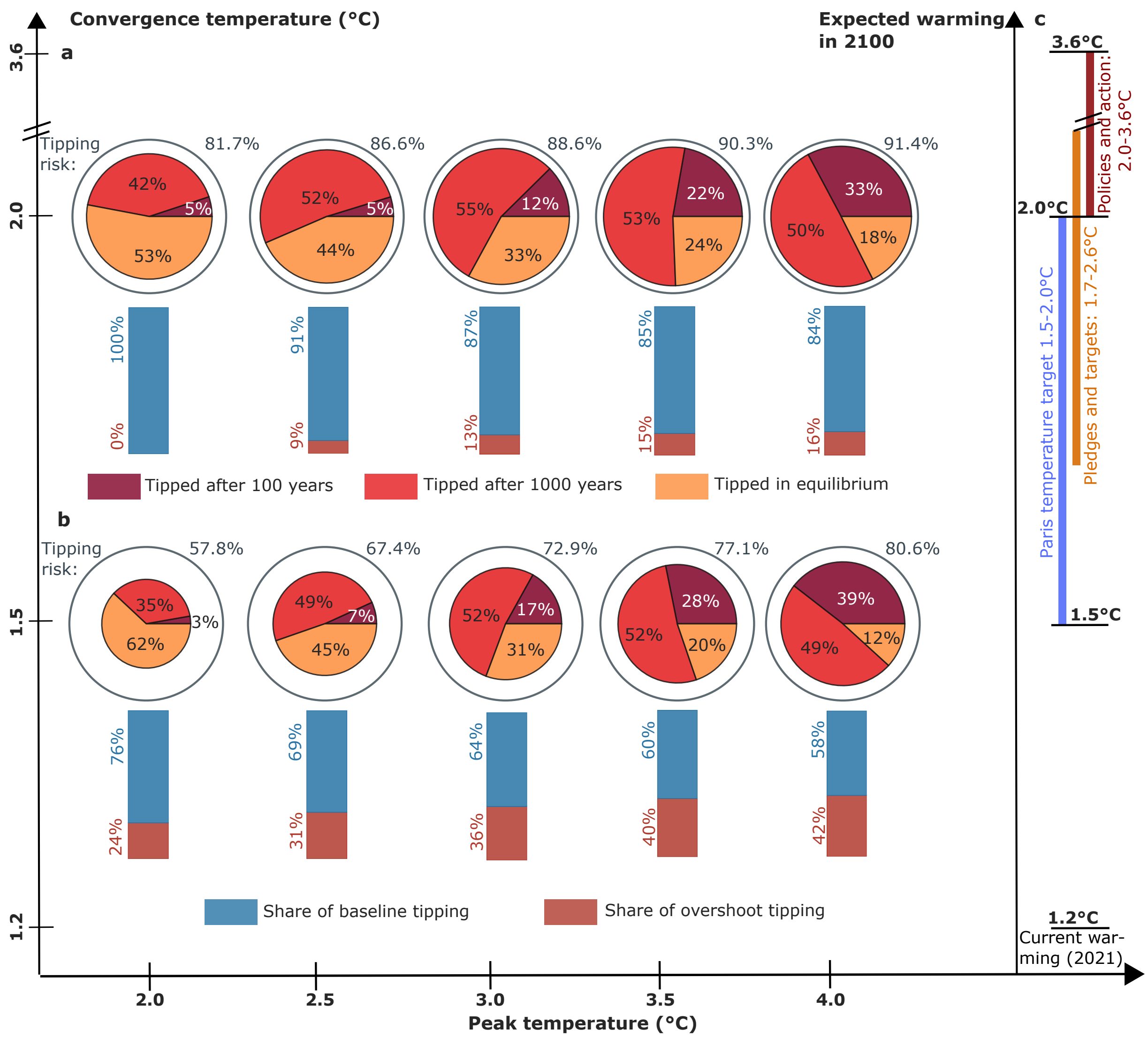
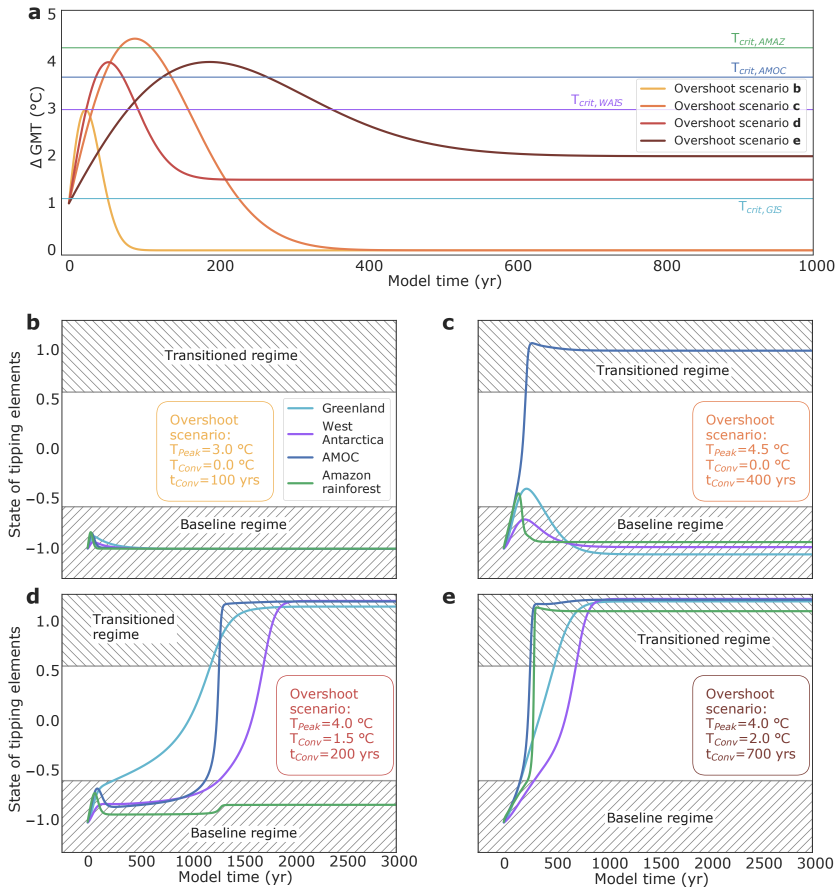
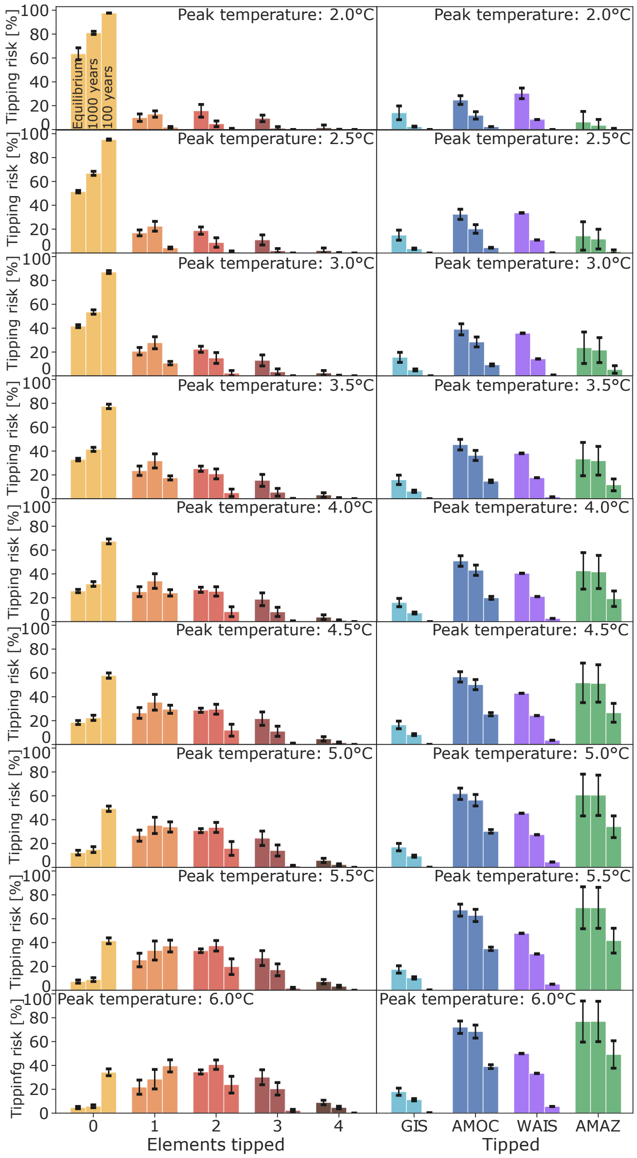

Convergence temperature (°C)
a
3.6
2.0
Tipping risk:
81.7%
42%
5%
53%
86.6%
52%
5%
44%
88.6%
55%
12%
33%
90.3%
53%
22%
24%
91.4%
50%
33%
18%
100%
0%
91%
9%
87%
13%
85%
15%
84%
16%
Tipped after 100 years
Tipped after 1000 years
Tipped in equilibrium
b
1.5
Tipping risk:
57.8%
35%
3%
62%
67.4%
49%
7%
45%
72.9%
52%
17%
31%
77.1%
52%
28%
20%
80.6%
39%
49%
12%
76%
24%
69%
31%
64%
36%
60%
40%
58%
42%
Share of baseline tipping
Share of overshoot tipping
1.2
2.0
2.5
3.0
3.5
4.0
Peak temperature (°C)
Expected warming in 2100
c
3.6°C
2.0°C
1.5°C
1.2°C
Current warming (2021)
Policies and action: 2.0-3.6°C
Pledges and targets: 1.7-2.6°C
Paris temperature target 1.5-2.0°C

Fig. 4 | Timing and mechanisms of tipping events following temperature overshoots. Tipping risk with respect to overshoot scenarios of 2.0–4.0°C and convergence temperatures within the Paris range of 1.5–2.0°C above pre-industrial levels. The *pie charts* split the tipping events into the time-scale when they occur. Either after 100 simulation years (dark red), 1,000 simulation years (light red), or in equilibrium simulations (after 50,000 simulation years, orange). The size of the pie chart indicates the overall tipping risk (e.g. 67.4% at T_{Conv}=1.5°C and T_{Peak}=2.5°C). The *bar chart* directly below the pie chart indicates the ratio between the two possible tipping mechanisms: (i) due to the convergence temperature being above the critical temperature for one or several tipping elements (*baseline tipping*, example see Greenland Ice Sheet in Extended Data Fig. 1d, e), and (ii) due to the overshoot trajectory (*overshoot tipping*, example see AMOC in Extended Data Fig. 1c). **a,** Scenario where global mean temperature converges to 1.5°C, or **b,** to 2.0°C. **c,** Expected warming in 2100 after the COP26 *pledges and targets* (orange vertical line: 1.7–2.6°C), and the *policies and action* (dark red vertical line: 2.0–3.6°C) together with the current warming of 1.2°C and the Paris temperature target (blue vertical line: 1.5–2.0°C). Note that the vertical axes are nonlinear due to visibility. The data for the vertical lines has been compiled from the November 2021 update by climateactiontracker[14]. The scenarios with lower convergence temperatures of 0.0, 0.5, and 1.0°C above pre-industrial are depicted in Extended Data Fig. 7. High-end climate scenarios and overshoots for peak temperatures between 4.5–6.0°C are shown in Extended Data Fig. 8.

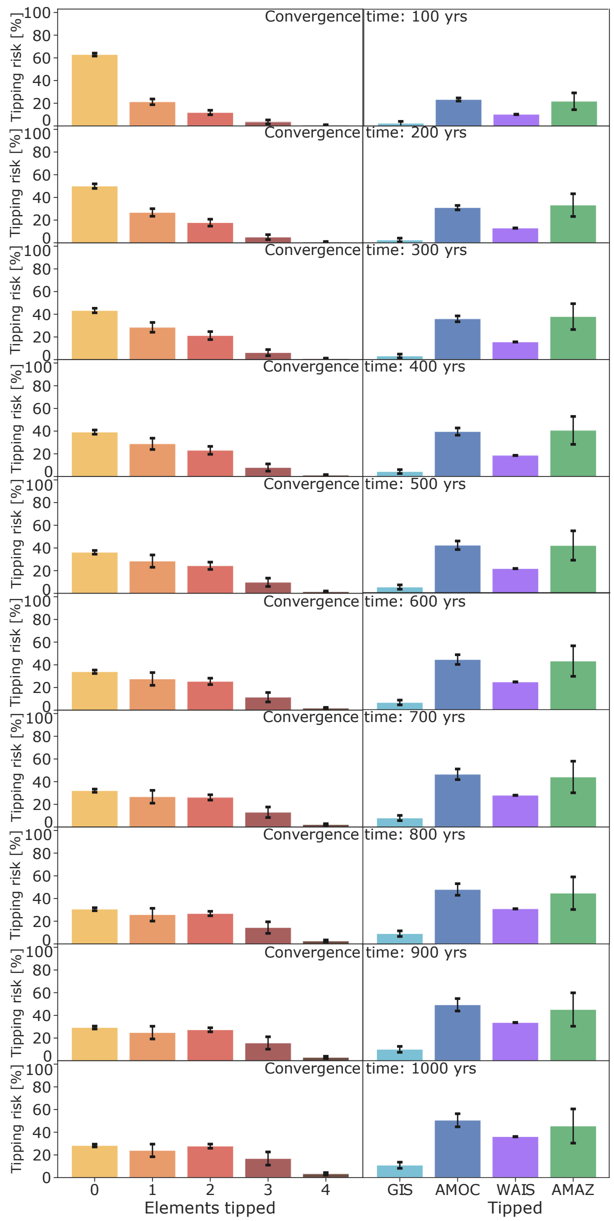
Extended Data Figure legends.



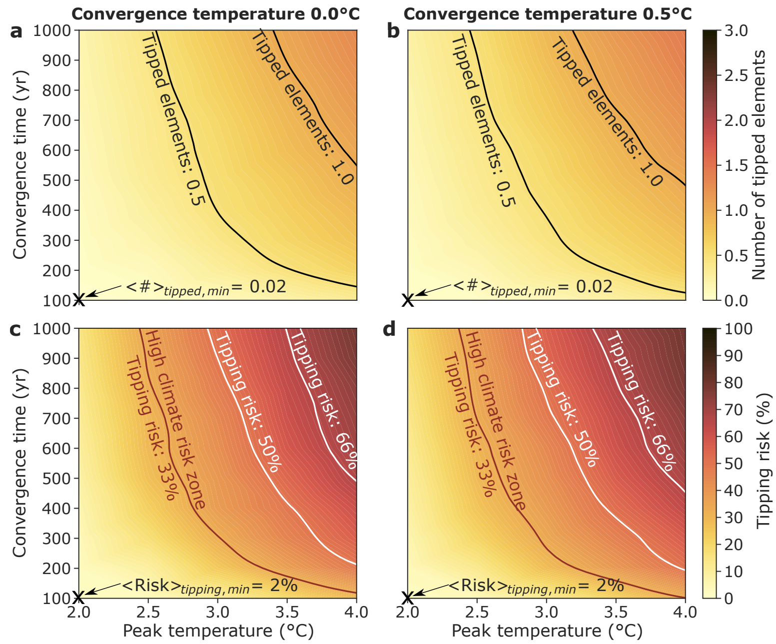
Extended Data Fig. 1 | Exemplary overshoot trajectories and their impact on tipping events. a, Time series of four different exemplary overshoot trajectories in dependence of the global mean surface temperature increase above pre-industrial levels (ΔGMT). Additionally, the four horizontal coloured lines show the critical temperatures of the Greenland Ice Sheet (GIS), the West Antarctic Ice Sheet (WAIS), the AMOC and the Amazon rainforest (AMAZ) for this specific ensemble member (for the entire ensemble of overshoots and tipping element set-ups, see Methods). **b–d,** The impact on tipping events in response to the applied overshoot scenario. Even though we only show one exemplary ensemble member here, it is apparent that higher temperature stabilisation levels (T_{Conv}) lead to a higher number of tipped elements (compare scenarios in **b, c** with scenarios in **d, e**), but also higher peak temperatures and convergence times have the same effect. The parameter values for this example are (same as in Fig. 1a,b): $T_{\text{crit, GIS}} = 1.1°\text{C}$, $T_{\text{crit, AMOC}} = 3.6°\text{C}$, $T_{\text{crit, WAIS}} = 3.0°\text{C}$, $T_{\text{crit, AMAZ}} = 4.3°\text{C}$, $s_{\text{GIS}\to\text{WAIS}} = 9.2$, $s_{\text{AMOC}\to\text{GIS}} = -3.1$, $s_{\text{GIS}\to\text{AMOC}} = 9.5$, $s_{\text{WAIS}\to\text{AMOC}} = 1.1$, $s_{\text{WAIS}\to\text{GIS}} = 1.5$, $s_{\text{GIS}\to\text{WAIS}} = 1.5$, $s_{\text{AMOC}\to\text{AMAZ}} = 3.0$, $\tau_{\text{GIS}} = 1602$ yrs, $\tau_{\text{AMOC}} = 172$ yrs, $\tau_{\text{WAIS}} = 1008$ yrs and $\tau_{\text{AMAZ}} = 56$ yrs. The interaction strength parameter is set to $d = 0.20$. For more details on the parameter values and meaning, see Methods.



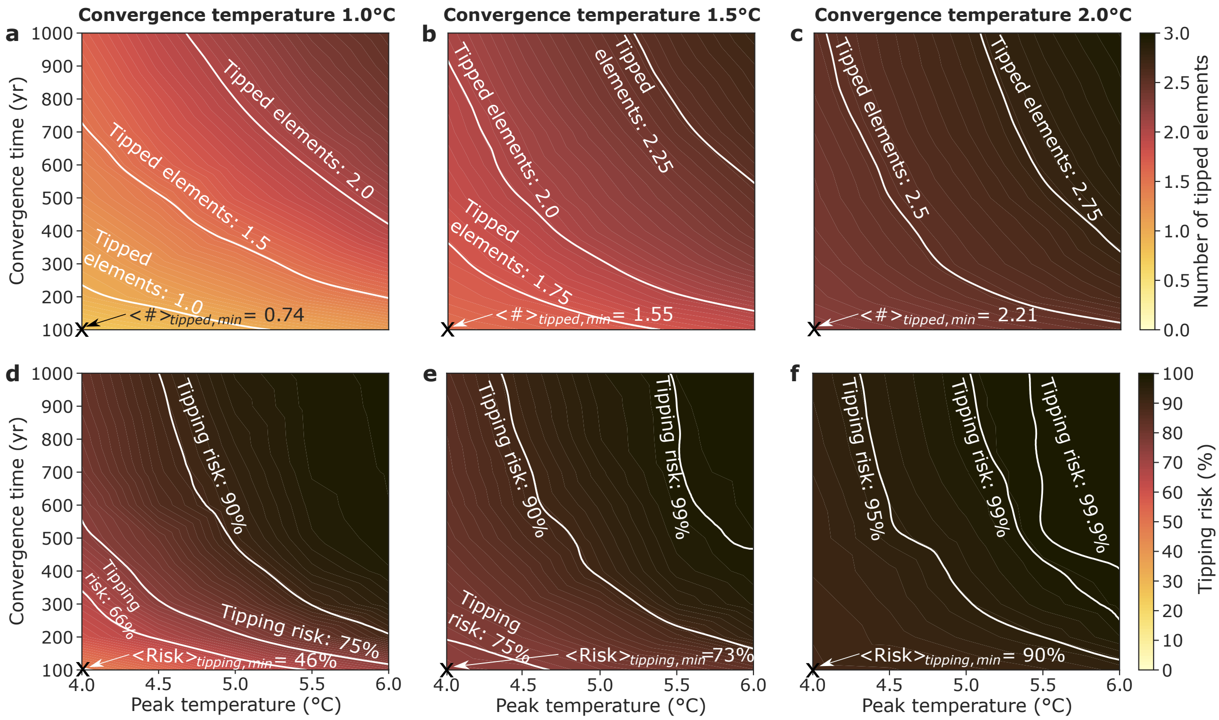
Extended Data Fig. 2 | The effect of time scales in overshoot scenarios on the risk for tipping events. In the left column, the probability of zero, one, two, three, or four tipped elements are shown for peak temperatures between $T_{\text{Peak}} = 2.0°\text{C}$ (lowest scenario) up to $T_{\text{Peak}} = 6.0°\text{C}$ (highest scenario). The right column breaks down the respective elements, which are responsible for the respective average number of tipped elements from the left column. The three parallel drawn bars in each panel detail the time scale of tipping into three scenarios. The left bar shows the result in equilibrium simulations (after 50,000 simulation years, long-term tipping), the bar in the middle shows the tipping events after 1,000 simulation years (mid-term tipping), and the right bar after 100 simulation years (short-term tipping). We depict the average over the entire ensemble as the bar height and the error bars show the standard deviation.



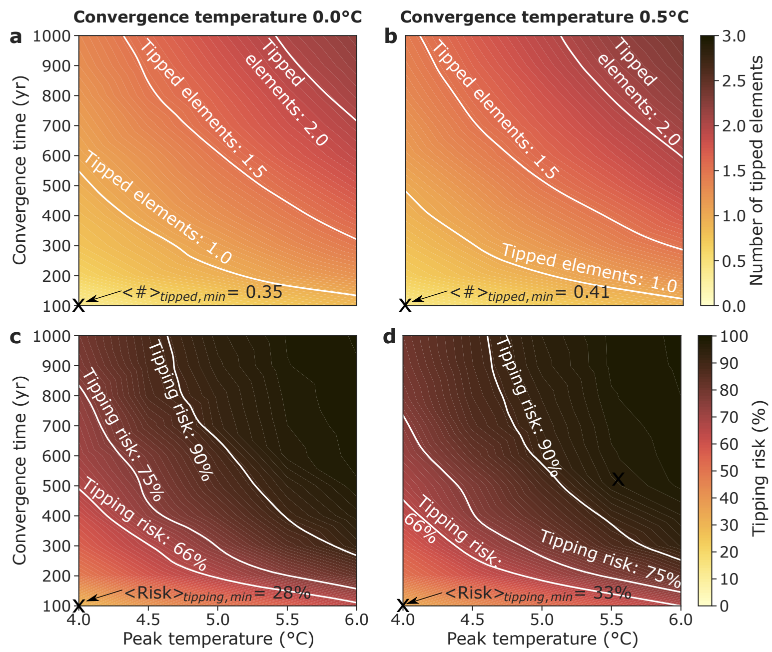
Extended Data Fig. 3 | The effect of the convergence time on the risk for tipping events. In the left column, the probability of zero, one, two, three, or four tipped elements are shown for convergence times of $t_{\text{Conv}} = 100$ years (uppermost row) up to $t_{\text{Conv}} = 1,000$ years (lowermost row). The right column breaks down the respective elements, which are responsible for the respective average number of tipped elements from the left column. We depict the average of the equilibrium run (long-term tipping after 50,000 simulation years) over the entire ensemble as the bar height and the error bars show the standard deviation.



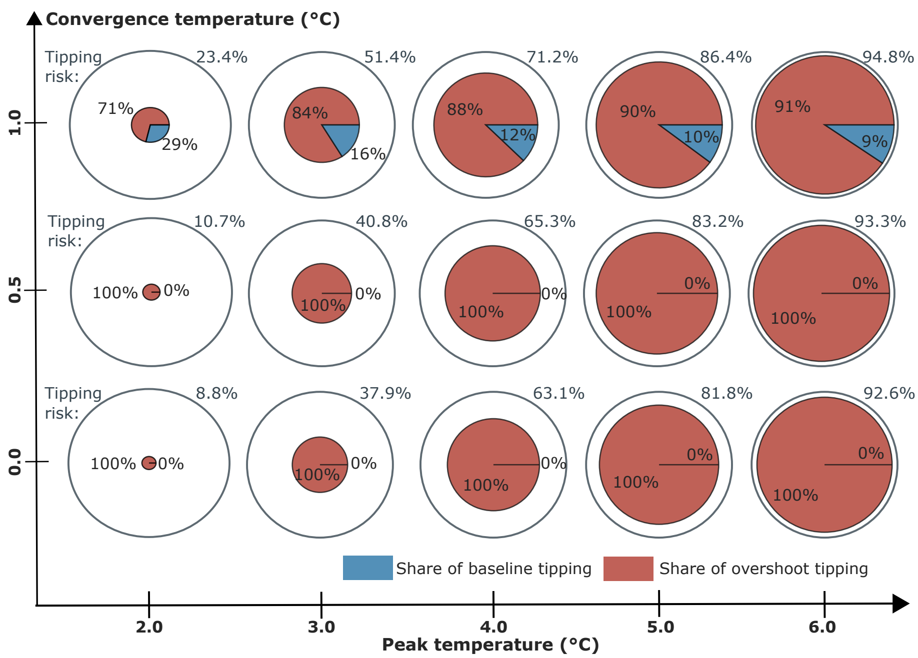
Extended Data Fig. 4 | Expected number and risk of tipping events at low convergence temperatures. Same as in Fig. 3 in the main manuscript, where the average number of tipped elements is shown for a set of convergence times and peak temperatures at a convergence temperature of **a,** 0.0°C (return to pre-industrial levels) and **b,** 0.5°C. The respective tipping risk that at least one tipping element ends up in the tipped regime is shown in panels **c, d**. Note that the *high climate risk zone* commences at higher peak and convergence times as compared to Fig. 3d in the main manuscript.



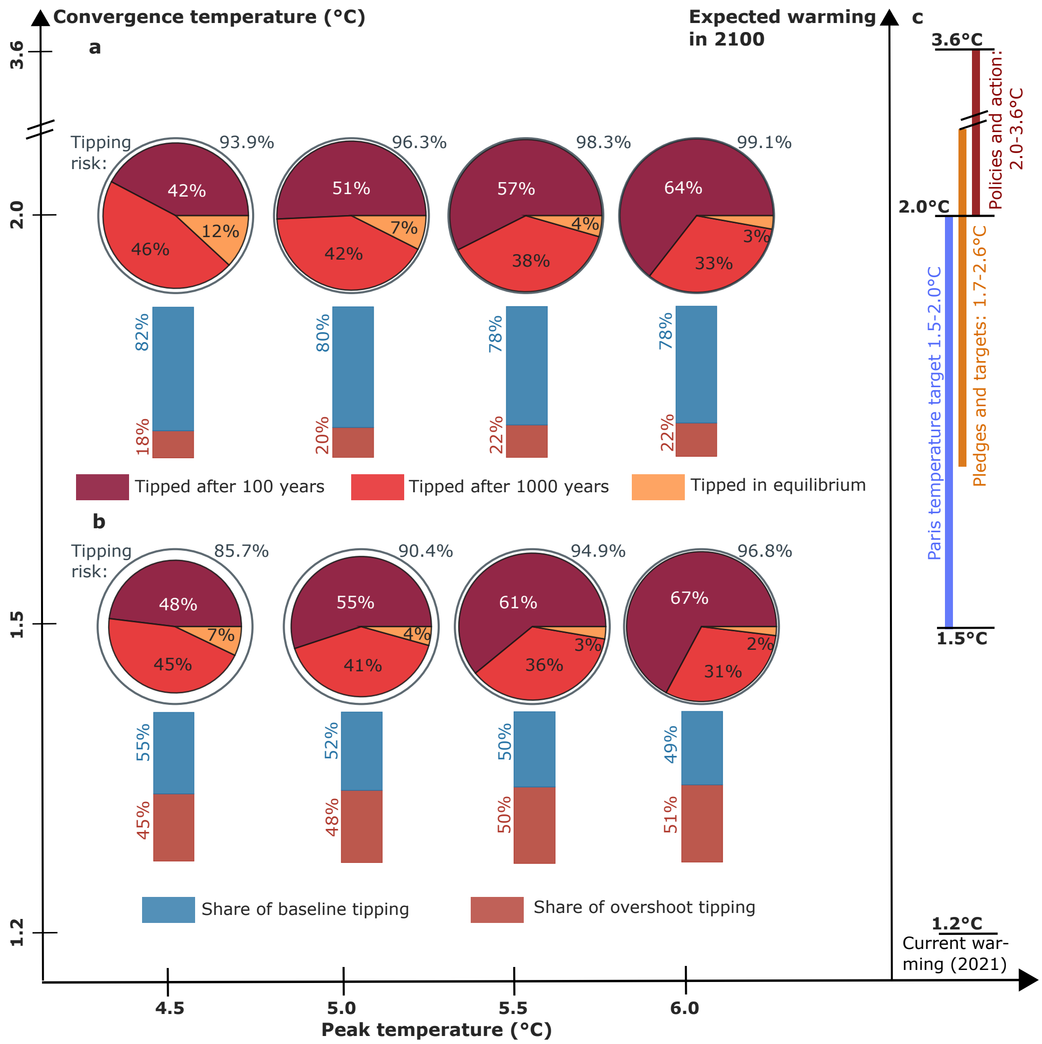
Extended Data Fig. 5 | Expected number and risk of tipping events for high-end temperature overshoots. Same as in Fig. 3 in the main manuscript, where the average number of tipped elements is shown for a set of convergence times and peak temperatures at a convergence temperature of **a,** 1.0°C, **b,** 1.5°C, and **c,** 2.0°C. The respective tipping risk that at least one tipping element ends up in the tipped regime is shown in panels **d, e, f**. For all high-end scenarios, the tipping risk for one tipping event to occur $\gtrsim 75\%$ if final convergence temperatures are between 1.5–2.0°C above pre-industrial levels.



Extended Data Fig. 6 | Expected number and risk of tipping events for high-end temperature overshoots at low convergence temperatures. Same as in Extended Data Fig. 3, where the average number of tipped elements is shown for a set of convergence times and peak temperatures at a convergence temperature of **a,** 0.0°C (return to pre-industrial levels) and **b,** 0.5°C. The respective tipping risk that at least one tipping element ends up in the tipped regime is shown in panels **c, d**.



Extended Data Fig. 7 | Mechanism for tipping following a temperature overshoot for low $T_{\mathbf{Conv}}$. Same as Fig. 4 of the main manuscript, but for lower convergence temperatures of 0.0, 0.5 and 1.0°C. To depict the tipping risk visually as the size of the pie charts, the reason (baseline or overshoot tipping) for tipping is depicted in the respective pie charts.



Extended Data Fig. 8 | Mechanism and timing of tipping events following a high-end temperature overshoot. Same as in Fig. 4 of the main manuscript, but for higher temperature overshoot trajectories peaking between 4.5–6.0°C. In these cases, tipping also plays a very important role at shorter timescale of 100 years, see the increasing fraction of the dark red part in the pie charts. **a,** Convergence temperature of 1.5°C, **b,** Convergence temperature of 2.0°C.