Dear Mr. Crucifix, Dear Reviewers,

We are grateful for the comments by the reviewer and the editor. We appreciate the very helpful suggestions which helped to further clarify and improve our manuscript.

We have now addressed all comments. Major changes in the revised manuscript include:

1. **Following the reviewer's suggestions, we have excluded ENSO from our analysis in the main manuscript and now discuss it as an additional structural robustness analysis in the supplementary information.**
2. **We have clarified and substantiated our arguments why each of the remaining four tipping elements can be modelled with the cusp-equation as in our approach and added further literature sources.**
3. **Further, we more broadly elaborated on the literature concerning the interactions between the four tipping elements, both from modelling and observation studies.**
4. **We have restructured the introduction and methods part to improve the presentation in line with the reviewers and editors comments.**

Please find below a detailed point-by-point response to the comments. We also attached the new version of our manuscript and supplement below and marked the changes in blue.

We are grateful for the opportunity to improve our manuscript and are looking forward to further feedback.

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

Editor's comments

We are grateful to the editor for this highly valuable summary. We have revised the manuscript thoroughly and extensively accordingly. Please find below a short summary of our response to the editor's comments. A more detailed answer is posted below as a reply to the comments from the reviewer. Since major parts of the revisions require additional literature sources, a reference list can be found at the end of this response letter.

Dear authors,

I have only received one review of the revised version of your manuscript, but I believe this will suffice to proceed with a decision. As you will see the reviewer still expresses some concerns, and has asked to see the paper again. I believe, though, that it should be possible to proceed reasonably swiftly, and let me comment on the concerns of this reviewer.

- The representation of the tipping point of ENSO is "inadequate". As a matter of fact, we had a reading club in my group around your paper and we came up with a similar concern. I would therefore support the reviewer's suggestion to emphasise the ENSO-free case, and consider the additional ENSO tipping element as a sensitivity experiment.

We agree with the editor that the representation of ENSO is not adequately represented by Equation (1). After careful consideration, we have therefore followed your advice and excluded ENSO from the main part of the manuscript and moved the corresponding analysis to the supplementary information as a thorough structural robustness analysis. Instead, we now show the case without ENSO as a tipping element in the main manuscript. Please see below for a more detailed answer.

- Regarding the ice sheet dynamics: I am less sure to follow the reviewer here, since actually you referred to the Leverman - Winkelman article which, with its Figure 1, seems to answer the reviewer comment. This said, the contributions by Ch. Schoof are worth citing. More generally, I understand the reviewer's concern that citing early assessments such as Kriegler's or Lenton's might take more from these papers than what they actually meant to provide: their objective was to provide a perspective based on available and sometimes fragmentary evidence. They would not stand as a justification for the bifurcation structure to be associated with the tipping elements being considered here.

We are very thankful for these considerations and we think that the manuscript has now substantially improved by the inclusion of additional evidence from literature. These sources justify the type of bifurcation used in this manuscript and give extra details on the interactions between the tipping elements. For both parts, we included evidence from conceptual models, but also performed an extensive literature research, also building on

literature from existing more complex models that found such a bifurcation type or clues for interactions between the tipping elements. For more details, please see our answer to the reviewer comments.

- Please consider all minor comments.

We answered all minor points.

Most sincerely,
Michel Crucifix

Reviewer 1 comments

In response to my earlier review, the authors have added the cascading analysis without ENSO (in the SM) and have added more argumentation on why ENSO is considered, and to support the coupling of the different tipping elements. The paper has improved, but I think it still needs a round of revision to make it suitable for publication in Earth System Dynamics, following the comments below.

Major:

1. The justification of modelling ENSO through an equation (1) is not adequate. In the deterministic case, the ENSO transition is between a fixed point and a limit cyle. In the limit cycle, El Nino's occur but also La Nina's and although the mean state is slightly skewed towards the warm phase, the effect of the oscillation on the mean state (and hence on the coupling to the other tipping elements) is rather small. The permanent El Nino state in the Pliocene is much debated as many GCMs just show El Nino variability during this period, and it is not relevant for the present climate change context as the geometry of the Pacific was different (open Panama gateway). As the results for the case without ENSO (Figs. S3-S5) are not essentially diffferent (apart from the Amazon Forest behavior in Fig. S5), the paper would be much better when the results without ENSO would appear in the main text and the results with ENSO are only discussed in the last section of the paper, mentioning the caveat that one cannot justify (1) for ENSO.

We thank the reviewer for this insightful comment and additional explanation. After careful consideration, we have followed the advice and excluded ENSO from the main manuscript and moved the corresponding analysis to the supplementary information as a structural robustness analysis. As advised, we only discuss the results including ENSO in the last section of our paper with a statement that Eq. (1) is not entirely appropriate for describing ENSO for the reasons put forward by the reviewer. In the revised manuscript, all figures have been adapted accordingly and large parts of the discussion on ENSO have been shifted to the supplement and the last part of the results section. The structural robustness analysis including ENSO are described in Section 3.4 (ll 425-470) and the supplementary material. In all other parts in the main manuscript, only results without ENSO are shown. Due to the exclusion of the ENSO node in the network, the ensemble size that we compute is reduced from 11 mio. ensemble members to 3.7 mio. ensemble members since the link from the Amazon rainforest to ENSO is not part of our uncertainty propagation anymore.

2. In section 2, it should at least be argued very well (i) why each of the tipping elements considered can be represented by an equation (1), e.g. based on conceptual models, and (ii) that there are indications from models and/or observations of coupling between the tipping elements with a plausible physical description.

Issue (i) is mentioned in lines 116-124, but the references for the MIS are rather sparse (e.g. papers Weertman, Schoof) so this needs to be extended.

We truly appreciate this suggestion and believe that including the additional evidence for each of the tipping elements and its respective representation via equation (1) has massively improved the manuscript (see Section 2.1 in ll 127-194). In the following, we outline our line of argumentation:

First, we are well-aware that the representation of a complex climate tipping element with all its interacting processes as well as positive and negative feedbacks in a single cusp bifurcation is an immense simplification.

Nonetheless, we would argue that for our purpose of studying the role of the interaction network and strengths, the overall structure of the remaining four elements (AMOC, Greenland Ice Sheet, West Antarctic Ice Sheet, Amazon rainforest) can be well-represented by a cusp bifurcation.

Based on the extensive body of literature, we assume each of these to be a tipping element of the climate system. Conceptual models and basic physical understanding of the feedbacks explicitly show this cusp structure for climate tipping elements (Bathiany et al., 2016, Dynam. Stat. Clim. Syst.), and also many more complex, process-based and highly resolved models indicate this.

In the following, we describe the four tipping elements considered here. The same argumentation can be found in the manuscript in Section 2.1.

AMOC:

Early conceptual models introduced in the 1960ies showed that the AMOC can exhibit a cusp-like behaviour, using simplified box models based on the so-called salt-advection feedback (Stommel, 1961, Tellus; Cessi, 1994, J. Phys. Oceanogr.). Many extensions and updates to the well-known box model approach have been put forward, each confirming the potential multi-stability of the AMOC (e.g. Wood et al., 2019, Clim. Dynam.). More complex Earth system models including EMICs (e.g., CLIMBER) and AOGCMs (e.g., the FAMOUS and HadGEM3 models) have shown hysteresis behaviour which is qualitatively similar to Eq. 1 (Rahmstorf et al., 2005, Geophys. Res. Lett.; Hawkins et al., 2011, Geophys. Res. Lett.; Mecking et al., 2016, Clim. Dynam.). Furthermore, paleoclimatic evidence suggests a bistability of the AMOC: In paleoclimate records, Dansgaard-Oeschger events (see e.g. Crucifix, 2012, Philos. Trans. R. Soc. A) have been

associated with large reorganisations of the AMOC (Ganopolski and Rahmstorf, 2002, Phys. Rev. Lett.; Timmermann et al., 2003, J. Climate; Ditlevsen et al., 2005, J. Climate), where ice core data links the events to sea-surface temperature increases in the North Atlantic. Even though there are considerable uncertainties, literature estimates the level of global warming sufficient for tipping the AMOC between 3.5–6.0 C (Schellnhuber et al., 2016, Nat. Clim. Change; Lenton, 2012, Ambio; Levermann et al., 2012, Clim. Change; Lenton et al., 2008, Proc. Natl. Acad. Sci.), considerably increasing above 4°C above pre-industrial levels (Kriegler et al., 2009, Proc. Natl. Acad. Sci.).

From these reasons, we think that Eq. (1) can be justified for the AMOC.

GREENLAND & WEST ANTARCTIC ICE SHEETS:

Previous studies have shown that multistability and the cusp-like structure can result from the melt-elevation feedback (Levermann and Winkelmann, 2016, The Cryosphere) as well as from the MISI (Schoof, 2007, J. Geophys. Res.-Earth; Weertman, 1974, J. Glaciol.; DeConto & Pollard, 2016, Nature).

Greenland Ice Sheet:

Previous studies have shown that a fold-bifurcation structure for the ice sheets can arise from the melt-elevation feedback (Levermann & Winkelmann, 2016, The Cryosphere) as well as from the Marine Ice Sheet Instability and other positive feedback mechanisms (e.g., DeConto & Pollard, 2016, Nature; Schoof, 2007, J. Geophys. Res.-Earth; Weertman, 1974, J. Glaciol.). In particular, dynamic ice sheet model simulations have identified irreversible ice loss once a critical temperature threshold is crossed (Toniazzo et al., 2004, J. Climate), leading to multiple stable states and hysteresis behaviour for the Greenland Ice Sheet (Robinson et al., 2012, Nat. Clim. Change; Ridley et al., 2010, Clim. Dyn.). In Robinson et al. (2012), the critical temperature range for an irreversible disintegration of the Greenland Ice Sheet has been estimated between 0.8–3.2 C of warming above pre-industrial levels. Paleoclimate evidence further suggests that there have been substantial, potentially self-sustained retreats of the Greenland Ice Sheet in the past. It has, for instance, been simulated that the Greenland Ice Sheet can become ice-free in case presumably warmer ocean conditions from the Pliocene are applied to an initially glaciated Greenland (Koenig et al., 2014, Geophys. Res. Lett.). Further, Greenland was nearly ice-free for extended interglacial periods during the Pleistocene (Schaefer et al., 2016, Nature). Sea-level reconstructions further support the notion that during Marine Isotope Stage 11 and the Pliocene, large parts of Greenland could have been disintegrated (Dutton et al., 2015, Science).

West Antarctic Ice Sheet:

Different processes make the West Antarctic Ice Sheet susceptible to tipping dynamics. Since large parts of West Antarctica are marine basins, changes in the ocean are key in driving the evolution of the ice sheet. The Marine Ice Sheet Instability can trigger self-sustained ice loss where the ice sheet is based below sea-level on retrograde sloping bedrock (Schoof, 2007, J. Geophys. Res.-Earth). This destabilising mechanism is possibly already underway in the Amundsen Sea region (Favier et al., 2014, Nat. Clim. Change; Joughin et al., 2014, Science). Once triggered, a single local perturbation via increased subshelf melting in the Amundsen region could lead to wide-spread retreat of the West Antarctic Ice Sheet (Feldmann & Levermann, 2015, Proc. Natl. Acad. Sci.). Further, a recent study shows strong hysteresis behaviour for the whole Antarctic Ice Sheet, identifying two major thresholds which lead to a destabilisation of West Antarctica around 2°C of global warming, and large parts of East Antarctica between 6–9°C of global warming (Garbe et al., 2020, Nature). It is likely that the West Antarctic Ice Sheet has experienced brief but dramatic retreats during the past five million years (Pollard & DeConto, 2009, Nature). Prior collapses have been suggested from deep-sea-core isotopes and sea-level records (Gasson, 2016, Proc. Natl. Acad. Sci.; Dutton et al., 2015, Science; Pollard & DeConto, 2005, Glob. Planet. Change).

Therefore, we argue that the main dynamics of the ice sheets, even though on time scales of centuries to millennia, can be modelled with Eq. (1).

AMAZON RAINFOREST:

Conceptual models of the Amazon identified multi-stability between rainforest, savannah and treeless states, leading to hysteresis (Staal et al., 2016, Ecosystems; Staal et al., 2015, Ecol. Complex.; Van Nes et al., 2014, Glob. Change Biol.). This hysteresis has been found to be shaped by local-scale tipping points of the Amazon rainforest and resilience might be diminished under climate change until the end of the 21st century (Staal et al., 2020, Nat. Commun.). More complex dynamic vegetation models also found alternative stable states of the Amazon ecosystem (Oyama & Nobre, 2003, Geophys. Res. Lett.) and suggest that rainforest dieback might be possible due to drying of the Amazon basin under future climate change scenarios (Nobre et al., 2016, Proc. Natl. Acad. Sci.; Cox et al., 2004, Their. Appl. Climatol.; Cox et al., 2000, Nature). Observational data further supports the potential for multi-stability of the Amazon rainforest (Ciemer et al., 2019, Nat. Geosci.; Hirota et al., 2011, Science; Staver et al., 2011, Science). While it remains an open question whether the Amazon has a single system-wide tipping point, the projected increase in droughts and fires (Malhi et al., 2009, Proc. Natl. Acad. Sci.; Cox et al., 2008, Nature) is likely to impact the forest cover on a local to regional scale, which might spread to other parts of the region via moisture-recycling feedbacks (Zemp et al., 2017, Nat. Commun.; Zemp et al., 2014, Atmospheric Chem. Phys.; Aragão, 2012, Nature). It is important to note that in contrast to the ice sheets and ocean circulation, the rainforest is able to adapt to changing climate conditions to a certain extent (Sakschewski et al., 2016, Nat. Clim. Change). However, this adaptive capacity might still be outpaced if climate change progresses too rapidly (Wunderling et al., 2020, in review). A dieback of the Amazon rainforest has been found under a business-as-usual scenario (Cox et al., 2004, Their. Appl. Climatol.), which would be equivalent to a global warming of more than 3°C

above pre-industrial levels (3.5–4.5 C (see also Schellnhuber et al., 2016, Nat. Clim. Change)), mainly due to more persistent El-Niño conditions (Betts et al., 2004, Theor. Appl. Climatol.).

Therefore, we also argue that the Amazon rainforest can be modelled with an equation of type Eq. (1).

Issue (ii) is dealt with in lines 167-176 and Table 2, but this by far insufficient and (apart from the ENSO-AMOC connection) without any references to model/observation results. One cannot simply refer only to Kriegler et al., as that assessment was very rough (Fig. 2 in their paper) and more than 10 years old.

We are very thankful for the reviewers comment since we agree that a better understanding of the interaction processes between the tipping elements does improve our work significantly and also yields a better motivation for the interactions between the tipping elements. Therefore, we supply each interaction pair in our set of four tipping elements with existing literature references. The references motivate why the respective link has a stabilising, destabilising or unclear effect on the influenced tipping element. However, a direct interaction strength between different tipping elements as it would be necessary for our conceptual model cannot be extracted from these literature sources listed. Therefore, we propagate all uncertainties in our large scale Monte Carlo ensemble. Please see below for an explanation of each of the interaction pairs between the four investigated tipping elements or Section 2.2 in ll 194-274 in the manuscript for the changes in the revised manuscript. This means that, although the expert elicitation in Kriegler et al. (2009, Proc. Natl. Acad. Sci.) was rough, the additional literature sources support and refine the results from an early expert elicitation.

1) **Greenland Ice Sheet (GIS) → AMOC: Increasing freshwater input from enhanced melting of the Greenland Ice Sheet can lead to a weakening of the AMOC, as supported by observations, paleo evidence as well as modelling studies (Caesar et al., 2018, Nature; Robson et al., 2014, Nat. Geosci.; Driesschaert et al., 2007, Geophys. Res. Lett.; Jungclaus et al., 2006, Geophys. Res. Lett.; Rahmstorf et al., 2005, Geophys. Res. Lett.). Between 1992 and 2018, the Greenland Ice Sheet has lost around 3900+-342 Gt of ice (Shepherd et al., 2020, Nature). The ice loss has strongly accelerated in recent years (Sasgen et al., 2020, Communs. Earth & Environ.), and Greenland has been subject to several extreme melt events in the past decade alone (Tedesco & Fettweis, 2020, The Cryosphere; Nghiem et al., 2012, Geophys. Res. Lett.; Tedesco et al., 2011, Environ. Res. Lett.). At the same time, an AMOC weakening of 15% (3+-1 Sv) has been observed since the 1950s (Caesar et al., 2018, Nature). This weakening has at least partially been attributed to freshwater influx into the North Atlantic deep water formation regions due to enhanced melting from Greenland. Paleoclimatic records further suggest that the AMOC could exist in multiple stable states, based on observed temperature**

changes associated with meltwater influx into the North Atlantic (Blunier and Brook, 2001, Science; Dansgaard et al., 1993, Nature). Therefore, it is very likely that a tipping of the Greenland Ice Sheet would lead to a destabilization of the AMOC (see Fig. 1).

2) **<u>AMOC → GIS</u>: Reversely, if the AMOC weakens, leading to a decline in its northward surface heat transport, Greenland might experience cooler temperatures (e.g. Jackson et al., 2015, Clim. Dyn.; Timmermann et al., 2007, J. Climate; Stouffer et al., 2006, J. Climate), which would have a stabilizing effect on the ice sheet. With the global climate model HadGEM3, it has been shown that temperatures in Europe could drop by several degrees if the AMOC collapses, regionally up to 8 C (Jackson et al., 2015, Clim. Dyn.). A cooling trend in sea surface temperatures (SST) over the subpolar gyre, as a result of a weakening AMOC, has been confirmed by recent reanalysis and observation data (Caesar et al., 2018, Nature; Jackson et al., 2016, Nat. Geosci.; Frajka-Williams, 2015, Geophys. Res. Lett.; Robson et al., 2014, Nat. Geosci.). This "fingerprint" translates a reduction in overturning strength by 1.7 Sv per century to 0.44 K SST-cooling per century (Caesar et al., 2018, Nature). AMOC regime shifts between weaker and stronger overturning strength during the last glacial period have been associated with large regional temperature changes in Greenland, for example during Dansgaard-Oeschger or Heinrich events (Barker and Knorr, 2016, PAGES). Moreover, there is paleoclimatic evidence from 3.6 million years ago that a weaker North Atlantic current as part of the AMOC fostered Arctic sea-ice growth which might have preceded continental glaciation in the northern hemisphere at that time (Karas et al., 2020, Glob. Planet. Change). Based on these findings we assume that a weakening of the AMOC would have a stabilising effect on the Greenland Ice Sheet (see Fig. 1).**

3) **<u>West Antarctic Ice Sheet (WAIS) → AMOC</u>: It remains unclear whether increased ice loss from the West Antarctic Ice Sheet has a stabilizing and destabilizing effect on the AMOC (see Fig. 1). Swingedouw et al.(2009) (Swingedouw et al., 2009, Clim. Dyn.) identified different processes based on freshwater hosing experiments into the Southern Ocean, which could be associated with a melting West Antarctic Ice Sheet. Using the EMIC LOVECLIM1.1, the authors revealed effects, some of which would enhance and others would weaken the AMOC strength: (i) First, deep water adjustments are observed. This means that an increase of the North Atlantic Deep Water formation is observed in response to a decrease in Antarctic bottom water production due to the conducted hosing experiment. This mechanism has been termed the so-called bipolar ocean seesaw. (ii) Second, salinity anomalies in the Southern Ocean are distributed to the North Atlantic, which dampens the North Atlantic DeepWater formation (compare to Seidov et al., 2005, Glob. Planet. Change). (iii) Third, the North Atlantic Deep Water formation is enhanced by southern hemispheric wind increase in response to a southern hemispheric**

cooling. The reason for this wind increase is the risen meridional temperature gradient between a cooler Antarctic region (due to the hosing experiment) and the equator. This effect has been termed the Drake Passage effect earlier (Toggweiler & Samuels, 1995, Deep Sea Res. Part I Oceanogr. Res. Pap.). Overall, the first and the third mechanism tend to strengthen the AMOC, while the second process would rather lead to a weakening of the AMOC. The specific time scales and relative strengths of these mechanisms is as of yet unclear (Swingedouw et al., 2009, Clim. Dyn.). In a coupled ocean-atmosphere model, a slight weakening of the AMOC was detected for a freshwater input of 1.0 Sv in the Southern Ocean over 100 years (Seidov et al., 2005, Global Planet. Change). However, other studies suggest a stabilisation of the AMOC if influenced by freshwater input from the West Antarctic Ice Sheet due to the effects from the bipolar ocean seesaw by decreasing Antarctic Bottom Water formation as described above (Swingedouw et al., 2008, Geophys. Res. Lett.). Therefore, the direction of this interaction pathway is unclear (see Fig. 1).

4) **AMOC → WAIS: The interaction from the AMOC to the West Antarctic Ice Sheet is destabilising (see Fig. 1). In case the AMOC shuts down, sea surface temperature anomalies could appear since the northward heat transport is diminished significantly. This could then lead to a warmer south and colder north, as observed in modelling studies (Weijer et al., 2019, J. Geophys. Res.-Oceans; Timmermann et al., 2007, J. Climate; Stouffer et al., 2006, J. Climate; Vellinga & Wood, 2002, Climatic Change). A model intercomparison study for EMICs and AOGCMs found a sharp decrease of surface air temperatures over the northern hemisphere, while a slight increase over the southern hemisphere and around the Antarctic Ice Sheet has been observed (Stouffer et al., 2006, J. Climate). In their study (Stouffer et al., 2006, J. Climate), a forcing of 1.0 Sv has been applied to the northern part of the North Atlantic Ocean. Therefore, we set this link as destabilising (see Fig. 1).**

5) **GIS → WAIS & WAIS → GIS: The interaction between the Greenland and the West Antarctic Ice Sheet can be regarded as mutually destabilising, however, with a different magnitude (see Fig. 1). It is a well-known phenomenon from tidal changes that grounding lines of ice sheets are varying (e.g. Sayag & Worster, 2013, Geophys. Res. Lett.). Therefore, the Greenland Ice Sheet and the West Antarctic Ice Sheet could influence each other by sea level rise if one or the other cryosphere element would melt. Gravitational, but also elastic and rotational impacts would then enhance the sea level rise in case one of the huge ice sheets would melt first since then only the other ice sheets exerts strong gravitational forces (Kopp et al., 2010, Clim. Change; Mitrovica et al., 2009, Science). The impact of this effect would be higher if Greenland becomes ice free earlier than the West Antarctic Ice Sheet because many marine terminating ice shelves are located in West Antarctica, but the interaction destabilises in both directions (see Fig. 1).**

6) **<u>AMOC → AMAZ (Amazon rainforest)</u>: Lastly, the interaction between the AMOC and the Amazon rainforest is set as unclear (see Fig. 1). It is suspected that the intertropical convergence zone (ITCZ) would be shifted southward in case the AMOC collapses. This could cause large changes in seasonal precipitation on a local scale, and could as such have strong impacts on the Amazon rainforest (Jackson et al., 2015, Clim. Dyn.; Parsons, 2014, Geophys. Res. Lett.). In the Earth system model ESM2M, it has been found that a strongly suppressed AMOC, through a 1.0 Sv freshwater forcing, leads to drying over many regions of the Amazon rainforest (Parsons, 2014, Geophys. Res. Lett.). However, some regions receive more rainfall than before. On a seasonal level, the wet season precipitation is diminished strongly, while the dry season precipitation is significantly increased (Jackson et al., 2015, Clim. Dyn.; Parsons, 2014, Geophys. Res. Lett.). This could have consequences for the current vegetation that is adapted to this partially strong seasonal precipitation. But overall, it remains unclear whether the influence from a tipped AMOC to the precipitation in South America has a reducing or increasing influence. Instead, it might differ from locality to locality and is set as unclear in our study (see Fig. 1).**

In the supplementary material, we provide the same discussion for the interactions that include ENSO (see *Structural sensitivity analysis including ENSO* of the supplementary material).

Minor:

1. l123-124: A collapse in the AMOC only affects the position of the Hopf bifurcation. So clarify what is meant here.

This is true. We meant that a collapsing AMOC can trigger a critical transition of ENSO (see e.g. Dekker et al., 2018 Earth Syst. Dynam.). To avoid misunderstandings, we have rephrased this sentence in the manuscript (see ll. 430-431).

2. l187-188: Current GCMs (in particular with high resolution ocean models) can adequately resolve nonlinear behavior in ENSO.

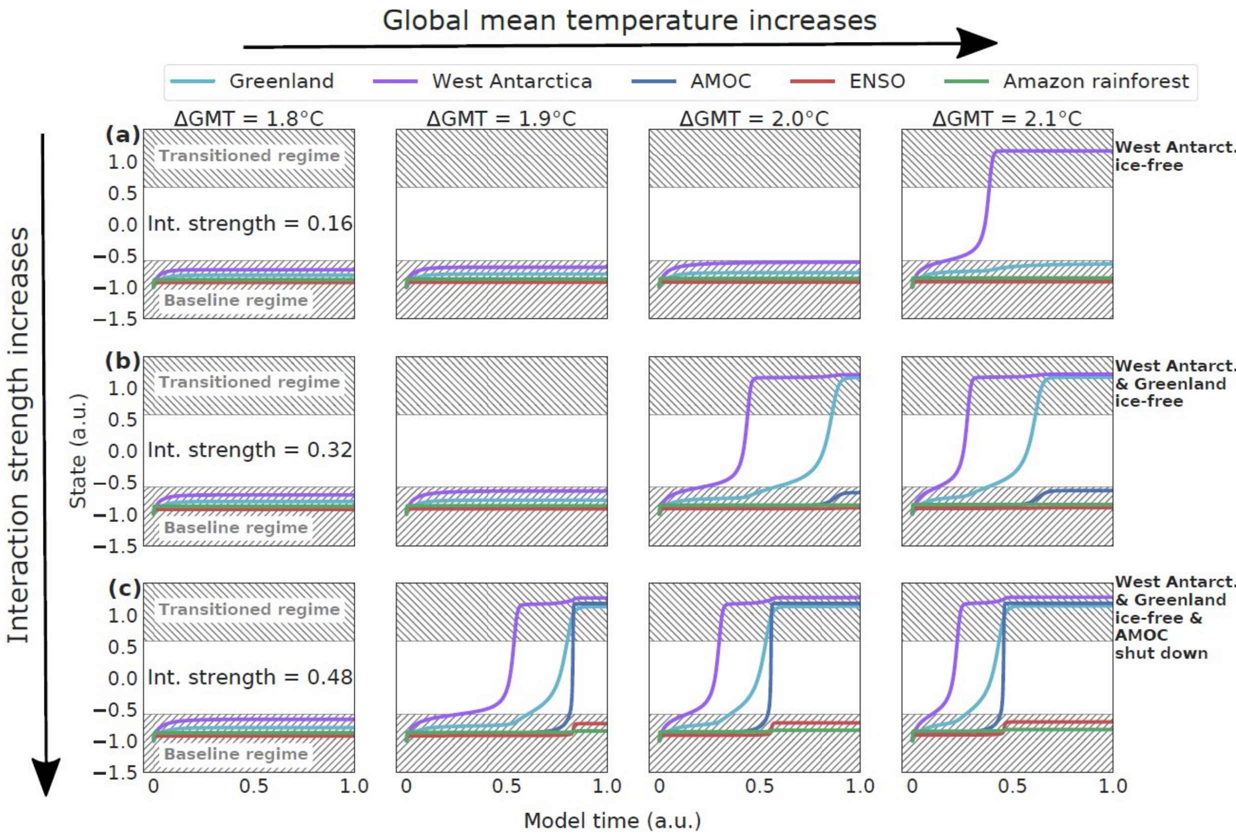
We agree with the reviewer and removed this statement from our manuscript. However, in terms of interacting tipping elements, we think state-of-the-art GCMs might not always be the best choice for studies such as this, since large ensembles computed over very long times would be required. Therefore, computational constraints might hinder such a wide analysis as it is done in this work, a point that was also raised for instance in Wood et al. (2019, Clim. Dynam.). Still, if possible, it would be great and highly desirable to investigate some or all of the interactions with GCMs or EMICs in the future (see ll. 305-306).

3. The x-axis label in Fig. 2 is not readable (at least in my .pdf file). Please adapt.

Thanks for letting us know. In our version, the x-axes labels are visible [panel a) GMT; panel b) Model time (a.u.)]. We now supply this figure as a high-resolution .png file instead of a .pdf file (see Fig. 2). Please let us know if the problem persists.

4. In Fig. 3, there is a small transition in ENSO which is also reflected in the WAIS response. However, it stays within the baseline regime for ENSO. What is this small transition and what is causing it?

Since we now exclude ENSO from our analysis in the main manuscript, we exclude these timelines from our analysis and replace them by timelines without ENSO (see new Fig. 3). However, for completeness, we attach this figure here and explain why there is a small transition in ENSO and WAIS: in panel c), for increases of the global mean temperature of 1.9°C or above for this particular choice of parameters, there is a critical transition of AMOC into the tipped state. Since there is a positive interaction link from AMOC to ENSO (see Fig. S2), there is also a small increase of the state in ENSO, that is, however, not sufficient to tip ENSO over. Furthermore, the state of ENSO is positively feeding back to the state of WAIS (see Fig. S2) such that this pattern is pushed forward to the state of WAIS.



5. I miss a discussion on the time of transition and the delayed effect one transition has on the occurrence of another one. Here the ice sheets play a dominant initiator role simply because their temperature threshold is lowest. However, it takes a significant amount of time for subsequent meltwater (and sea level) to affect other tipping elements. Of course, it is not in the approach followed in the paper but it is relevant to discuss in the last section.

We appreciate this comment since such a discussion was indeed missing in the discussion of our manuscript. Therefore, we mention the significant time delay that emerges from the transitions of the cryosphere components that might tip themselves only on the order of centuries up to millennia (see ll 513-520).

Finally, the software used for the results in the paper should be made publicly available (e.g. through github) so other researchers can check the computations.

We agree that it would help other researchers when the code is published for the construction of the Monte Carlo ensemble as well as the computation of the tipping events. Thus, we created a github repository that explains the software package (PyCascades, doi: 10.5281/*zenodo*.4153102) in detail and also contains a folder with the climate tipping elements. At the end of the main manuscript, we supply a "Code

Availability Statement", where we refer to this repository that also includes a doi (see ll 525-526).

List of References

1. Aragão, L.E., 2012. Environmental science: The rainforest's water pump. *Nature*, *489*(7415), pp.217-218.
2. Barker, S. and Knorr, G., 2016. A paleo-perspective on the AMOC as a tipping element. *PAGES Magazine*, *24*(1), pp.14-15.
3. Bathiany, S., Dijkstra, H., Crucifix, M., Dakos, V., Brovkin, V., Williamson, M.S., Lenton, T.M. and Scheffer, M., 2016. Beyond bifurcation: using complex models to understand and predict abrupt climate change. *Dynamics and Statistics of the Climate System*, *1*(1).
4. Betts, R.A., Cox, P.M., Collins, M., Harris, P.P., Huntingford, C. and Jones, C.D., 2004. The role of ecosystem-atmosphere interactions in simulated Amazonian precipitation decrease and forest dieback under global climate warming. *Theoretical and applied climatology*, *78*(1-3), pp.157-175.
5. Blunier, T. and Brook, E.J., 2001. Timing of millennial-scale climate change in Antarctica and Greenland during the last glacial period. *Science*, *291*(5501), pp.109-112.
6. Caesar, L., Rahmstorf, S., Robinson, A., Feulner, G. and Saba, V., 2018. Observed fingerprint of a weakening Atlantic Ocean overturning circulation. *Nature*, *556*(7700), pp.191-196.
7. Cessi, P., 1994. A simple box model of stochastically forced thermohaline flow. *Journal of Physical Oceanography*, *24*(9), pp.1911-1920.
8. Ciemer, C., Boers, N., Hirota, M., Kurths, J., Müller-Hansen, F., Oliveira, R.S. and Winkelmann, R., 2019. Higher resilience to climatic disturbances in tropical vegetation exposed to more variable rainfall. *Nature Geoscience*, *12*(3), pp.174-179.
9. Cox, P.M., Betts, R.A., Jones, C.D., Spall, S.A. and Totterdell, I.J., 2000. Acceleration of global warming due to carbon-cycle feedbacks in a coupled climate model. *Nature*, *408*(6809), pp.184-187.
10. Cox, P.M., Betts, R.A., Collins, M., Harris, P.P., Huntingford, C. and Jones, C.D., 2004. Amazonian forest dieback under climate-carbon cycle projections for the 21st century. *Theoretical and Applied Climatology*, *78*(1-3), pp.137-156.
11. Cox, P.M., Harris, P.P., Huntingford, C., Betts, R.A., Collins, M., Jones, C.D., Jupp, T.E., Marengo, J.A. and Nobre, C.A., 2008. Increasing risk of Amazonian drought due to decreasing aerosol pollution. *Nature*, *453*(7192), pp.212-215.

12. Crucifix, M., 2012. Oscillators and relaxation phenomena in Pleistocene climate theory. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, *370*(1962), pp.1140-1165.
13. Dansgaard, W., Johnsen, S.J., Clausen, H.B., Dahl-Jensen, D., Gundestrup, N.S., Hammer, C.U., Hvidberg, C.S., Steffensen, J.P., Sveinbjörnsdottir, A.E., Jouzel, J. and Bond, G., 1993. Evidence for general instability of past climate from a 250-kyr ice-core record. *Nature*, *364*(6434), pp.218-220.
14. DeConto, R.M. and Pollard, D., 2016. Contribution of Antarctica to past and future sea-level rise. *Nature*, *531*(7596), pp.591-597.
15. Dekker, M.M., Von Der Heydt, A.S. and Dijkstra, H.A., 2018. Cascading transitions in the climate system. *Earth System Dynamics*, *9*(4), pp.1243-1260.
16. Ditlevsen, P.D., Kristensen, M.S. and Andersen, K.K., 2005. The recurrence time of Dansgaard–Oeschger events and limits on the possible periodic component. *Journal of Climate*, *18*(14), pp.2594-2603.
17. Driesschaert, E., Fichefet, T., Goosse, H., Huybrechts, P., Janssens, I., Mouchet, A., Munhoven, G., Brovkin, V. and Weber, S.L., 2007. Modeling the influence of Greenland ice sheet melting on the Atlantic meridional overturning circulation during the next millennia. *Geophysical Research Letters*, *34*(10).
18. Dutton, A., Carlson, A.E., Long, A., Milne, G.A., Clark, P.U., DeConto, R., Horton, B.P., Rahmstorf, S. and Raymo, M.E., 2015. Sea-level rise due to polar ice-sheet mass loss during past warm periods. *Science*, *349*(6244).
19. Favier, L., Durand, G., Cornford, S.L., Gudmundsson, G.H., Gagliardini, O., Gillet-Chaulet, F., Zwinger, T., Payne, A.J. and Le Brocq, A.M., 2014. Retreat of Pine Island Glacier controlled by marine ice-sheet instability. *Nature Climate Change*, *4*(2), pp.117-121.
20. Feldmann, J. and Levermann, A., 2015. Collapse of the West Antarctic Ice Sheet after local destabilization of the Amundsen Basin. *Proceedings of the National Academy of Sciences*, *112*(46), pp.14191-14196.
21. Frajka‐Williams, E., 2015. Estimating the Atlantic overturning at 26 N using satellite altimetry and cable measurements. *Geophysical Research Letters*, *42*(9), pp.3458-3464.
22. Ganopolski, A. and Rahmstorf, S., 2002. Abrupt glacial climate changes due to stochastic resonance. *Physical Review Letters*, *88*(3), p.038501.
23. Garbe, J., Albrecht, T., Donges, J.F., Levermann, A. and Winkelmann, R., 2020. Hysteresis of the Antarctic Ice Sheet. *Nature*, *585*(7826), pp.538-544.
24. Gasson, E., DeConto, R.M., Pollard, D. and Levy, R.H., 2016. Dynamic Antarctic ice sheet during the early to mid-Miocene. *Proceedings of the National Academy of Sciences*, *113*(13), pp.3459-3464.
25. Hawkins, E., Smith, R.S., Allison, L.C., Gregory, J.M., Woollings, T.J., Pohlmann, H. and De Cuevas, B., 2011. Bistability of the Atlantic overturning circulation in a global climate model and links to ocean freshwater transport. *Geophysical Research Letters*, *38*(10).

26. Hirota, M., Holmgren, M., Van Nes, E.H. and Scheffer, M., 2011. Global resilience of tropical forest and savanna to critical transitions. *Science*, *334*(6053), pp.232-235.
27. Jackson, L.C., Kahana, R., Graham, T., Ringer, M.A., Woollings, T., Mecking, J.V. and Wood, R.A., 2015. Global and European climate impacts of a slowdown of the AMOC in a high resolution GCM. *Climate Dynamics*, *45*(11-12), pp.3299-3316.
28. Jackson, L.C., Peterson, K.A., Roberts, C.D. and Wood, R.A., 2016. Recent slowing of Atlantic overturning circulation as a recovery from earlier strengthening. *Nature Geoscience*, *9*(7), pp.518-522.
29. Joughin, I. and Alley, R.B., 2011. Stability of the West Antarctic ice sheet in a warming world. *Nature Geoscience*, *4*(8), pp.506-513.
30. Joughin, I., Smith, B.E. and Medley, B., 2014. Marine ice sheet collapse potentially under way for the Thwaites Glacier Basin, West Antarctica. *Science*, *344*(6185), pp.735-738.
31. Jungclaus, J.H., Haak, H., Esch, M., Roeckner, E. and Marotzke, J., 2006. Will Greenland melting halt the thermohaline circulation?. *Geophysical Research Letters*, *33*(17).
32. Karas, C., Khélifi, N., Bahr, A., Naafs, B.D.A., Nürnberg, D. and Herrle, J.O., 2020. Did North Atlantic cooling and freshening from 3.65–3.5 Ma precondition Northern Hemisphere ice sheet growth?. *Global and Planetary Change*, *185*, p.103085.
33. Koenig, S.J., DeConto, R.M. and Pollard, D., 2014. Impact of reduced Arctic sea ice on Greenland ice sheet variability in a warmer than present climate. *Geophysical Research Letters*, *41*(11), pp.3933-3942.
34. Kopp, R.E., Mitrovica, J.X., Griffies, S.M., Yin, J., Hay, C.C. and Stouffer, R.J., 2010. The impact of Greenland melt on local sea levels: a partially coupled analysis of dynamic and static equilibrium effects in idealized water-hosing experiments. *Climatic Change*, *103*(3-4), pp.619-625.
35. Kriegler, E., Hall, J.W., Held, H., Dawson, R. and Schellnhuber, H.J., 2009. Imprecise probability assessment of tipping points in the climate system. *Proceedings of the national Academy of Sciences*, *106*(13), pp.5041-5046.
36. Lenton, T.M., Held, H., Kriegler, E., Hall, J.W., Lucht, W., Rahmstorf, S. and Schellnhuber, H.J., 2008. Tipping elements in the Earth's climate system. *Proceedings of the national Academy of Sciences*, *105*(6), pp.1786-1793.
37. Lenton, T.M., 2012. Arctic climate tipping points. *Ambio*, *41*(1), pp.10-22.
38. Levermann, A., Bamber, J.L., Drijfhout, S., Ganopolski, A., Haeberli, W., Harris, N.R., Huss, M., Krüger, K., Lenton, T.M., Lindsay, R.W. and Notz, D., 2012. Potential climatic transitions with profound impact on Europe. *Climatic Change*, *110*(3-4), pp.845-878.
39. Levermann, A. and Winkelmann, R., 2016. A simple equation for the melt elevation feedback of ice sheets. *The Cryosphere*, *10*(4), pp.1799-1807.
40. Malhi, Y., Aragão, L.E., Galbraith, D., Huntingford, C., Fisher, R., Zelazowski, P., Sitch, S., McSweeney, C. and Meir, P., 2009. Exploring the likelihood and mechanism of a climate-change-induced dieback of the Amazon rainforest. *Proceedings of the National Academy of Sciences*, *106*(49), pp.20610-20615.

41. Mecking, J.V., Drijfhout, S.S., Jackson, L.C. and Graham, T., 2016. Stable AMOC off state in an eddy-permitting coupled climate model. *Climate Dynamics*, *47*(7-8), pp.2455-2470.
42. Mitrovica, J.X., Gomez, N. and Clark, P.U., 2009. The sea-level fingerprint of West Antarctic collapse. *Science*, *323*(5915), pp.753-753.
43. Nghiem, S.V., Hall, D.K., Mote, T.L., Tedesco, M., Albert, M.R., Keegan, K., Shuman, C.A., DiGirolamo, N.E. and Neumann, G., 2012. The extreme melt across the Greenland ice sheet in 2012. *Geophysical Research Letters*, *39*(20).
44. Nobre, C.A., Sampaio, G., Borma, L.S., Castilla-Rubio, J.C., Silva, J.S., and Cardoso, M., 2016. Land-use and climate change risks in the Amazon and the need of a novel sustainable development paradigm, *Proceedings of the National Academy of Sciences*, 113, pp.10759–10768.
45. Oyama, M.D. and Nobre, C.A., 2003. A new climate‐vegetation equilibrium state for tropical South America. *Geophysical Research Letters*, *30*(23).
46. Parsons, L.A., Yin, J., Overpeck, J.T., Stouffer, R.J. and Malyshev, S., 2014. Influence of the Atlantic Meridional Overturning Circulation on the monsoon rainfall and carbon balance of the American tropics. *Geophysical Research Letters*, *41*(1), pp.146-151.
47. Pollard, D. and DeConto, R.M., 2005. Hysteresis in Cenozoic Antarctic ice-sheet variations. *Global and Planetary Change*, *45*(1-3), pp.9-21.
48. Pollard, D. and DeConto, R.M., 2009. Modelling West Antarctic ice sheet growth and collapse through the past five million years. *Nature*, *458*(7236), pp.329-332.
49. Rahmstorf, S., Crucifix, M., Ganopolski, A., Goosse, H., Kamenkovich, I., Knutti, R., Lohmann, G., Marsh, R., Mysak, L.A., Wang, Z. and Weaver, A.J., 2005. Thermohaline circulation hysteresis: A model intercomparison. *Geophysical Research Letters*, *32*(23).
50. Ridley, J., Gregory, J.M., Huybrechts, P. and Lowe, J., 2010. Thresholds for irreversible decline of the Greenland ice sheet. *Climate Dynamics*, *35*(6), pp.1049-1057.
51. Robinson, A., Calov, R. and Ganopolski, A., 2012. Multistability and critical thresholds of the Greenland ice sheet. *Nature Climate Change*, *2*(6), pp.429-432.
52. Robson, J., Hodson, D., Hawkins, E. and Sutton, R., 2014. Atlantic overturning in decline?. *Nature Geoscience*, *7*(1), pp.2-3.
53. Sasgen, I., Wouters, B., Gardner, A.S., King, M.D., Tedesco, M., Landerer, F.W., Dahle, C., Save, H. and Fettweis, X., 2020. Return to rapid ice loss in Greenland and record loss in 2019 detected by the GRACE-FO satellites. *Communications Earth & Environment*, *1*(1), pp.1-8.
54. Sayag, R. and Worster, M.G., 2013. Elastic dynamics and tidal migration of grounding lines modify subglacial lubrication and melting. *Geophysical Research Letters*, *40*(22), pp.5877-5881.
55. Schaefer, J.M., Finkel, R.C., Balco, G., Alley, R.B., Caffee, M.W., Briner, J.P., Young, N.E., Gow, A.J. and Schwartz, R., 2016. Greenland was nearly ice-free for extended periods during the Pleistocene. *Nature*, *540*(7632), pp.252-255.

56. Schellnhuber, H.J., Rahmstorf, S. and Winkelmann, R., 2016. Why the right climate target was agreed in Paris. *Nature Climate Change*, *6*(7), pp.649-653.
57. Schoof, C., 2007. Ice sheet grounding line dynamics: Steady states, stability, and hysteresis. *Journal of Geophysical Research: Earth Surface*, *112*(F3).
58. Seidov, D., Stouffer, R.J. and Haupt, B.J., 2005. Is there a simple bi-polar ocean seesaw?. *Global and Planetary Change*, *49*(1-2), pp.19-27.
59. Shepherd, A., Ivins, E., Rignot, E., Smith, B., van den Broeke, M., Velicogna, I., Whitehouse, P., Briggs, K., Joughin, I., Krinner, G. and Nowicki, S., et al., 2020. Mass balance of the Greenland Ice Sheet from 1992 to 2018. *Nature*, *579*(7798), pp.233-239.
60. Staal, A., Dekker, S.C., Hirota, M. and van Nes, E.H., 2015. Synergistic effects of drought and deforestation on the resilience of the south-eastern Amazon rainforest. *Ecological Complexity*, *22*, pp.65-75.
61. Staal, A., Dekker, S.C., Xu, C. and van Nes, E.H., 2016. Bistability, spatial interaction, and the distribution of tropical forests and savannas. *Ecosystems*, *19*(6), pp.1080-1091.
62. Staver, A.C., Archibald, S. and Levin, S.A., 2011. The global extent and determinants of savanna and forest as alternative biome states. *Science*, *334*(6053), pp.230-232.
63. Stocker, T.F., Wright, D.G. and Broecker, W.S., 1992. The influence of high‐latitude surface forcing on the global thermohaline circulation. *Paleoceanography*, *7*(5), pp.529-541.
64. Stommel, H., 1961. Thermohaline convection with two stable regimes of flow. *Tellus*, *13*(2), pp.224-230.
65. Stouffer, R.J., Yin, J., Gregory, J.M., Dixon, K.W., Spelman, M.J., Hurlin, W., Weaver, A.J., Eby, M., Flato, G.M., Hasumi, H. and Hu, A., 2006. Investigating the causes of the response of the thermohaline circulation to past and future climate changes. *Journal of Climate*, *19*(8), pp.1365-1387.
66. Swingedouw, D., Fichefet, T., Huybrechts, P., Goosse, H., Driesschaert, E. and Loutre, M.F., 2008. Antarctic ice‐sheet melting provides negative feedbacks on future climate warming. *Geophysical Research Letters*, *35*(17).
67. Swingedouw, D., Fichefet, T., Goosse, H. and Loutre, M.F., 2009. Impact of transient freshwater releases in the Southern Ocean on the AMOC and climate. *Climate Dynamics*, *33*(2-3), pp.365-381.
68. Tedesco, M., Fettweis, X., Van den Broeke, M.R., Van de Wal, R.S.W., Smeets, C.J.P.P., van de Berg, W.J., Serreze, M.C. and Box, J.E., 2011. The role of albedo and accumulation in the 2010 melting record in Greenland. *Environmental Research Letters*, *6*(1), p.014005.
69. Tedesco, M. and Fettweis, X., 2020. Unprecedented atmospheric conditions (1948–2019) drive the 2019 exceptional melting season over the Greenland ice sheet. *Cryosphere*, *14*, pp.1209-1223.

70. Timmermann, A., Gildor, H., Schulz, M. and Tziperman, E., 2003. Coherent resonant millennial-scale climate oscillations triggered by massive meltwater pulses. *Journal of Climate*, *16*(15), pp.2569-2585.
71. Timmermann, A., Okumura, Y., An, S.I., Clement, A., Dong, B., Guilyardi, E., Hu, A., Jungclaus, J.H., Renold, M., Stocker, T.F. and Stouffer, R.J., 2007. The influence of a weakening of the Atlantic meridional overturning circulation on ENSO. *Journal of Climate*, *20*(19), pp.4899-4919.
72. Toggweiler, J.R. and Samuels, B., 1995. Effect of Drake Passage on the global thermohaline circulation. *Deep Sea Research Part I: Oceanographic Research Papers*, *42*(4), pp.477-500.
73. Toniazzo, T., Gregory, J.M. and Huybrechts, P., 2004. Climatic impact of a Greenland deglaciation and its possible irreversibility. *Journal of Climate*, *17*(1), pp.21-33.
74. van Nes, E.H., Hirota, M., Holmgren, M. and Scheffer, M., 2014. Tipping points in tropical tree cover: linking theory to data. *Global Change Biology*, *20*(3), pp.1016-1021.
75. Vellinga, M. and Wood, R.A., 2002. Global climatic impacts of a collapse of the Atlantic thermohaline circulation. *Climatic Change*, *54*(3), pp.251-267.
76. Weertman, J., 1974. Stability of the junction of an ice sheet and an ice shelf. *Journal of Glaciology*, *13*(67), pp.3-11.
77. Weijer, W., Cheng, W., Drijfhout, SS, Fedorov, AV, Hu, A., Jackson, LC, et al.(2019). Stability of the Atlantic Meridional Overturning Circulation: A review and synthesis. J. Geophys. Res.: Oceans, 124, 5336–5375. *Journal of Geophysical research*.
78. Wood, R.A., Rodríguez, J.M., Smith, R.S., Jackson, L.C. and Hawkins, E., 2019. Observable, low-order dynamical controls on thresholds of the Atlantic Meridional Overturning Circulation. *Climate Dynamics*, *53*(11), pp.6815-6834.
79. Wunderling, N., Staal, A., Sakschewski, B., Hirota, M., Tuinenburg, O., Donges, J., Barbosa, H. and Winkelmann, R., 2020. Network dynamics of drought-induced tipping cascades in the Amazon rainforest (in review, preprint available from ResearchSquare under the doi 10.21203/rs.3.rs-71039/v1).
80. Zemp, D.C., Schleussner, C.F., Barbosa, H.M.J., Van der Ent, R.J., Donges, J.F., Heinke, J., Sampaio, G. and Rammig, A., 2014. On the importance of cascading moisture recycling in South America. *Atmospheric Chemistry and Physics*, 14, 13337-13359.
81. Zemp, D.C., Schleussner, C.F., Barbosa, H.M., Hirota, M., Montade, V., Sampaio, G., Staal, A., Wang-Erlandsson, L. and Rammig, A., 2017. Self-amplified Amazon forest loss due to vegetation-atmosphere feedbacks. *Nature Communications*, *8*(1), pp.1-10.