Dear Mr Crucifix, Dear Reviewers,

Thank you very much for the provided reviews on our manuscript "Interacting tipping elements increase risk of climate domino effects under global warming". The comments help us to sharpen and improve our research paper substantially.

The main changes in the manuscript in response to the comments from the reviewers comprise:

1. **Structural robustness analysis with respect to ENSO (see also Figs. N1 to N4 below)**
2. **Change framing of introduction to highlight the usefulness of the conceptual approach as a hypothesis generator for more process-detailed studies**
3. **Change framing of the conclusions of our results to improve the helpfulness to the community for instance by including ideas on which experiments could be used to investigate interactions of tipping elements in more process-based Earth system models in the future.**
4. **Improved motivation for the choice of interaction functions and interaction strength parameters.**

Please find below a detailed point-by-point response to the reviewer comments. We are happy to include the proposed changes to our manuscript.

Sincerely yours,
Nico Wunderling, Jonathan Donges, Jürgen Kurths & Ricarda Winkelmann

Reviewer #1:

The authors are discussing domino effects of individual tipping elements when the elements are coupled. The authors are investigating a set of coupled systems for evaluating how tipping phenomena cascade in the coupled systems. My major concern is that although the authors succeeded in showing how tipping phenomena cascade in the toy model, the set of coupled systems cannot imply anything related to the actual climate, in my opinion, because the set of coupled systems is too conceptual to infer something in a real climate. Thus, the authors should discuss this gap more carefully to clarify the limitations as well as surely ensured implications of the current study. This is my major concern.

We agree with the reviewer that our model is based on a couple of simplifications that should be made clearer with respect to its limitations. Opposed to a toy model, we view our model as a hypothesis generator with which we can arrive at interesting and valuable qualitative results (*hypotheses*) that can then, afterwards, be examined or checked by more complex models such as EMICs or GCMs. On the other side, it is and cannot be our aim with this model to make pure quantitative statements, let alone predictions.

Contrasting this, we see this study as a step towards more in-depth studies using more complex EMICs or GCMs. But despite the many recent progresses in EMICs and GCMs, these models would be required to resolve the nonlinear behavior of all or a sufficient subset of tipping elements which is not yet the case to our knowledge. On top of that, computational constraints might have hindered such a wide analysis as of yet which has also been mentioned for instance in Wood et al. (Clim. Dyn., 2019). These problems are overcome by our, admittedly simplified, model with its merits on the qualitative side (eg. role of tipping elements and impacts of interactions) rather than on exact quantifications or even predictions. This is why we feel that the *conceptual investigation* of the Earth system with emulator-like models such as this is worthwhile and creates interesting insights into the dynamics of interacting tipping elements. We will rewrite the introduction with such a section in more detail.

In our manuscript, the main qualitative findings are:

1. **We find that the ice sheets are the tipping elements which are most likely to initiate cascades of tipping events. Especially tipping cascades from the Greenland Ice Sheet to the AMOC as well as (less, but also significant) from the West Antarctic Ice Sheet to the AMOC fall into this category (see Fig. 1 and Fig. 6e,f of the main manuscript). This is also supported by many literature studies with conceptual models (eg. Wood et al., Clim. Dyn. 2019, Stommel, Tellus 1961, etc.), where the AMOC is influenced by freshwater input, mainly from a melting Greenland Ice Sheet. Furthermore, a reduction of the AMOC has also been found in data and general circulation models (Caesar et al., Nature 2018, Rahmstorf et**

al., Nat. Clim. Change, 2015, Hawkins et al., GRL 2011). Thus we consider this result as very robust and physically meaningful.

2. **While the ice sheets are the initiators of tipping cascades, we found that the AMOC is a mediator/transmitter of cascades. In our model, this results merely comes from the fact that the AMOC has the most connections to other tipping elements (i.e., from a topological point of view). But also in the real climate system, the AMOC connects the two polar regions and the equator due to its specific structure influenced by the melting ice from Greenland as well as from Antarctica (eg. Swingedouw et al., Clim. Dyn. 2009, Hu et al., Journal of Climate 2013). Thus, we think that this role as a connector would remain in a more process based study with, for instance, GCMs.**

3. **Furthermore, we think that the reduction of the critical temperatures for all tipping elements but Greenland is also a robust result that would hold under further studies (see Fig. 4 and Fig. 5).**

In a revised version of the manuscript, we would emphasize these points made here and write it in a clearer way, also emphasizing that future research should aim at attaining more details on the specific interaction pairs.

On top of that, we performed a structural robustness analysis and recomputed all our results without ENSO since it is debated whether ENSO is a tipping element and how a tipped state might play out with climate change, e.g.: will ENSO be permanent, will it be stronger, …? Please also have a look into our comment to reviewer #2 on more details about the literature on ENSO under climate change and paleo evidence.
Thus, to improve our model, we recomputed all our results to check for robustness without taking ENSO into account as a tipping element, see new Figs N1 to N4.

The main messages regarding the role of the tipping elements still hold and, thus, are robust (the ice sheets (mainly Greenland) are initiators, the AMOC transmits cascades, see Fig. N3). Also, the critical temperature for West Antarctica and AMOC goes down, while the critical temperature for the Greenland Ice Sheet increases alongside its uncertainty due to the strong negative feedback loop between Greenland and AMOC (Figs. N1 and N2). However, an interesting difference to the five node network including ENSO is that the Amazon rainforest can now only be influenced by the AMOC. Thus, the reduction in critical temperature is smaller than in our previous experiments, where the strong influence of ENSO impacted the Amazon rainforest's state. Now that we removed ENSO from the list of tipping elements, it is only interesting to look into specific tipping cascades of size two, but not of size three. The only remaining meaningful tipping cascade of size three is Greenland-West Antarctica-AMOC since cascades including the Amazon rainforest depend on the uncertain link between AMOC and the Amazon

rainforest. We would like to present this robustness study in the supplementary material of the revised manuscript and discuss these findings in the paper. (Please also compare to comment to the reviewer #2)

There are some minor points as well. 1. Line 6, “between” should be “among”. 2. Line 7, insert “(AMOC)” after “Atlantic Meridional Overturning Circulation”. 3. Line 35, “more simple” should be “simpler”. 4. Line 86, “more simple” should be “simpler”.

Thank you very much for these minor points. These issues will be corrected in the revised version of the manuscript.

Reviewer #2:

This paper presents an interesting extension of the Dekker et al. (2018) work on cascading tipping behavior by considering the possible cascading interactions of five potential tipping elements. The strength of the paper is clearly the large-scale MonteCarlo approach such that the overall behavior of the dynamical system (1) is studied. A clear weakness of the paper is the connection to climate dynamics. I suggest that the authors try to rewrite the paper to strengthen the latter aspect; the comments below are intended to help with this.

Thank you very much for this comment. We also feel and are aware that the connection to the real climate needs better explanation: we think of our model more as some kind of hypothesis generator with which we can arrive at qualitative results (*hypotheses*) that can then, afterwards, be examined or checked by more complex models such as EMICs or GCMs. On the other side, it is and cannot be our aim with this model to make pure quantitative statements, let alone predictions.

Contrasting this, we see this study as a step towards more in-depth studies using more complex EMICs or GCMs. But despite the many recent progresses in EMICs and GCMs, these models would be required to resolve the nonlinear behavior of all or a sufficient subset of tipping elements which is not yet the case to our knowledge. On top of that, computational constraints might have hindered such a wide analysis as of yet which has also been mentioned for instance in Wood et al. (Clim. Dyn., 2019). These problems are overcome by our, admittedly simplified, model with its merits on the qualitative side (eg. role of tipping elements and impacts of interactions) rather than on exact quantifications. This is why we feel that the *conceptual investigation* of the Earth system with emulator like models such as this is worthwhile. We will rewrite the introduction with such a section in more detail.

Thus, conceptual models such as this here can infer interesting qualitative statements about the connection of tipping elements in the Earth system, such as the roles of tipping elements or the destabilisation with respect to increasing interaction strength (see Fig. 1 and 4 of the main manuscript). With that, we also contradict the possibility that the strong negative feedback between AMOC and the Greenland Ice Sheet could be a halt point for further tipping events as has been proposed earlier (Gaucherel & Moron, International J. of Climatology 2017).

[Compare also to comment of reviewer #1]

1. Whereas one could justify (e.g. from conceptual models) that saddle-node bifurcations, underlying the individual dynamics term in (1), are relevant for the AMOC, ice sheets and Amazon rainforest, this does not hold for ENSO. Although this is mentioned in the paper (e.g. l63-64 and l75-78), there is no discussion on this issue. ENSO is also problematic because its behavior may not change substantially under climate change(e.g., in CMIP5 models (Kim et al.,

2014).) The best way out is probably to omit ENSO from the list of tipping elements; the results will very likely still be interesting. If the authors want to keep ENSO, they should better justify the use of (1) for this tipping element.

We also agree that ENSO is the most controversial element within our subset of five tipping elements, we checked our results for the robustness in case ENSO is not taken into account in the list of tipping elements. The results with all simulations recomputed can be found in the new Figs. N1-N4 that were sent along with this letter and are explained in the following.

> **The main messages regarding the role of the tipping elements still hold and, thus, are robust (the ice sheets (mainly Greenland) are initiators, the AMOC transmits cascades, see Fig. N3). Also, the critical temperature for West Antarctica and AMOC goes down, while the critical temperature for the Greenland Ice Sheet increases alongside its uncertainty due to the strong negative feedback loop between Greenland and AMOC (Figs. N1 and N2). However, an interesting difference to the five node network including ENSO is that the Amazon rainforest can now only be influenced by the AMOC. Thus, the reduction in critical temperature is smaller than in our previous experiments, where the strong influence of ENSO impacted the Amazon rainforest's state. Now that we removed ENSO from the list of tipping elements, it is only interesting to look into specific tipping cascades of size two, but not of size three. The only remaining meaningful tipping cascade of size three is Greenland-West Antarctica-AMOC since cascades including the Amazon rainforest depend on the uncertain link between AMOC and the Amazon rainforest.**
> **Thus, we would like to present these robustness results in the supplementary material alongside a better justification of ENSO.**

Furthermore, we agree that ENSO as a tipping element needs better justification overall. We included the ENSO in our study since it has vital impact on other tipping elements as has already been found in Kriegler et al. (2009, PNAS), as for instance on the drying of the Amazon rainforest, especially if it is to become more frequent or even permanent (see also Duque-Villegas, 2020, ESDD).
In a revised version of the manuscript, we will also further elaborate on changing ENSO properties under climate change (Kim et al., 2014, Nature Climate Change, Collins et al., 2010, Nature Geoscience, Cai et al., 2014, Nature Climate Change). Whereas Kim et al. (2014) and Collins et al. (2015) emphasize the uncertainty of how ENSO will change under global warming, Cai et al. (2014) show that ENSO will increase its frequency twofold. However, certain ENSO characteristics under climate change such as an intensification of ENSO driven drying in the western Pacific and rainfall increases in the central and

eastern equatorial Pacific seem robust due to nonlinear responses to surface warming (Power et al., 2013, Nature).

Moreover, it was found that the global warming trend since the early 1990s has provided a more favorable background state for the Atlantic capacitor effect which leads to increased biennial variability in the Pacific leading to conditions that are more favorable for major El-Nino events. For this study, observational data and reanalysis data has been used (Wang et al., 2017, Nat. Communs.). More observational evidence is available from paleo data from the Pliocene (4.5 - 3.0 mio. years ago), although the Pliocene had different environmental conditions. It is hypothesized that there may have been permanent El-Nino conditions (Wara et al., 2005, Science; Ravelo et al., 2006, Gsa Today; Fedorov et al., 2006, Science). Of course the Pliocene had different environmental conditions compared to today, although the CO2 concentration is believed to be similar as today.

Furthermore, we feel that it is necessary to improve our explanations on why we were including ENSO in the saddle-node form if we assume that ENSO could be seen as a tipping element. The main argument is the topological equivalence (e.g. Kuznetsov et al,. 2004) of the two separated states (ENSO as it is today and a permanent ENSO) with a nonlinear reaction to changes in forcing in between. It is unclear whether ENSO would show hysteretic effects, even if we follow the argumentation above. However, since we are not investigating a possible "backtipping" to the original state, but only increasing the forcing (the global mean temperature only increases), our analysis remains valid.

2. The coupling between the tipping elements is too sketchy at the moment and requires more discussion and analysis. The coupling terms s_{i,j} are now more or less 'guessed' but there are results of EMICs (e.g., Climber, Loveclim and modern variants) where such linear coupling coefficients could be estimated (e.g. from regression analysis). This would also shed more light on the part of the state vector (x_i in (1)) where the coupling occurs (as now only sketched in Table 2). Dekker et al. (2018) have done this to establish the relation between the AMOC and ENSO (meridional Atlantic temperature difference and the equatorial wind stress). I realize that this is more work, but it would enhance the quality and possible impact of the paper significantly.

We agree with the reviewer that it would be great to include more sophisticated coupling terms from more complex models instead of using the s_{i,j} estimations from the expert elicitation done in Kriegler et al. (2009). In case we would aim at using such coupling terms derived from more complex models, there would arise a couple of difficulties that make their usage impossible in our view:

> **i) Despite many recent advances in GCMs and EMICs, we are unsure whether we should use models that are partially not yet able to represent the nonlinear**

behaviour of all tipping elements to further calibrate our interactions between the tipping elements with their results.
For instance the issue of ENSO representation is not yet resolved in many GCMs, tipping of the Amazon rainforest is not yet comprehensively understood and some GCMs are said to have an AMOC that is too linear. Furthermore, GCMs and EMICs mostly do not have interactive ice sheets making it difficult to estimate interaction parameters from them.

Thus, we would rather argue that we would need a new generation of models that would explicitly include the potential to investigate such nonlinear interactions.

Also, from an observational data point of view (mainly paleo data) it would be very difficult to estimate the interaction strength due to uncertainties in the relevant paleo data and the very different timescales of the functioning of the tipping elements (eg. Ice sheets on the order of millennia, Amazon rainforest much quicker on the order of tens of years).

ii) While some connections (GIS -> AMOC, AMOC -> ENSO) have been better established with EMICs like CLIMBER-2 and Loveclim as well as GCMs (Rahmstorf et al., 2005, GRL; Driesschaert et al., 2007, GRL; Sterl et al., 2008, GRL, Jungclaus et al., 2006, GRL, Wood et al., 2019, Climate Dynamics), other connections are less well established (e.g.: connections between the Greenland and West Antarctic Ice Sheet). Thus, we would feel that this would introduce a bias in the level of details of the interactions, even if we would be able to retrieve some connection terms, while others will remain unknown. However, the concerning literature can and will be cited in the revised version of the manuscript to motivate the interactions given in Kriegler et al. (2009).

iii) Interaction und individual dynamics terms would have different complexity. At the same time, it would intuitively not be clear how different physical interactions can be reduced to a comparable dimensionless interaction strength parameter for all tipping element pairs. This again would make the experiments difficult where we scale up the interaction parameter d to investigate tipping temperatures (Figs 4 and 5) and the role of tipping elements (Fig. 1).

Following this, we agree that our study should be seen as the basis of more in-depth investigations of tipping interactions. Hence, we feel that this would be beyond the scope for this paper, although some few interaction links have been investigated with conceptual models, EMICs or GCMs (e.g., Dekker et al., 2018, ESD, Wood et al., 2019, Clim. Dyn., Rahmstorf et al., 2005, GRL, Hawkins et al., 2011, GRL).

A last remark to the expert elicitation from Kriegler et al. (2009):

In such an expert elicitation, there are of course uncertainties and they are reflected in the large spread of the estimated values. On the other hand, at this expert elicitation, there have been leading experts for each of the five tipping elements. Thus, we assume that the expert elicitation is more than "guess-work", although there are large uncertainties. For instance, the increase of the likelihood of tipping of the AMOC in response to a tipping Greenland Ice Sheet is increased by a factor of 1 to 10. This is a large spread. This interval and the intervals from the other links between the tipping elements are taken into account into the large scale Monte Carlo simulation propagating these uncertainties.

3. With ENSO removed and a better justification of the linear coupling from EMIC results (points 1 and 2 above), the interpretation of the results in Fig. 4-6 can be much improved. This in particular holds for the interesting result that the coupling destabilizes the reference climate state (as mentioned in the paper l268-270). Section 4 can then be substantially improved and it would be particularly helpful to the community if suggestions would be given on climate model experiments (even with EMICs) which could test the occurrence of this cascading behavior. There are several more minor issues but as the paper probably is rewritten substantially with different results, I will not mention these here.

We agree that our conclusion (Section 4) can be much improved with the new set of simulations and robustness checks of all our results without ENSO. We will rewrite this section in a revised version of our manuscript.

Potential investigations with EMICs, GCMs or conceptual models could be very helpful. Some possible examples are:

1. **One such experiment could be the investigation of changing precipitation patterns over Amazonia due to a tipped AMOC, i.e., whether rainfall will increase or decrease and whether this would potentially be sufficient to induce a tipping cascade. This would shed light on the interaction pair AMOC-Amazon rainforest. This could potentially also be extended to the tipping chain of a melting Greenland Ice Sheet, its influence on AMOC which then impacts the Amazon rainforest. This could be done by hosing experiments as described in Wood et al. (2019, Clim. Dyn.)**

2. **Also, the influence of the disintegration of the West Antarctic Ice Sheet on the AMOC could be investigated by introducing freshwater input into the AMOC around the West Antarctic Ice Sheet. Then one could observe the reaction of AMOC under different hosing parameters (amount of freshwater input) as has already often been done for Greenland and AMOC. There exist already some**

comparison experiments of run-off from Greenland and West Antarctica (Ivanovic et al., GRL, 2018), but we have not found isolated experiments on this.

3. **Then, further: if the EMIC would have interactive ice sheets, it would be possible to investigate the tipping triplet GIS-AMOC-WAIS to investigate the impact of the Greenland Ice Sheet on West Antarctica and vice versa. This could for instance be done by hosing experiments around Greenland or West Antarctica (or both).**

Furthermore, it might be worthwhile to perform a new expert elicitation on the connection pattern (feedbacks) between the tipping elements, but also on the set of tipping elements itself. We will include such ideas and suggestions for ESM model experiments into our new version of the manuscript.

Results without ENSO as a tipping element

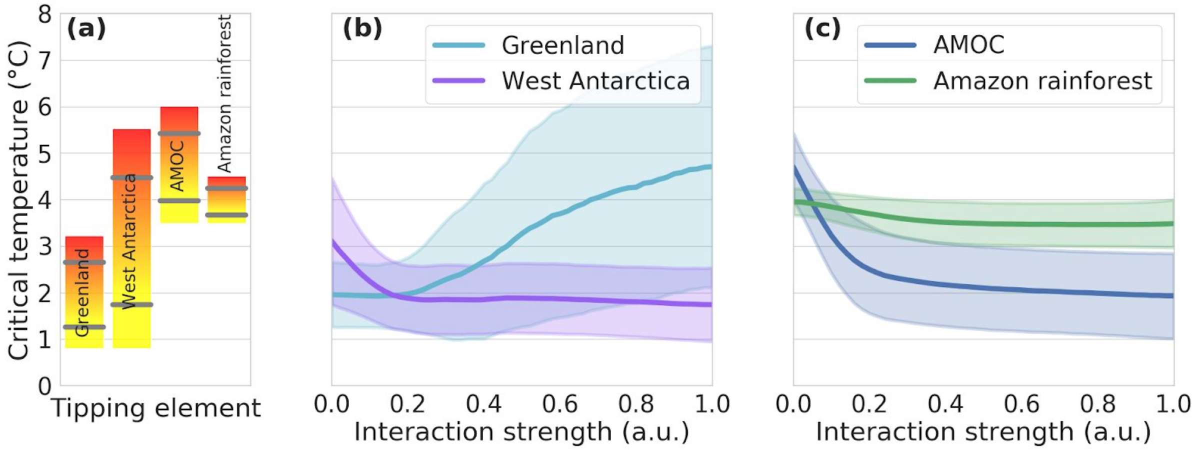

Fig. N1 (compare to Fig. 4 of the main manuscript): Shift of critical temperature ranges due to interactions omitting ENSO. (a) Critical global mean temperatures for each of the four investigated tipping elements, without taking interactions into account (as reproduced from literature (Schellnhuber et al. (2016), Nat. Clim. Change). The grey bars indicate the standard deviation arising when drawing from a random uniform distribution between the respective upper and lower temperature limits. These bars correspond to the critical temperature ranges in case of zero interaction strength in panels b and c. (b, c) Change of critical temperature ranges with increasing interaction strength for the Greenland Ice Sheet and West Antarctic Ice Sheet (panel b) and the Atlantic Meridional Overturning Circulation (AMOC) and Amazon rainforest (panel c). The standard deviation of the critical temperatures for each tipping element within the Monte Carlo ensemble is given as respective colour shading.

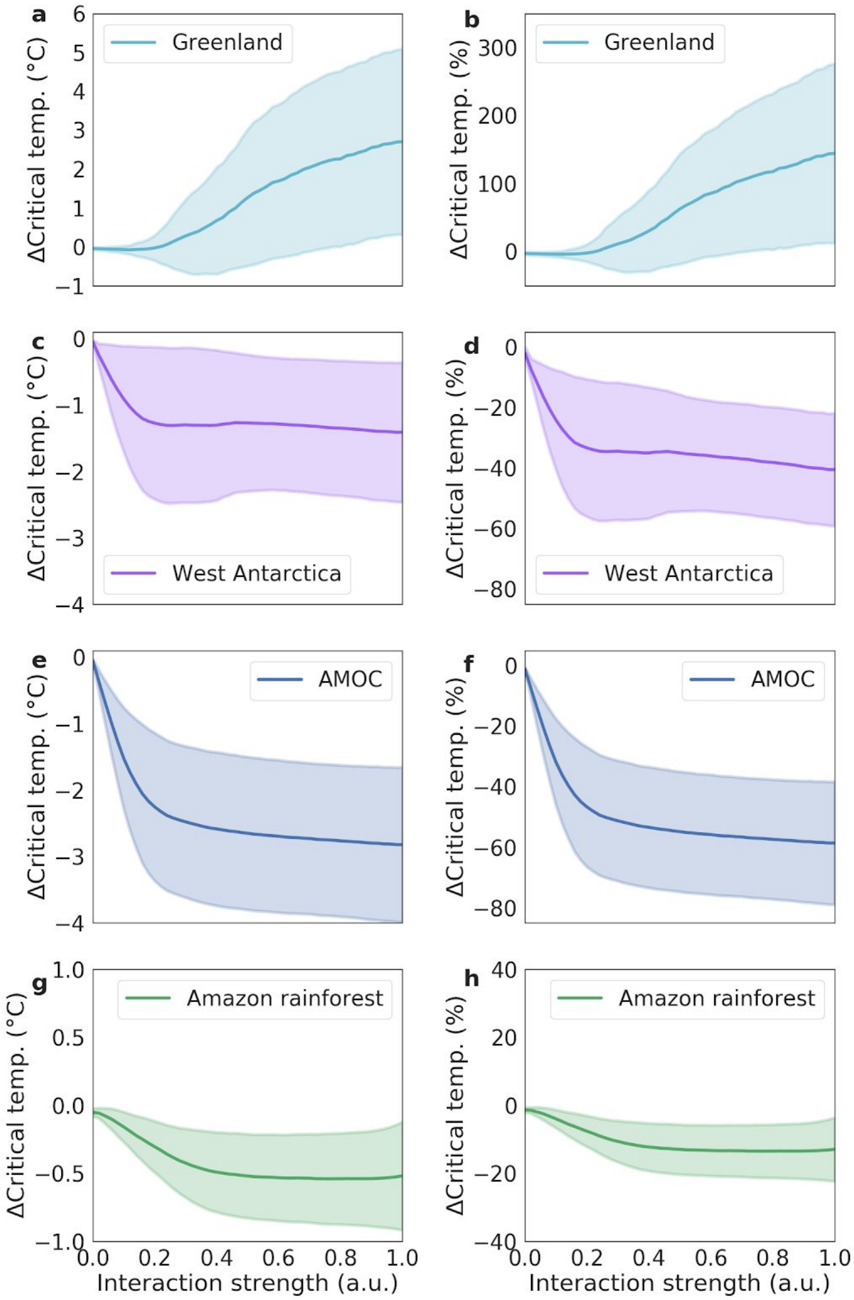

Fig. N2 (compare to Fig. 5 of the main manuscript): Difference in critical temperatures with respect to the interaction strength without ENSO as a tipping element. Difference of critical temperatures in °C (left panels) and % (right panels) compared to the respective initially drawn critical temperature for the four investigated tipping elements: (a, b) Greenland Ice Sheet, (c, d) West Antarctic Ice Sheet, (e, f) AMOC, (g, h) Amazon rainforest. The standard deviation from the ensemble members is shown as respective colour shading

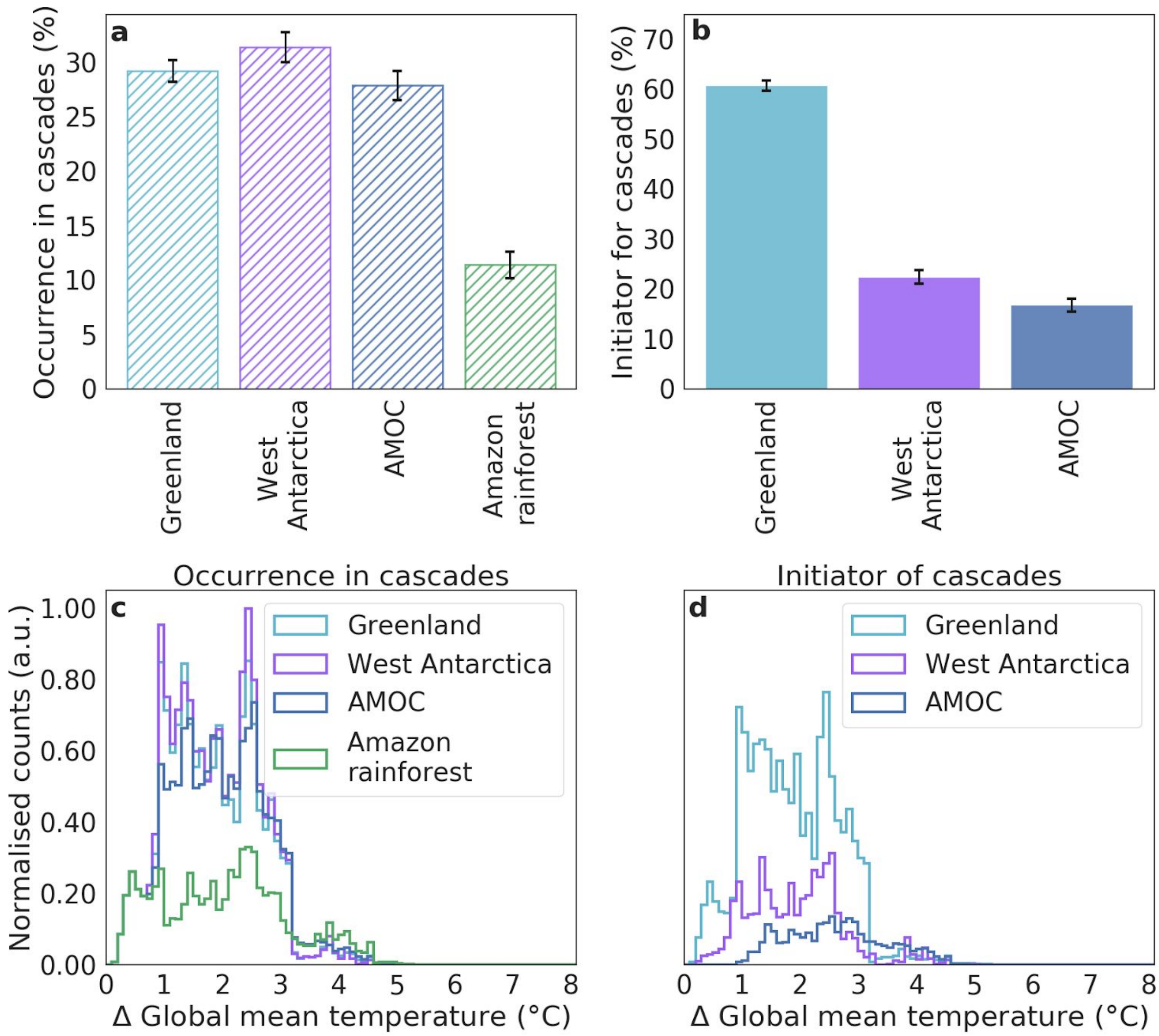

Fig. N3 (compare to Fig.1 and Fig.S1 of the main manuscript and supplement): *Role* of tipping elements in cascades without ENSO as a tipping element. a) Relative frequency in percent of occurrence of a certain tipping element in a tipping cascade (hatched bars). The standard deviation is computed by evaluating the deviation between reasonable network settings. b) Relative frequency in percent that a certain tipping element causes a tipping cascade (coloured bars). We define that the cause of a cascade is the element, whose critical temperature is closest to the temperature of the cascade. Again the error bars show the standard deviation between different network settings as in a. c) Count versus global mean temperature increase at which a tipping cascade occurs divided into the respective five tipping elements. d) Same as in c, but for the tipping element which causes the cascade. N.B.: Panel c) and d) are set to the same scale normalised to the highest value in the histogram.

Note also that the Amazon rainforest cannot be an initiator of cascades anymore since it does not influence any other tipping element, but is only influenced (by the AMOC). [Initiators: 65+-2% (GIS), 23+-3% (WAIS), 12+-2% (AMOC), 0% (AMAZ)

Occurrence: 29+-1% (GIS), 31+-2% (WAIS), 28+-2% (AMOC), 11+-2%(AMAZ)]

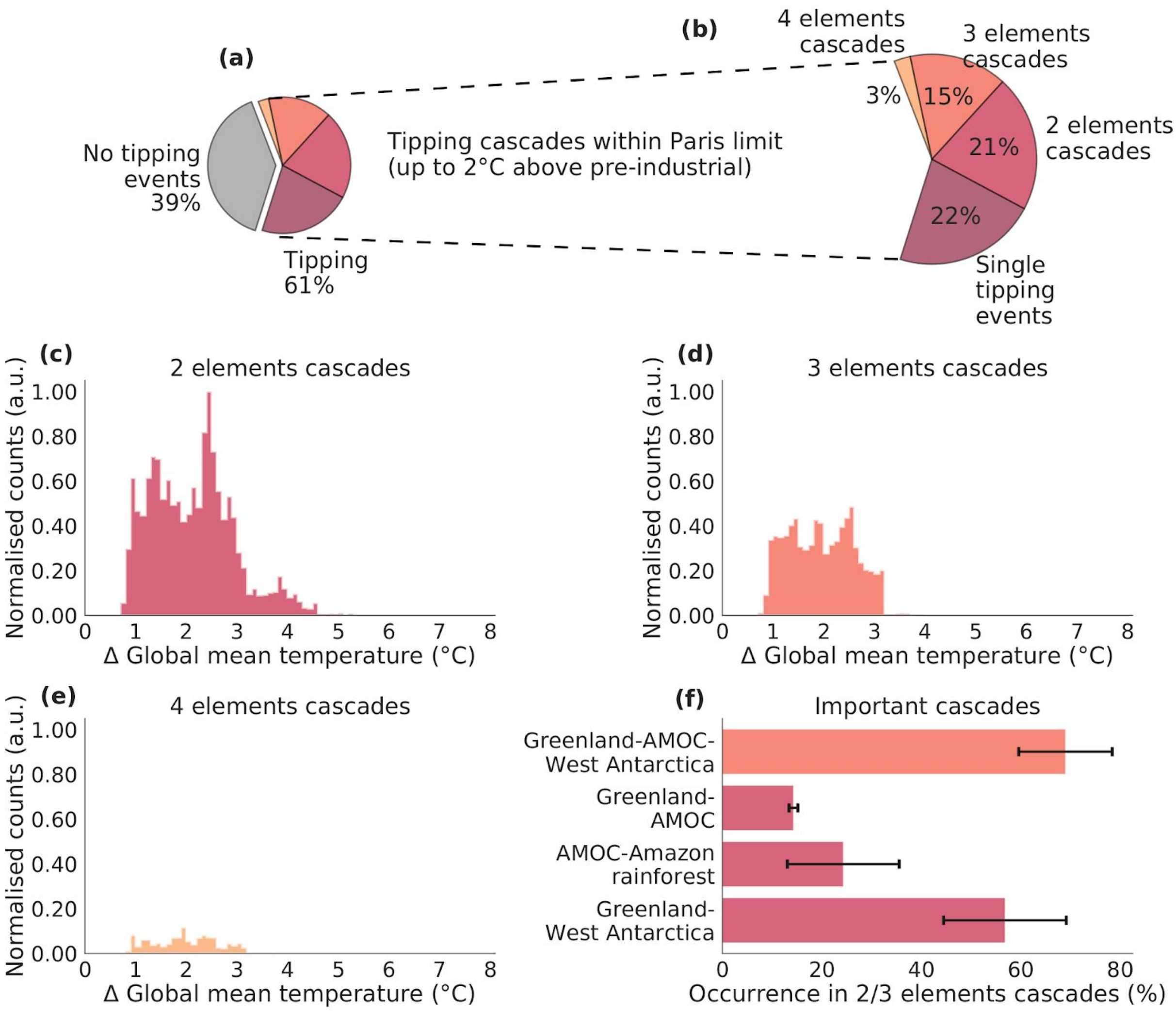

Fig. N4 (compare with Fig. 6 of the main manuscript): Tipping cascades without ENSO as a tipping element. (a, b) For global warming up to 2.0°C above pre-industrial, the colour shading illustrates the fraction of model representations in the Monte-Carlo ensemble without tipping events (grey), with a singular tipping event (purple) and with cascades including two (red), three (dark orange) and four (orange) elements. (c, d, e) Occurrence of tipping cascades of size two, three and four versus global mean temperature increase. The counts are normalised to the highest value of the most frequent tipping cascade (in cascades of size two). Tipping cascades of size three and four are set to the same scale to secure comparability. (f), Dominant cascades of size two/three for temperature increases from 0-8°C above pre-industrial. Other cascades are not shown, since their relative occurrence is much smaller than for the ones shown. The standard deviation represents the difference between the nine different network settings. Uncertainties are larger for network representations, where unclear links are involved, e.g., for the AMOC-Amazon rainforest tipping pair (compare Fig. 1 of the main manuscript).