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

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Table of contents

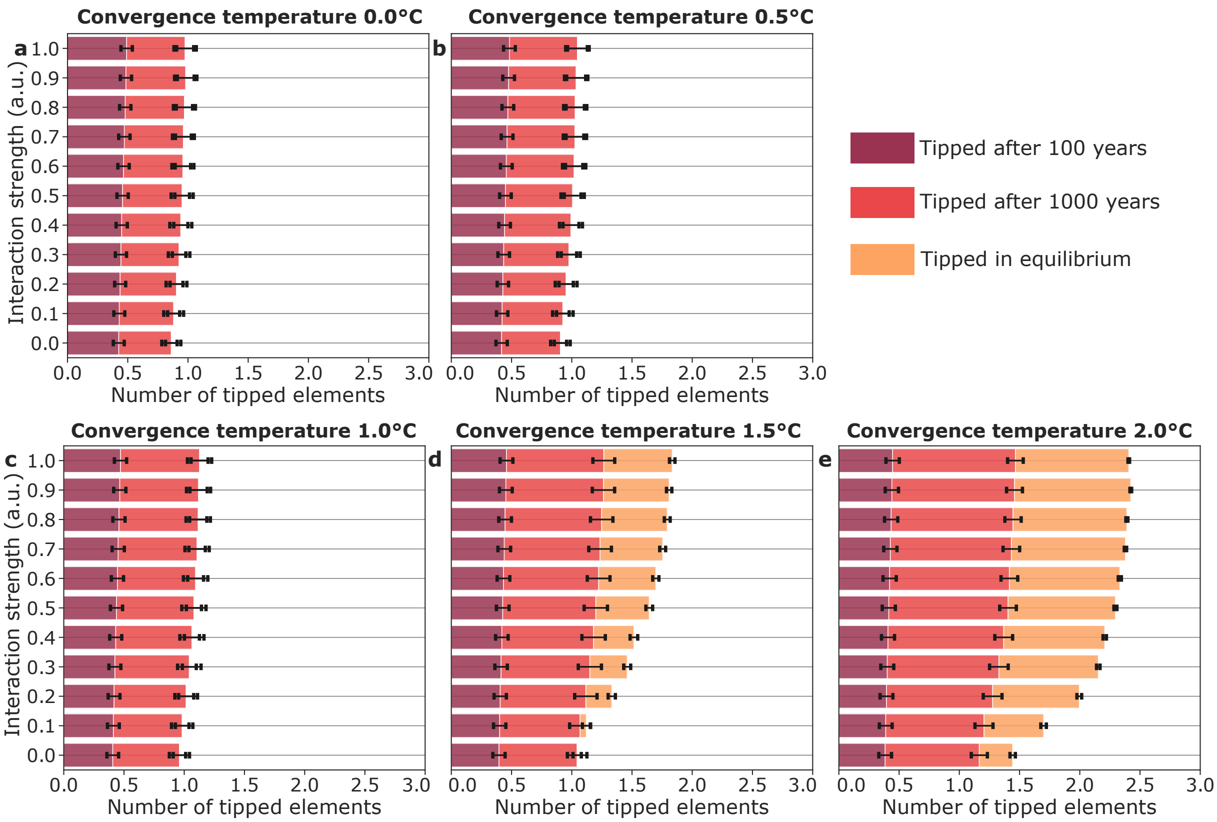
This file includes the following supplementary information:

1 Potential for nonlinearities in individual Earth system components

In the following, we outline the evidence for potential nonlinearities in the four investigated potential climate tipping elements, i.e. the Greenland Ice Sheet, the West Antarctic Ice Sheet, the AMOC, and the Amazon rainforest: (i) For the Greenland Ice Sheet contrasting model studies deliberate about the existence of a tipping point, but agree on the existence of an irreversibility threshold[1,2], while early warning signals are consistent with a nonlinear degradation for a parts of western Greenland[3]. Also, paleo-climatic evidence suggests significantly smaller, potentially tipped, Greenland and West Antarctic Ice Sheets, e.g. in the mid Pliocene[4,5], where the Pliocene is suspected to be among the best analogues of future climate[6]. (ii) For the West Antarctic Ice Sheet, besides its paleo-climatic evidence[5], a partial destabilisation with consistent early warning signals has been suggested, especially in the Amundsen Sea[7,8,9]. If this part is destabilised, this could be sufficient to trigger a large and potentially irreversible retreat of parts of West Antarctica[10]. For both, the Greenland and West Antarctic Ice Sheet, there are important feedbacks (melt-elevation feedback for the Greenland Ice Sheet, and marine ice sheet instability for the West Antarctic Ice Sheet) leading to a one-dimensional differential equation, exhibiting a double fold-like bifurcation[11,12]. (iii) While there is medium confidence about an AMOC tipping point[4], there is evidence of a significant weakening since the 1950s[13,14]. Further, early warning signals are consistent with a preceding critical transition[15]. Conceptual representations of the AMOC in experiments and subsequent modelling studies have suggested a one-dimensional differential equation for AMOC stability[16,17]. (iv) For the Amazon rainforest, five of seven CMIP6 models, featuring dynamic vegetation, exhibit localised abrupt dieback[18]. Also, several earlier studies have suggested hysteresis behaviour in the Amazon rainforest[19,20,21] and, again, early warning signals of a potential critical transition have been reported[22]. Derived from Lotka-Volterra dynamics[23], it has been found that a single vegetation species can be modelled as one-dimensional fold-bifurcation depending on the temperature increase[24].

2 The role of interactions and cascading effects

An interesting aspect are the effects of interactions on the risk of (cascading) transitions in overshoot scenarios. The average number of tipped elements increases with increasing interaction strength (Fig. S1). Here, an interaction strength of 0.0 represents four individual uncoupled tipping elements, while an interaction strength of 1.0 represents the case where the interactions are approximately as important as the individual dynamics[25]. For convergence temperatures of 1.5 or 2.0°C, we find a notable effect of increasing number of tipped elements due to cascading interactions between interaction strength values of 0.0–0.3. The total effect at a convergence temperature of 1.5°C increases the average tipped number from 1.04±0.04 at an interaction strength of 0.0 to 1.46±0.03 at an interaction strength of 0.3 (increase of 40.4±3.9%). For a convergence temperature of 2.0°C, the increase of the average number of tipped elements makes up an additional 49.3±2.1%. In this case, a further increase of the interaction strength from 0.3 to 1.0, only leads to a marginal additional tipping risk of 12.1±0.5%. The reason for this nonlinear increase in tipping at low to moderate interaction strength levels are cascading transitions because higher convergence temperatures cause more tipping cascades than lower convergence temperatures (compare Fig. S1c with Fig. S1d, e). This effect is most clearly apparent in the equilibrium effects over a long time scale (orange bars), while time scales up to 1,000 years show a relatively linear increase of tipped elements with increasing interaction strength (red bars), and in contrast to a nearly constant number of tipped elements for time scales up to 100 years (dark red bars). This implies that the interactions between climate tipping elements require a significant amount of time for their effect to be observable in the number of tipped elements. This can be explained by the roles of the tipping elements in cascading transitions. It has been found in earlier research that the slow tipping elements (Greenland and West Antarctic Ice Sheet) are the main initiators of cascading transitions[25], but they also need the largest amount of time to commence a transition, the effects of which can then be transported to further tipping elements (AMOC and Amazon rainforest) via the respective physical interactions. Therefore, the role of interactions, and with that the amount of tipping cascades, can most clearly been seen for the long-term equilibrium experiments (orange bars in Fig. S1c–e). Lastly, it is notable that the proportion of equilibrium tipping events goes down with decreasing convergence temperature (Fig. S1). For convergence temperatures of 0.0, 0.5, and 1.0°C above pre-industrial levels, elements tipped in equilibrium do not play a role because in these latter scenarios the number of baseline tipping scenarios is insignificantly small and overshoot tipping does only rarely occur for the slow tipping elements.



Supplementary Fig. 1 | Effect of interaction strength between climate tipping elements. Number of tipped elements against the interaction strength, separated into the respective tipping times (dark red: tipped after 100 simulation years, red: tipped after 1,000 simulation years, orange: tipped in equilibrium after simulation 50,000 years) for a convergence temperature of **a,** 0.0°C, **b,** 0.5°C, **c,** 1.0°C, **d,** 1.5°C and **e,** 2.0°C above pre-industrial levels. Data are shown as mean values ± standard deviation separated into the three tipping times (100, 1,000, and 50,000 simulation years). Here, the standard deviation represents uncertainties in the different interaction network realisations.

Uncertain parameter	**Value**	**Literature reference**
Critical temperatures		
$T_{\text{crit, GIS}}$	$0.8 - 3.0$ (°C)	M^c^Kay et al.(2021)[26]
$T_{\text{crit, WAIS}}$	$1.0 - 3.0$ (°C)	M^c^Kay et al.(2021)[26]
$T_{\text{crit, AMOC}}$	$1.4 - 8.0$ (°C)	M^c^Kay et al.(2021)[26]
$T_{\text{crit, AMAZ}}$	$2.0 - 6.0$ (°C)	M^c^Kay et al.(2021)[26]
Interaction strengths		
$s_{\text{GIS}\to\text{AMOC}}$	$1 - 10$ (pos.)	Wunderling et al.(2021)[25]
$s_{\text{AMOC}\to\text{GIS}}$	$1 - 10$ (neg.)	Wunderling et al.(2021)[25]
$s_{\text{GIS}\to\text{WAIS}}$	$1 - 10$ (pos.)	Wunderling et al.(2021)[25]
$s_{\text{AMOC}\to\text{AMAZ}}$	$2 - 4$ (unc.)	Wunderling et al.(2021)[25]
$s_{\text{WAIS}\to\text{AMOC}}$	$1 - 3$ (unc.)	Wunderling et al.(2021)[25]
$s_{\text{WAIS}\to\text{GIS}}$	$1 - 2$ (pos.)	Wunderling et al.(2021)[25]
$s_{\text{AMOC}\to\text{WAIS}}$	$1 - 1.5$ (pos.)	Wunderling et al.(2021)[25]
Tipping times		
τ_{GIS}	$1,000 - 15,000$ (yrs)	M^c^Kay et al.(2021)[26]
τ_{WAIS}	$500 - 13,000$ (yrs)	M^c^Kay et al.(2021)[26]
τ_{AMOC}	$15 - 300$ (yrs)	M^c^Kay et al.(2021)[26]
τ_{AMAZ}	$50 - 200$ (yrs)	M^c^Kay et al.(2021)[26]

Supplementary Tab. 1 | Parameter uncertainties. This table shows the parameter uncertainties that are taken into account in our large-scale Monte Carlo simulation. There are uncertainties in three categories: (i) The critical temperature regime for the four respective tipping elements (T_{crit} in Eq. 1). (ii) The interaction strength parameter between two tipping elements each representing a physical interaction mechanism (s_{ij} in Eq. 1 and Fig. 1c). Whether the interaction is positive, negative or the sign is uncertain is noted behind the strength values in brackets. The interaction strength parameter uncertainties are taken from Wunderling et al. (2021)[25], which are based on Kriegler et al. (2009)[27]. (iii) The tipping time scale (τ_i in Eq. 1). For more details, see Methods in the main manuscript.

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