Supplementary Information

Polar ice sheets are decisive contributors to uncertainty in climate tipping projections

Jonathan P. Rosser, Ricarda Winkelmann and Nico Wunderling

1 Supplementary Notes 1:Key Earth system components

The six key Earth system components in this study have been chosen based upon key literature[1,2,3]. Some of these components are suggested climate tipping elements, while others are threshold-free feedbacks or do not possess a clear self-amplifying feedback. Still, all of the six considered Earth system components are important due to their interactions with other elements or the overall stability of the Earth system. Hereafter, we discuss each of the considered elements briefly:

The Greenland Ice Sheet (GIS) has been shown to exhibit a melt-elevation feedback[4] as well as a strong ice sheet albedo feedback[5]. This could lead to potentially significant tipping of the ice sheet into a rapid decay state, adding to sea level rise. Paleoclimate evidence supporting this is provided by the existence of previous ice-free (or nearly ice-free) states in Greenland during interglacial periods in the Pleistocene and Pliocene[6,7].

The West Antarctic Ice Sheet (WAIS) is believed to have a number of feedbacks that may lead to instability, including the marine ice sheet instability[8,9,10] as well as the marine ice cliff instability[10] and the melt-elevation feedback[4]. This could lead to rapid decline of some of the West Antarctic ice Sheet over the next few decades or centuries. An assessment of the likelihood of WAIS collapse occuring was given in Vaughan and Spouge (2002)[11]. There is strong paleoclimate evidence for climate-driven rapid collapses of the WAIS in the past 5 Myr[12]. It has been suggested that this destabilising mechanism may have already been triggered in some parts of the WAIS, particularly in the Amundsen and Bellingshausen sea regions[13].

Many conceptual models have suggested the AMOC could exhibit a collapse/tipping point behaviour through the salt-advection feedback[14,15]. This behaviour has also been shown through forcing in more complex Earth system models[16 17]. The degree of AMOC collapse and its behaviour in climate models varies greatly between different models and their forcing, the resolution and formulation of a model can have a big impact on the bistability of the AMOC[18]. Paleoclimate evidence has also been used to support the potential existence of an AMOC collapse mechanism, linking it to past sudden climate transitions such as Dansgaard-Oeschger events[19]. Recent observational records and CMIP-simulation results suggest a significant weakening of the AMOC during the last century[20,21].

The Amazon Rainforest has been suggested to show a range of stability states between rainforest, savannah and treeless states in conceptual models[22,23,24]. The stability and hysteresis behaviour of the Amazon Rainforest has been shown to depend greatly on local-scale tipping points[25] which can spread to other regions of the rainforest through moisture-recycling feedbacks[26,27,28]. However, it remains an open question as to whether the Amazon has a single system-wide tipping point and the extent to which it will be able to adapt to changing climatic conditions[29]. On top of pure climatic threats through climate change induced droughts, direct anthropogenic pressures from deforestation and fires additionally pressure the state of the rainforest[30].

The Arctic Summer Sea Ice is a threshold-free feedback without hysteresis and therefore cannot be considered a tipping element[31]. In particular, it has been shown that additional greenhouse gas emissions lead to a near-linear decline of Arctic (summer) sea ice area[32]. However, it has a reasonably clear range of disintegration, short timescale of tipping and considerable feedbacks onto other tipping elements, in particular the AMOC[33,34]. Therefore, although it does not behave as a tipping element, it can change qualitatively between different states and have significant impacts on components in our model so the inclusion of this element in our analysis is warranted. This linear variation between the qualitatively different states of ice behaviour has been represented in this model as a monotonic linear response to feedback with no threshold.

ENSO has been assessed to very likely not be a tipping element[31]. It appears to show qualitative and significant changes in behaviour and dynamical state in climate change simulations, but likely lacks a clear self-perpetuating dynamic[35]. However, as it is a very strong connector of different regions in the Pacific and beyond, ENSO has strong potential to influence other tipping elements via its numerous interactions[3]. Therefore, we have included ENSO in this study. However, as it is an uncertain tipping point, we have included it as a monotonic response function to the tipping forcing without a non-linear tipping response. This is so that it reflects current literature but is still able to influence other tipping elements.

2 Supplementary Notes 2: Interactions between tipping elements and key Earth system components

The interactions between tipping elements and key Earth system components represent physical links in the real climate system that can cause the state of one tipping element to influence the state of another. The initial list of interactions was taken from earlier literature[36] with additional interactions involving the ENSO taken from a recent review[3] (supplementary information). The majority of values remain as taken from[2,36] and these choices are explained in more detail there.[3] gives a comprehensive update of many links (including the ASSI links) but does not give specific values. The links taken from this paper are those corresponding to ASSI and the WAIS→GIS link. Previously, the GIS→WAIS link (mediated through sea level rise from the melting Greenland Ice Sheet impacting on the marine-terminating regions of West Antarctica) was rated as strong, with a maximum value of 1. However, in Wunderling et al (2023a)[3] this was revised to a moderate link and so the strength was reduced to a maximum of 0.5. The links between AMOC and ASSI were not given specific values in previous analyses but were rated as weak/moderate more recently in literature[3]. The ASSI→AMOC link represents AMOC weakening due to ASSI decline. ASSI decline leads to southward advection of lighter water to the North Atlantic convection sites which reduces convection and weakens the AMOC. It is thus a destabilising link and it is given a potential range of [0.1,0.5]. The

AMOC→ASSI link represents a weaker AMOC reducing heat transport to the North Atlantic and so stabilising the ASSI. This leads to a stabilising link which is given a potential range of [−0.5,−0.1]. The full list of interaction strengths is given in Table S2.

3 Supplementary Methods 1: Parameter Distribution Tables

Earth system component	Temperature Threshold [°C]	Characteristic Time [years]
Amazon Rainforest (AMAZ)	[2.0, 6.0]	[25, 200]
Atlantic Meridional Overturning Circulation (AMOC)	[1.4, 8.0]	[15, 300]
Arctic Summer Sea Ice (ASSI)	[1.3, 2.9]	[10, 50]
El Niño Southern Oscillation (ENSO)	[3.0, 6.0]	[50, 200]
Greenland Ice Sheet (GIS)	[0.8, 3.0]	[1,000, 15,000]
West Antarctic Ice Sheet (WAIS)	[1.0, 3.0]	[500, 13,000]

Supplementary Tab. 1 | Threshold parameters. Parameter ranges for temperature threshold and characteristic time used for the climate elements in this study. The values for these parameters were taken from and informed by Kriegler et al. (2009)[1] and Wunderling et al.(2021)[2].

Interaction	Strength Range
AMOC→AMAZ	[−0.4, 0.4]
ENSO→AMAZ	[0.1, 1.0]
ASSI→AMOC	[0.1, 0.5]
GIS→AMOC	[0.1, 1.0]
WAIS→AMOC	[−0.3, 0.3]
AMOC→ASSI	[−0.5, −0.1]
AMOC→ENSO	[0.1, 0.2]
AMOC→GIS	[−1.0, −0.1]
WAIS→GIS	[0.1, 0.2]
AMOC→WAIS	[0.1, 0.15]
GIS→WAIS	[0.1, 0.5]
ENSO→WAIS	[0.1, 0.5]

Supplementary Tab. 2 | Interaction parameters. Parameter ranges for the strength of the interactions between elements in this study. A positive value of an interaction indicates a destabilising interaction while a negative value indicates a stabilising interaction. The values for these parameters were taken from recent literature[1,2,3,31]. The values for the ASSI interactions are based on recent literature to gauge the signs and approximate strengths of links, with the key decision making process to assign ranges described in Section 2 of the supplement

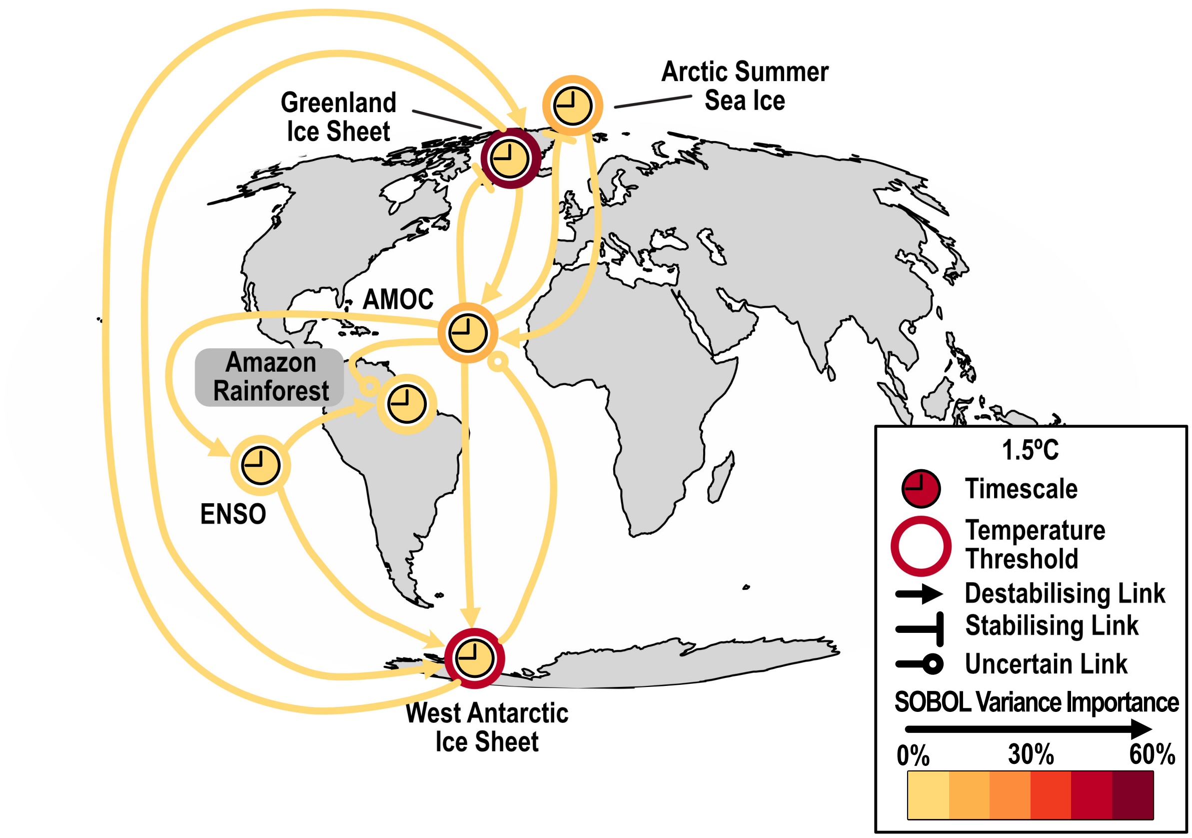
4 Supplementary Notes 3: Tipping Risk

Feature Removed	Tipping Risk / %	Percentage change from control/ %
None/Control	69.1	0%
GIS	50.2	−27
AMOC	55.7	−19
WAIS	42.2	−39
AMAZ	58.3	−16
ENSO	58.3	−16
ASSI	61.4	−11
AMOC→AMAZ	66.8	−3.3
ENSO→AMAZ	69.1	0.0
ASSI→AMOC	65.4	−5.4
GIS→AMOC	67.9	−1.7
WAIS→AMOC	68.9	−2.9
AMOC→ASSI	70.7	2.3
AMOC→ENSO	68.6	−0.7
AMOC→GIS	74.8	8.2
WAIS→GIS	67.5	−23.3
AMOC→WAIS	67.2	−2.7
GIS→WAIS	64.2	−7.1
ENSO→WAIS	61.0	−11.7

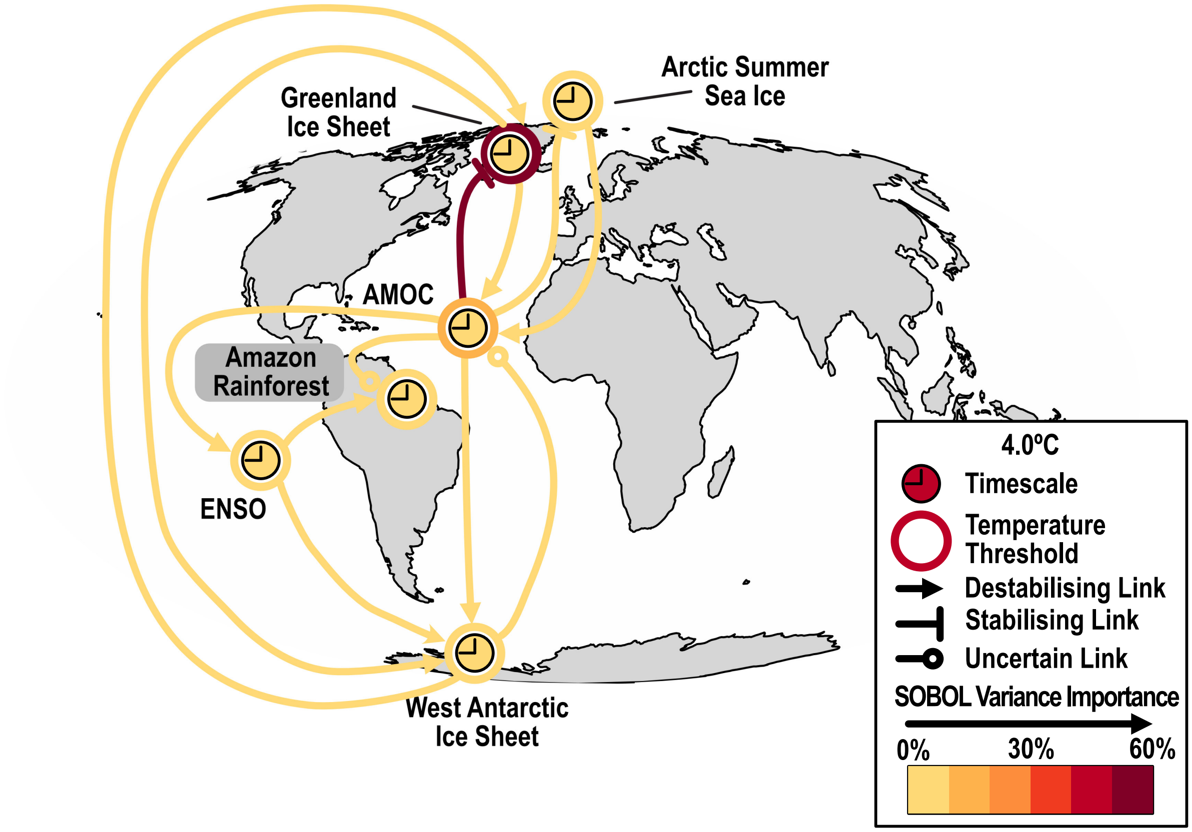
Supplementary Tab. 3 | Tipping risk assessment for node/link removal. Tipping risk (chance of at least one tipping element being tipped during the run) for a range of scenarios at 1.5°C of global warming above pre-industrial levels where a single feature (either a tipping element or interaction between two elements), was removed to observe the impact of this on the system. As described in the modelling approach section of the main text, the phrase tipping risk is used here to maintain coherence. For the ASSI (and ENSO in the case it is not a tipping point) this represents the chance that the climate component transitions into a qualitatively different state, albeit not via a true tipping point.

5 Supplementary Discussion 1: Representation of unclear tipping points

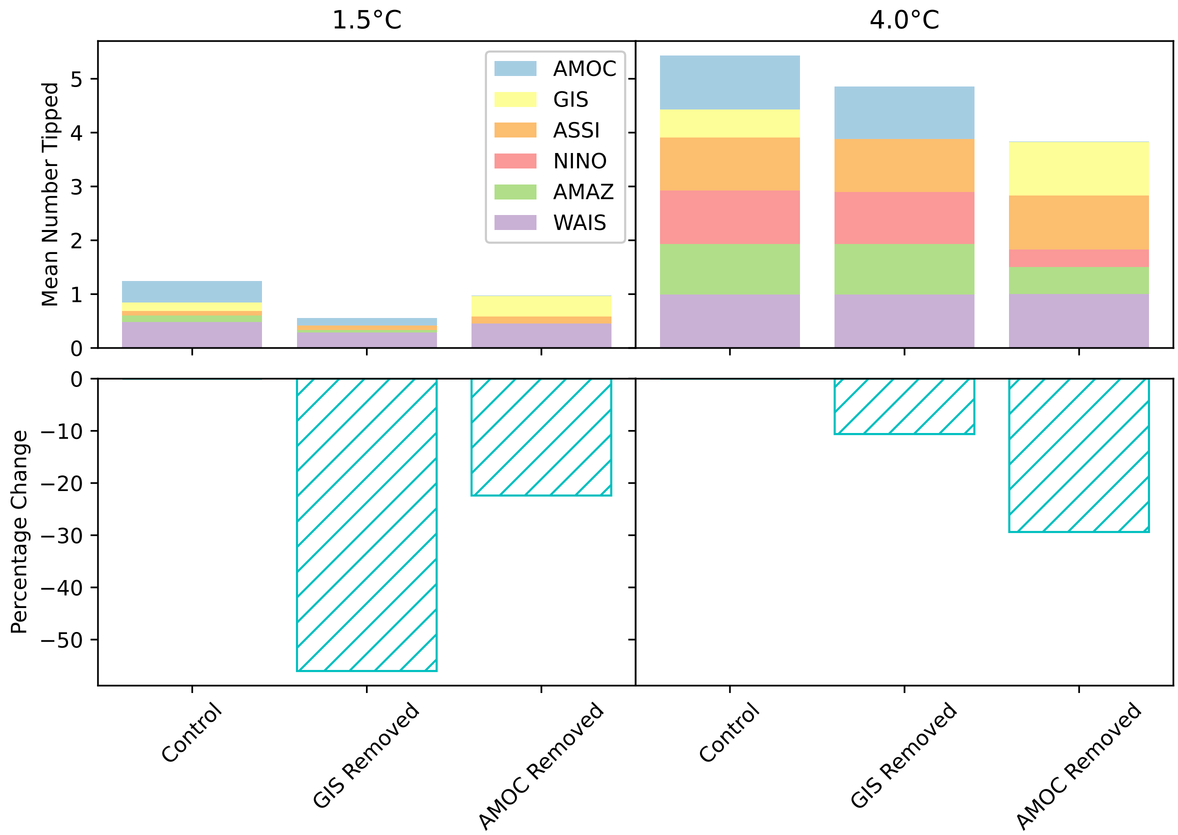
As discussed in Section 1 of the Supplement, ASSI and ENSO can be considered as unlikely tipping points and are more likely to respond as threshold-free feedbacks. Due to this, monotonic linear response functions were used in the analysis in the main body. For comparison, the analysis was also conducted using bifurcation tipping points to represent both ASSI and ENSO. Figures from this analysis are included below for completeness and comparison. The figures show broadly similar results, with the polar ice sheets emphasised in the SOBOL plots, and the differing influences of missing elements and nodes shown similarly in the Leave One Out analysis. A key difference is that ENSO does not appear as prominently in this as it is much less likely to vary as a non-linear tipping point than as a linear response as under the linear response with any forcing it will vary in response and begin to influence other factors. When represented as a bifurcation, it will remain in roughly the same state until it undergoes tipping, so the variation is lower in the bifurcation case and so the impact of the uncertainty is weaker.



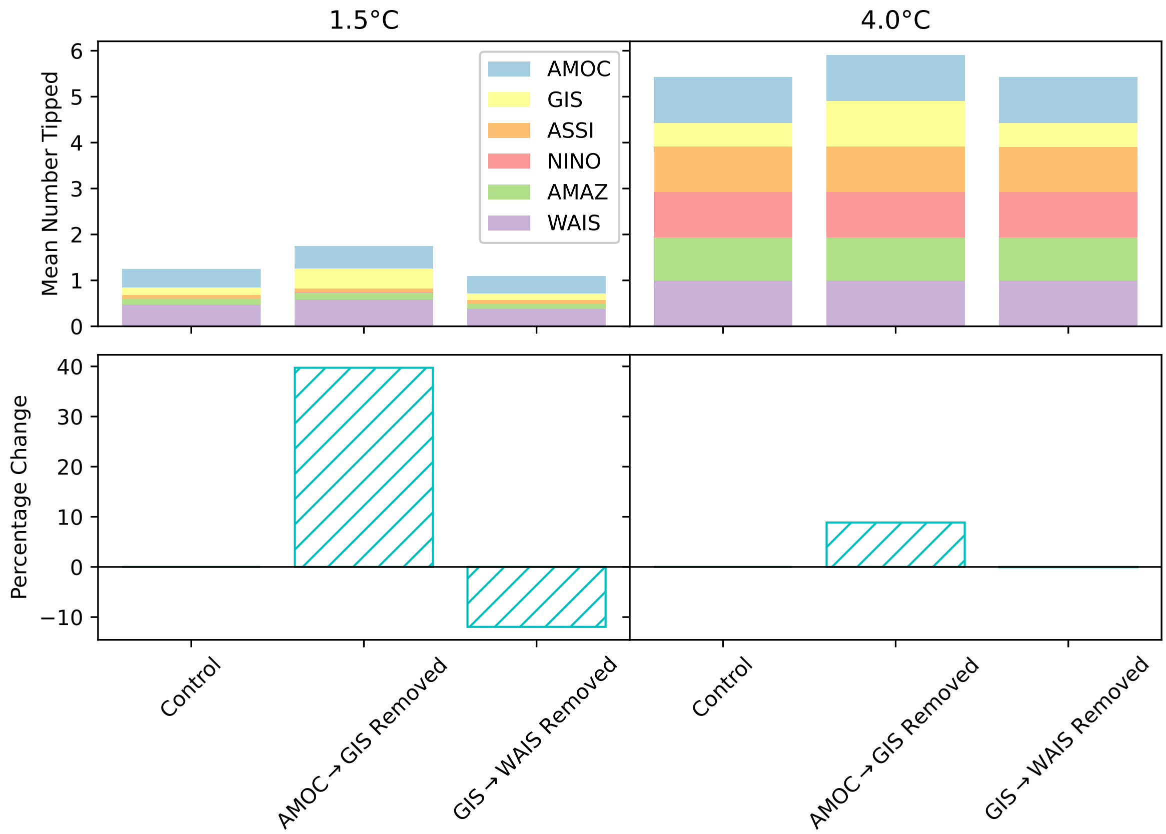
Supplementary Fig. 1 | Sobol variance analysis at 1.5°C. Sobol variance importance (for total number of elements tipped) of the links, thresholds and tipping timescales of different elements in the system, assessed at 1.5°C global warming. The colour of the inner clock shape demonstrates the variance importance of the uncertainty of the tipping timescale for that element, while the colour of the outer ring shows the importance of the uncertainty in the threshold temperature. The links can be classified as destabilising (arrow), stabilising (bar) or uncertain (circle) based on their end-shape (in brackets). The colour of each of these links again gives the variance importance of their uncertainties. In this plot, the temperature threshold of the Greenland and West Antarctic Ice Sheets show the darkest colours and the greatest Sobol variance importance.



Supplementary Fig. 2 | Sobol variance analysis at 4.0°C. Sobol variance importance (for total number of elements tipped) of the links, thresholds and tipping timescales of different elements in the system, assessed at 4.0°C global warming. The colour of the inner clock shape demonstrates the variance importance of the uncertainty of the tipping timescale for that element, while the colour of the outer ring shows the importance of the uncertainty in the threshold temperature. The links can be classified as destabilising (arrow), stabilising (bar) or uncertain (circle) based on their end-shape (in brackets). The colour of each of these links again gives the variance importance of their uncertainties. In this plot, the temperature thresholds of the Greenland Ice Sheet and the AMOC→GIS link show the darkest colours and strongest variance importance.



Supplementary Fig. 3 | Impact of GIS/AMOC removal on tipping. Mean number of tipped elements for three scenarios at both 1.5°C (left) or 4.0°C (right). These scenarios are the control runs where all elements are enabled, the scenario when the GIS is completely removed from the dynamics and counting of the system, and the scenario where the AMOC is completely removed. The upper panels show the change in mean number of elements tipped as well as the composition of these changes by tipping element. The lower panels show the percentage change in overall tipping for each scenario.



Supplementary Fig. 4 | Impact of AMOC→GIS/GIS→WAIS removal on tipping. Mean number of tipped elements for three scenarios at both 1.5°C (left) or 4.0°C (right). These scenarios are the control runs where all elements are enabled, the scenario when the AMOC→GIS link is completely removed from the dynamics, and the scenario where the GIS→WAIS link is removed. The upper panels show the change in mean number of elements tipped as well as the composition of these changes by tipping element. The lower panel shows the percentage change in mean number of elements tipped for each scenario.

Supplementary references

1. Kriegler, E., Hall, J. W., Held, H., Dawson, R. & Schellnhuber, H. J. Imprecise probability assessment of tipping points in the climate system. *Proceedings of the National Academy of Sciences* **106**, 5041–5046 (2009).

2. Wunderling, N., Donges, J. F., Kurths, J. & Winkelmann, R. Interacting tipping elements increase risk of climate domino effects under global warming. *Earth System Dynamics* **12**, 601–619 (2021).

3. Wunderling, N. *et al.* Climate tipping point interactions and cascades: A review. *EGUsphere (accepted)* **2023**, 1–45 (2023a). URL `https://egusphere.copernicus.org/preprints/2023/egusphere-2023-1576/`.

4. Levermann, A. & Winkelmann, R. A simple equation for the melt elevation feedback of ice sheets. *The Cryosphere* **10**, 1799–1807 (2016).

5. Box, J. *et al.* Greenland ice sheet albedo feedback: thermodynamics and atmospheric drivers. *The Cryosphere* **6**, 821–839 (2012).

6. Schaefer, J. M. *et al.* Greenland was nearly ice-free for extended periods during the pleistocene. *Nature* **540**, 252–255 (2016).

7. Dutton, A. *et al.* Sea-level rise due to polar ice-sheet mass loss during past warm periods. *Science* **349** (2015).

8. Schoof, C. Ice sheet grounding line dynamics: Steady states, stability, and hysteresis. *Journal of Geophysical Research: Earth Surface* **112** (2007).

9. Weertman, J. Stability of the junction of an ice sheet and an ice shelf. *Journal of Glaciology* **13**, 3–11 (1974).

10. DeConto, R. M. & Pollard, D. Contribution of Antarctica to past and future sea-level rise. *Nature* **531**, 591–597 (2016).

11. Vaughan, D. G. & Spouge, J. R. Risk estimation of collapse of the West Antarctic Ice Sheet. *Climatic Change* **52**, 65–91 (2002).

12. Pollard, D. & DeConto, R. M. Modelling West Antarctic ice sheet growth and collapse through the past five million years. *Nature* **458**, 329–332 (2009).

13. Favier, L. *et al.* Retreat of Pine Island Glacier controlled by marine ice-sheet instability. *Nature Climate Change* **4**, 117–121 (2014).

14. Stommel, H. Thermohaline convection with two stable regimes of flow. *Tellus* **13**, 224–230 (1961).

15. Cessi, P. A simple box model of stochastically forced thermohaline flow. *Journal of Physical Oceanography* **24**, 1911–1920 (1994).

16. Huisman, S. E., Den Toom, M., Dijkstra, H. A. & Drijfhout, S. An indicator of the multiple equilibria regime of the atlantic meridional overturning circulation. *Journal of Physical Oceanography* **40**, 551–567 (2010).

17. Rahmstorf, S. *et al.* Thermohaline circulation hysteresis: A model intercomparison. *Geophysical Research Letters* **32** (2005).

18. Gent, P. R. A commentary on the atlantic meridional overturning circulation stability in climate models. *Ocean Modelling* **122**, 57–66 (2018).

19. Ganopolski, A. & Rahmstorf, S. Abrupt glacial climate changes due to stochastic resonance. *Physical Review Letters* **88**, 038501 (2002).

20. Caesar, L., Rahmstorf, S., Robinson, A., Feulner, G. & Saba, V. Observed fingerprint of a weakening Atlantic Ocean overturning circulation. *Nature* **556**, 191–196 (2018).

21. Caesar, L., McCarthy, G. D., Thornalley, D., Cahill, N. & Rahmstorf, S. Current Atlantic meridional overturning circulation weakest in last millennium. *Nature Geoscience* **14**, 118–120 (2021).

22. Staal, A., Dekker, S. C., Xu, C. & van Nes, E. H. Bistability, spatial interaction, and the distribution of tropical forests and savannas. *Ecosystems* **19**, 1080–1091 (2016).

23. Staal, A. *et al.* Forest-rainfall cascades buffer against drought across the Amazon. *Nature Climate Change* **8**, 539–543 (2018).

24. van Nes, E. H., Hirota, M., Holmgren, M. & Scheffer, M. Tipping points in tropical tree cover: linking theory to data. *Global Change Biology* **20**, 1016–1021 (2014).

25. Staal, A. *et al.* Hysteresis of tropical forests in the 21st century. *Nature Communications* **11**, 4978 (2020).

26. Zemp, D. *et al.* On the importance of cascading moisture recycling in South America. *Atmospheric Chemistry and Physics* (2014).

27. Zemp, D. C. *et al.* Self-amplified Amazon forest loss due to vegetation-atmosphere feedbacks. *Nature Communications* **8**, 1–10 (2017).

28. Wunderling, N. *et al.* Recurrent droughts increase risk of cascading tipping events by outpacing adaptive capacities in the Amazon rainforest. *Proceedings of the National Academy of Sciences* **119**, e2120777119 (2022).

29. Sakschewski, B. *et al.* Resilience of Amazon forests emerges from plant trait diversity. *Nature Climate Change* **6**, 1032–1036 (2016).

30. Lovejoy, T. E. & Nobre, C. Amazon tipping point. *Science Advances* **4**, eaat2340 (2018).

31. Armstrong McKay, D. I. *et al.* Exceeding 1.5°C global warming could trigger multiple climate tipping points. *Science* **377**, eabn7950 (2022).

32. Notz, D. & Stroeve, J. Observed arctic sea-ice loss directly follows anthropogenic co2 emission. *Science* **354**, 747–750 (2016).

33. Allison, I. *et al.* *The Copenhagen diagnosis: updating the world on the latest climate science* (Elsevier, 2011).

34. Notz, D. & Community, S. Arctic sea ice in CMIP6. *Geophysical Research Letters* **47**, e2019GL086749 (2020).

35. Latif, M. & Keenlyside, N. S. El Niño/Southern Oscillation response to global warming. *Proceedings of the National Academy of Sciences* **106**, 20578–20583 (2009).

36. Wunderling, N. *et al.* Global warming overshoots increase risks of climate tipping cascades in a network model. *Nature Climate Change* **13**, 75–82 (2023b).