Interacting tipping elements increase risk of climate domino effects under global warming

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Abstract. There exists a range of subsystems in the climate system possibly exhibiting threshold behaviour which could be triggered under global warming within this century resulting in severe consequences for biosphere and human societies. While their individual tipping thresholds are fairly well understood, it is of yet unclear how their interactions might impact the overall stability of the Earth's climate system. This cannot be studied yet with state-of-the-art Earth system models due to computational constraints as well as missing and uncertain process representations of some tipping elements.

Here, we explicitly study the effects of known physical interactions among the Greenland and West Antarctic Ice Sheet, the Atlantic Meridional Overturning Circulation (AMOC), the El-Niño Southern Oscillation (ENSO) and the Amazon rainforest using a conceptual network approach. We analyse the risk of domino effects being triggered by each of the individual tipping elements under global warming in equilibrium experiments, propagating uncertainties in critical temperature thresholds, interaction strengths and interaction structure via a Monte-Carlo approach.

Overall, we find that the interactions tend to destabilise the network of tipping elements. Furthermore, our analysis reveals the qualitative role of each of the five tipping elements showing that the polar ice sheets on Greenland and West Antarctica are oftentimes the initiators of tipping cascades, while the AMOC acts as a mediator, transmitting cascades.

This implies that the ice sheets, which are already at risk of transgressing their temperature thresholds within the Paris range of 1.5 to 2 °C, are of particular importance for the stability of the climate system as a whole.

1 Introduction

In the Earth system, there exists a range of large-scale subsystems, the so-called *tipping elements*. They can undergo sudden, qualitative and possibly irreversible changes in response to environmental perturbations once a certain critical threshold in forcing is exceeded (Lenton et al., 2008). Under such conditions, the actual tipping process might then take years up to millennia depending on the respective element separating critical forcing and realisation time of tipping (Hughes et al., 2013; Lenton et al., 2008). Among the tipping elements are cryosphere entities such as the continental ice sheets on Greenland and Antarctica, biosphere components such as the Amazon rainforest or coral reefs as well as circulation patterns such as monsoon systems or the Atlantic Meridional Overturning Circulation. With continuing global warming, critical thresholds of some tipping elements might be exceeded within this century triggering severe consequences for the biosphere and human societies. These critical thresholds can be quantified with respect to the global mean temperature (GMT) resulting in three clusters of tipping elements that are characterised by their critical temperature (between 1-3 °C, 3-5 °C, above 5 °C respectively) (Schellnhuber et al., 2016). In the most vulnerable cluster from 1-3 °C above pre-industrial, there are mostly cryosphere entities such as the Greenland and West Antarctic Ice Sheet, the Arctic summer sea ice and mountain glaciers.

However, the tipping elements are not isolated systems but they interact on a global scale (Lenton et al., 2019; Kriegler et al., 2009). These interactions can have stabilising or destabilising effects on the probability of tipping cascades and it remains an important issue to understand how this affects the overall stability of the Earth system. Despite the considerable recent progresses in global Earth system modelling, current state-of-the-art global Earth system models cannot yet comprehensively simulate the nonlinear behaviour of many of the tipping elements due to uncertainties in process representations that would be relevant for modelling threshold behaviour as well as due to computational limitations, as for instance for the polar ice sheets or the AMOC (Wood et al., 2019). Furthermore, the interactions between tipping elements have also not yet been described in a framework of simpler process-based models in general since the interaction structure of tipping elements is not yet fully understood and partially explicitly based on expert knowledge.

In turn, for a subset of five tipping elements an expert elicitation was conducted synthesising a causal interaction structure and an estimation for the probability of cascading, nonlinear responses (Kriegler et al., 2009). These tipping elements are the Greenland Ice Sheet, the West Antarctic Ice Sheet, the Atlantic Meridional Overturning Circulation (AMOC), the El-Niño Southern Oscillation (ENSO) and the Amazon rainforest (see Fig. 1). Although this network is not complete with respect to the physical interactions between the tipping elements and the actual set of tipping elements themselves (Wang & Hausfather, 2020; Lenton et al., 2019; Steffen et al., 2018), it is a first step towards an interaction structure of important subregions in the Earth system. To our best knowledge, an update of this assessment or a comparably comprehensive expert assessment has not been undertaken since Kriegler et al. (2009).

The network from this expert elicitation has already been used in an earlier study to evaluate the interactions between the tipping elements in a Boolean approach based on graph grammars. Here, it was found that the strong positive-negative feedback loop between the Greenland Ice Sheet and the AMOC might act as a stabiliser to the Earth system (Gaucherel & Moron, 2017). Also, large economic damages have been found using this network with respect to the social cost of carbon using a stochastic and dynamic evaluation of tipping points in an integrated assessment model (Cai et al., 2016) alongside other studies that quantified economic impacts of tipping and tipping interactions (Lemoine & Traeger, 2016; Cai et al., 2015). In the light of the recent studies that hypothesise a considerable risk of tipping cascades up to a potential global cascade ("hothouse state") (Lenton et al., 2019; Steffen et al., 2018), we aim at developing a conceptual network model in this work that can check whether interactions of tipping elements have stabilising, destabilising or no effect on the stability of the global climate state. As such, we view our study as an hypotheses generator that results in qualitative results (rather than exact quantifications, let alone predictions) that can then be examined by more complex process-detailed Earth system models. This is why we argue that the conceptual investigation of the Earth system with a complex systems approach such as the one presented here is worthwhile, also since some tipping elements might already show early warning signals of their beginning disintegration as recent studies suggest (Lenton et al., 2019; Caesar et al., 2018; Nobre et al., 2016; Favier et al., 2014). The results of this study can lay the foundations and possibly guide towards a more detailed analysis with more complex models or data based approaches.

Observations from the last decades show that all five tipping elements are already impacted by progressing global warming (Wang & Hausfather, 2020; Lenton et al., 2019; IPCC, 2014; Levermann et al., 2010). The mass loss rate of Greenland and West Antarctica has increased and accelerated over the past decades (Shepherd et al., 2018; Khan et al., 2014; Zwally et al., 2011). Recent studies suggest that some parts, especially in the Amundsen basin in West Antarctica, might already have crossed a tipping point (Favier et al., 2014). The grounding lines of glaciers in this region are retreating rapidly, which could induce an instability mechanism (Marine Ice Sheet Instability) eventually leading to the disintegration of the whole region. Also from paleo records, it is suggested that parts of Antarctica and larger parts of Greenland might already have experienced strong ice retreat in the past, especially during the Pliocene as well as in the Marine Isotope Stages 5e and 11 (Dutton et al., 2015).

It has also been shown that the AMOC experienced a significant slow-down since the mid of the last century (Caesar et al., 2018) potentially due to freshening of the Atlantic ocean by increased meltwater inflows from Greenland (Bakker et al., 2016; Böning et al., 2016). This trend and a bistability was also found in global circulation models and Earth system models of intermediate complexity (Drijfhout et al., 2012; Hawkins et al., 2011; Driesschaert et al., 2007; Jungclaus et al., 2006; Rahmstorf et al., 2005). Using proxies from sea surface, air temperatures and a global climate model, it has been observed that the AMOC slowed down significantly before the beginning of the Holocene (Ritz et al., 2013).

The Amazon rainforest is not only directly impacted by anthropogenic climate change for instance through severe droughts or heat waves (Marengo et al., 2015; Brando et al., 2014), but also by deforestation and fire (Malhi et al., 2009). This increases the risk that parts of it will transit from a rainforest to a savanna state for instance through a diminished moisture recycling ratio (Staal et al., 2018; Zemp et al., 2017). It is suspected that the Amazon rainforest could be close to a critical deforestation ratio which might, together with global warming, suffice to start such a critical transition (Nobre et al., 2016). This could cause 30-50% of the forest to shift to tropical savanna or dry forests (Nobre et al., 2016).

While the other four tipping elements could be viewed as exhibiting a transition between two stable states, tipping of ENSO could imply a transition from irregular occurrences to a more permanent state of strong El-Niño conditions (Lenton et al., 2008; Kriegler et al., 2009; Dekker et al., 2018). However, whether ENSO can be subject to a major tipping event of that kind requires further discussion since the response of ENSO to ongoing global warming remains debated among scientists. While some literature studies emphasise the uncertainty about future ENSO changes (Kim et al., 2014; Collins et al., 2010), another study found that the frequency of El-Niño events can increase twofold in climate change scenarios in simulations of CMIP3, CMIP5 and perturbed physics models (Cai et al., 2014). Also some ENSO characteristics seem to react robustly to global warming (Santoso et al., 2013; Power et al., 2013; Kim et al., 2014), 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).

Moreover, from an observational data point of view, it was found that the global warming trend since the early 1990s has enhanced the Atlantic capacitor effect which might lead to more favourable conditions for major El-Niño events on a biennial rhythm (Wang et al., 2017). Paleo evidence from the Pliocene (4.5−3.0 mio. years ago) with atmospheric CO_2 levels comparable to today's climate state suggests that there may have been permanent El-Niño conditions during that epoch (Wara et al., 2005; Ravelo et al., 2006; Fedorov et al., 2006).

Overall, changes in the frequency of major El-Niño events seem likely, also based on intermediate complexity and conceptual models (Timmermann et al., 2005; Dekker et al., 2018), but whether this poses the possibility of a permanent and potentially irreversible tipped ENSO continues to be debated. A more frequent ENSO could have strong impacts on global ecosystems up to a potential dieback of the Amazon rainforest (Duque-Villegas et al., 2019). Given the particular uncertainties regarding ENSO compared to the other tipping elements, we decided to include ENSO as a tipping element in the main manuscript, but performed a comprehensive structural robustness analysis excluding ENSO as a tipping element (see supplement and supplementary Figs. S3 to S6).

In section 2, we provide an overview of the dynamics of the tipping elements and their interactions are represented in our model. We also describe the construction of the large scale Monte-Carlo ensemble which enables us to propagate the parameter uncertainties of the tipping elements. In section 3, we explore how the ranges of the critical temperatures of the tipping elements change with increasing interaction strength between them. It is also shown which tipping elements initiate and transmit tipping cascades revealing the respective role of the tipping element. Section 4 draws together the results and discusses the limitations of our approach. It also outlines possible investigations of tipping element interaction with more process-detailed models.

2 Methods

2.1 Threshold effects and network modelling approach

For each of the five tipping elements investigated here, conceptual models exist that describe their basic dynamics. These conceptual models show distinct states of the tipping elements separated by a bifurcation, in most cases implying a hysteresis behaviour. In these conceptual approaches, tipping leads to an abrupt shift for instance from an “on” to an “off” (shutdown) state for the AMOC (Wood et al., 2019; Stommel, 1961), from ice-covered to essentially ice-free Greenland or West Antarctica (Levermann & Winkelmann, 2016) and from a tree-covered state to a partial savanna or treeless state in the Amazon rainforest (Staal et al., 2015; Nes et al., 2014). For ENSO, the threshold effect can be described by a Hopf-bifurcation (Timmermann et al., 2003; Dekker et al., 2018) based on a conceptual model by Zebiak & Cane (1987). The representation as a Hopf-bifurcation implies that no hysteresis occurs for ENSO. In coupled experiments for AMOC and ENSO with these conceptual models, it was found that a changing AMOC can induce a bifurcation in ENSO, too (Timmermann et al., 2005; Dekker et al., 2018).

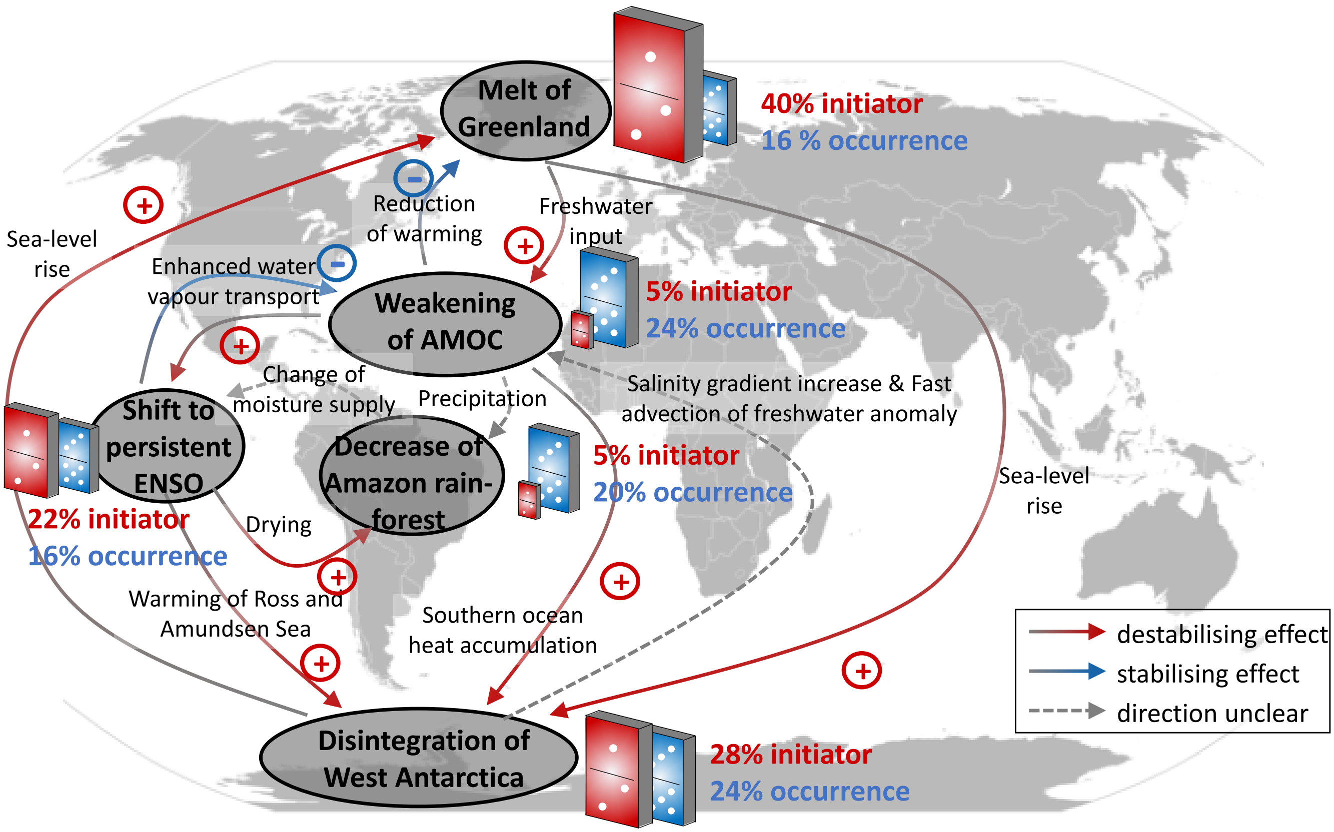

Figure 1. Interactions between climate tipping elements and their roles in tipping cascades. The Greenland Ice Sheet, West Antarctic Ice Sheet, Atlantic Meridional Overturning Circulation (AMOC), El-Niño Southern Oscillation (ENSO) and the Amazon rainforest are depicted together with their main interaction pathways (Kriegler et al., 2009). The interaction links between the tipping elements are colour-marked, where red arrows depict destabilising effects and blue arrows depict stabilising effects. Where the direction is unclear, the link is marked in grey. A more thorough description of each of the tipping elements and the links can be found in Tables 1 and 2. Where tipping cascades arise, the relative size of the dominoes illustrates in how many model representations the respective climate components initiates (red domino) or is part of (blue domino) cascading transitions. Standard deviations for these values are given in Figs. S1(a) and (b). Generally, the polar ice sheets are found to more frequently take on the role as initiators than the equatorial tipping elements.

Based on these conceptual models as well as building on first coupled experiments with a discrete state Boolean model (Gaucherel & Moron, 2017) and an economic impact study (Cai et al., 2016), we here describe the interactions of the five tipping elements in a network approach using a set of coupled, topologically equivalent differential equations (Kuznetsov, 2004). This means that the main dynamics of each of the tipping elements are condensed to a non-linear differential equation with two stable states representing the current baseline state and a possible transitioned state capturing the qualitative dynamics of the respective tipping element (see Sect. 2.2, Eqs. 1 and 2). While this serves as a straight-forward stylised representation for the Greenland Ice Sheet, the West Antarctic Ice Sheet, the AMOC and the Amazon rainforest, it does not so for ENSO since the nature of its potential tipping point as discussed above would be more directly represented by a Hopf-bifurcation (Dekker et al., 2018; Zebiak & Cane, 1987). However, we choose to represent ENSO in the same way as the other tipping elements making use of the topological equivalence of the two separated dynamic states (Kuznetsov, 2004). We argue that this simplification is justified for our analysis since we are mainly interested in the two qualitatively different states of the tipping elements in equilibrium and not in transient dynamics (Krönke et al., 2020; Brummitt et al., 2015). Also, we do not investigate a possible "backtipping" (i.e. hysteresis behaviour is not relevant for this study), but the forcing represented by the increase of the global mean temperature is only increased.

2.2 Differential equation model and physical interpretation of interactions

Each tipping element in the network is modelled by the non-linear differential equation

$$\frac{dx_i}{dt} = \left[\overbrace{-x_i^3 + x_i + c_i}^{\text{Individual dynamics term}} + \overbrace{\frac{1}{2}\sum_{\substack{j \\ j\neq i}} d_{ij}\,(x_j+1)}^{\text{Coupling term}} \right] \frac{1}{\tau_i}, \tag{1}$$

where x_i indicates the state of a certain tipping element, c_i is the critical parameter and τ_i the typical tipping time scale with $i = \{$Greenland Ice Sheet, West Antarctic Ice Sheet, AMOC, ENSO, Amazon rainforest$\}$. This approach has already been used frequently for qualitatively describing tipping dynamics in different applications and network types and has been applied to systems in climate, ecology, economics and political science (Klose et al., 2020; Krönke et al., 2020; Wunderling et al., 2020; Dekker et al., 2018; Brummitt et al., 2015; Abraham et al., 1991). While the first term (*Individual dynamics term*) indicates the dynamical properties of each tipping element, the second term (*Coupling term*) describes the interactions of each tipping element to the other elements (Fig. 1). If the prefactors in front of the cubic and the linear term are one and the additive coupling term is neglected, the critical values where state changes occur are $c_{i\ 1,2} = \pm\sqrt{4/27}$. The differential equation is bistable for critical parameters between c_1 and c_2 and can here be separated into a *transitioned* and a *baseline* state, where $x_i = -1$ denotes the baseline state and $x_i = +1$ the completely transitioned one. The critical parameter c_i is modelled by the increase of the global mean temperature, i.e., $c_i = \frac{\sqrt{4/27}}{T_{\text{limit, i}}} \cdot \Delta\text{GMT}$, where $T_{\text{limit, i}}$ is the critical temperature and ΔGMT the increase of the global mean temperature. This means that a state change occurs as soon as the increase of the GMT is higher than the critical temperature (see Table 1).

In addition, we also model the physical interactions between the tipping elements as a linear coupling (first order approach). The coupling term $\frac{1}{2}\sum_j d_{ij}\,(x_j+1)$ consists of a sum of linear couplings to other elements x_j with $d_{ij} = d\cdot s_{ij}/5$. It is necessary to add $+1$ on top of x_j such that the direction (sign) of coupling is only determined by d_{ij} and not by the state x_j.

Tipping element	ΔT_{limit} (°C)
Greenland	0.8 – 3.2
West Antarctica	0.8 – 5.5
AMOC	3.5 – 6.0
ENSO	3.5 – 7.0
Amazon rainforest	3.5 – 4.5

Table 1. Nodes in the network of tipping elements. For each tipping element in the network (see Fig. 1) a range of critical temperatures ΔT_{limit} is known from literature (Schellnhuber et al., 2016). In this temperature range, the tipping element is likely to undergo a transition.

Thus, equation 1 becomes

$$\frac{dx_i}{dt} = \left[-x_i^3 + x_i + \frac{\sqrt{4/27}}{T_{\text{limit, i}}} \cdot \Delta\text{GMT} + \frac{d}{10} \cdot \sum_{\substack{j \\ j \neq i}} s_{ij} \left(x_j + 1 \right) \right] \frac{1}{\tau_i}. \tag{2}$$

Here d is the *interaction strength* parameter that we vary in our simulations and s_{ij} is the link strength based on the expert elicitation (Kriegler et al., 2009) (see Table 2 & Sect. 2.5, *model initialisation and uncertainties*). The processes behind the interactions between the TEs are listed in Table 2.

Note that we adapted the link from ENSO to AMOC from uncertain to negative since there is only a stabilising process known in literature (Lenton & Williams, 2013). In this network of tipping elements, very strong interactions exist, e.g., between Greenland and the AMOC. On the one hand melting of Greenland increases the likelihood tipping of the AMOC via freshwater influx in the North Atlantic, while on the other hand a transitioned AMOC would hinder warm water from the equator reaching Greenlandic regions thus cooling the ice sheet (see exemplary timelines Fig. 2(b)). The reason for a state transition is twofold, either through the increase of GMT or through the coupling to other tipping elements (Fig. 2(a)). Further important couplings are the impact of Greenland on West Antarctica via rising sea levels intensified by gravitational changes that are more pronounced on the Southern hemisphere if the gravitational power of Greenland is lost through disintegration of its ice sheet. Strong interactions also exist in lower, equatorial latitudes between the ENSO and the Amazon rainforest, where a transitioned ENSO might significantly lower the precipitation over Amazonia.

The interaction strength d is described as a dimensionless constant of interaction strength between the tipping elements (see Eq. 2). It is varied over a wide range in our simulations due to the uncertainties in the actual physical interaction strength between the tipping elements such that a variety of different scenarios can be investigated, i.e., for $d \in [0;1]$. An interaction strength of 0 implies no coupling between the elements such that only the individual dynamics remain. If the interaction strength reaches high values around 1, the coupling term reaches the same magnitude as the individual dynamics term. In principle, more complex and data- or model-based interaction terms could be developed. But, while some interactions (Greenland Ice Sheet & AMOC or AMOC & ENSO) have been established better with EMICs like CLIMBER-2 and Loveclim as well as

Edge	Maximal link strength s_{ij} (a.u.)	Physical process
Greenland → AMOC	$+10$	Freshwater inflow
AMOC → Greenland	-10	AMOC breakdown, Greenland cooling
Greenland → West Antarctica	$+10$	Grounding line retreat
ENSO → Amazon rainforest	$+10$	Drying over Amazonia
ENSO → West Antarctica	$+5$	Warming of Ross and Amundsen seas
AMOC → Amazon rainforest	± 2 up to $\pm$ 4	Changes in hydrological cycle
West Antarctica → AMOC	± 3	Increase in meridional salinity gradient ($-$), Fast advection of freshwater anomaly to North Atlantic ($+$)
AMOC → ENSO	$+2$	Cooling of North-East tropical Pacific with thermocline shoaling and weakening of annual cycle in EEP
West Antarctica → Greenland	$+2$	Grounding line retreat
ENSO → AMOC	-2	Enhanced water vapour transport to Pacific
AMOC → West Antarctica	$+1.5$	Heat accumulation in Southern Ocean
Amazon rainforest → ENSO	± 1.5	Changes in tropical moisture supply

Table 2. Edges in the network of tipping elements. For each edge in the network of Fig. 1, there is a strength and a sign for each interaction of the tipping elements. The sign indicates if the interaction between the tipping elements is increasing or decreasing the danger of tipping cascades. After Kriegler et al. (2009) (Kriegler et al., 2009), the strength s_{ij} gives the index in terms of increased or decreased probability of cascading transitions. E.g., if Greenland transgresses its threshold, the probability that the AMOC does as well is increased by a factor of 10 (see entry for Greenland → AMOC). Then a random number between $+1$ and $s_{ij} = s_{\text{Greenland}\rightarrow\text{AMOC}} = +10$ is drawn for our simulations. The other way round, the probability that Greenland transgresses its threshold in case the AMOC is in the transitioned state is decreased by a factor of $\frac{1}{10}$. Then a random number between -1 and $s_{ij} = s_{\text{AMOC}\rightarrow\text{Greenland}} = -10$ is drawn. Furthermore, the main physical processes that connect pairs tipping elements are described in this table. The link strengths are grouped into strong, intermediate and weak links. Data and physical processes are taken from existing literature (Lenton & Williams, 2013; Kriegler et al., 2009).

GCMs (Rahmstorf et al., 2005; Driesschaert et al., 2007; Sterl et al., 2008; Jungclaus et al., 2006; Wood et al., 2019), other interactions are less well established (for instance interactions between the Greenland and West Antarctic Ice Sheet) potentially leading to biased coupling strengths. Furthermore, some more complex models cannot yet adequately resolve the nonlinear behaviour of some of the tipping elements, for instance ENSO. Thus, deriving interaction strength parameters from them might be misleading. Also from a paleo climate point of view, the estimation of interaction strength parameters could be difficult due to the sparsity of data that are available as of yet. To overcome these shortcomings, we propagate the considerable uncertainties linked to the properties of the tipping elements that have been determined in the expert elicitation in Kriegler et al. (2009) and critical temperature temperature thresholds in Schellnhuber et al. (2016) with a large scale Monte-Carlo simulation (see Sect. 2.5). This allows, in principle, to derive qualitative results from the model that accommodate these large uncertainties, despite the conceptual nature of the interaction term.

In summary this implies that in our model, if the critical temperature threshold of a tipping element is surpassed, it transgresses into the transitioned state and can potentially increase the likelihood of further tipping events via its interactions: for instance, the increased freshwater influx from Greenland Ice Sheet melt can induce a slow-down or even collapse of the AMOC (Fig. 2(b)). In our simulations, we consider increases of the global mean temperature from 0 up to 8 °C above pre-industrial, which could be reached in worst-case scenarios for the extended representative concentration pathway 8.5 (RCP 8.5) until 2500 (Schellnhuber et al., 2016; IPCC, 2014).

2.3 Time series and evaluation of tipping cascades

As long as the state of a certain tipping element is negative, we call this the *baseline* state. However, when the state variable of a tipping element crosses the limit of the lower grey hatched area within the course of a simulation run, a state transition occurs due to the global mean temperature and interactions between the respective tipping elements (see Figs. 2 and 3). The respective tipping element then ends up in the upper hatched area and remains in the *transitioned* state. The time series for an in-depth example include temperature increases of 1.8, 1.9, 2.0 and 2.1 °C (columns) above pre-industrial and interaction strengths of 0.16, 0.32 and 0.48 (rows, see Fig. 3). From left to right panels, the global mean temperature is increased by 0.1 °C and hence a tipping cascade is initiated.

In our example, the interaction strength determines the size of the tipping cascade, here from one to three (see Figs. 3(a), (b) and (c)). Still, the size, the timing and the occurrence of cascades also depend on the specific initial conditions. However, in general, the size of tipping cascades increases with higher interaction strengths and higher global warming. In these examples, we only show conditions where a tipping event takes place. This might not be the case for other conditions, e.g., lower global mean temperature increases, other couplings or other initial conditions. The initial conditions for the specific example of Fig. 3 can be found in supplementary Table S1.

We count tipping cascades as the difference in the number of transitioned elements at a steady interaction strength d with two slightly different global mean temperatures in the following way: we increase the GMT slightly (by 0.1 °C) between two subsequent equilibrium simulations. In case the number of transitioned elements differs between these two simulations, then

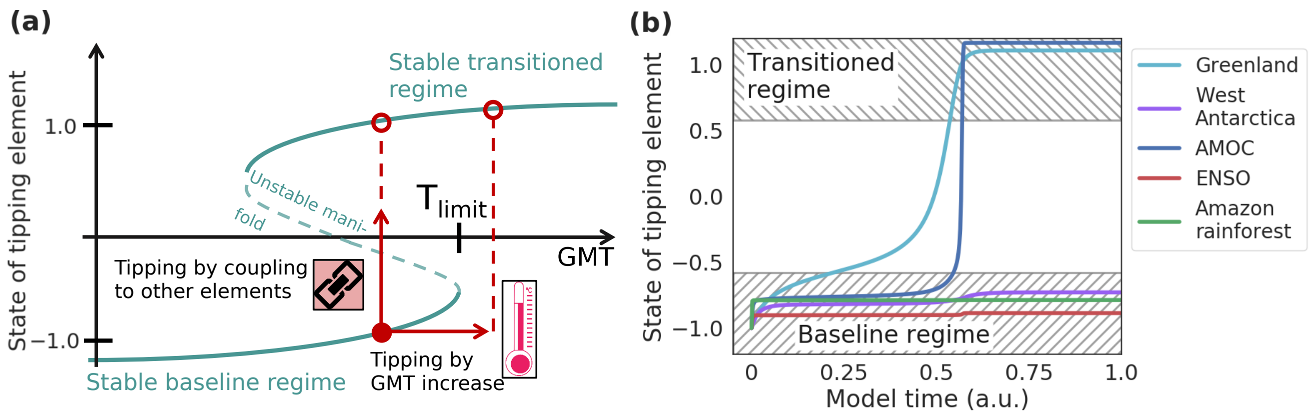

Figure 2. Schematic of generalised tipping element and time-series of tipping cascade. **(a)** Exemplary bifurcation diagram of a tipping element with two stable regimes: The lower state indicates the stable baseline regime, the upper state the stable transitioned regime. In case of the Greenland Ice Sheet, for instance, these correspond to its pre-industrial, almost completely ice-covered state (stable baseline regime) and an almost ice-free state (stable transitioned regime), as can be expected on the long-term for higher warming scenarios (Robinson et al., 2012). There are two ways how a tipping element can transgress its critical boundary (*unstable manifold*) and transition into the transitioned state, either by an increase of the global mean temperature or via interactions with other climate components. In both cases, the tipping element ends up in the stable transitioned regime indicated by the red full and hollow circles. **(b)** Exemplary time series showing a tipping cascade of two elements. Here, Greenland transgresses its critical temperature ($T_{\text{limit, Greenland}}$) first, i.e., would become ice-free. Through its interaction with the AMOC (in particular, due to increased freshwater flux into the North Atlantic from the melting ice sheet), the AMOC then transgresses the unstable manifold in vertical direction (following the path of the red upward directed arrow in panel **(a)**. This example is based on a scenario with global mean temperature increase of 3.0 °C above pre-industrial levels and an interaction strength d of 0.10 (see methods in Chapt. 2).

a cascade of the respective size is counted at the GMT, where the state change occurred. Furthermore, the tipping element whose critical temperature threshold is closest to the temperature of tipping is counted as the tipping element which initiated this cascade.

2.4 Time scales

The five tipping elements in the coupled system of differential equations form a so-called *fast-slow system* (Kuehn, 2011) describing a dynamical system with slowly varying parameters compared to fast changing states x_i. We calibrate typical tipping time scales by multiplying the right hand side of equation 1 with the inverse of the typical tipping time scale τ_i such that a critical transition from the baseline to the transitioned state takes the adjusted amount of time in our model. Based on literature values for tipping times (Dekker et al., 2018; Winkelmann et al., 2015; Robinson et al., 2012; Lenton et al., 2008), we set the tipping time scale for the Greenland Ice Sheet, West Antarctic Ice Sheet, AMOC, ENSO and the Amazon rainforest to 4900,

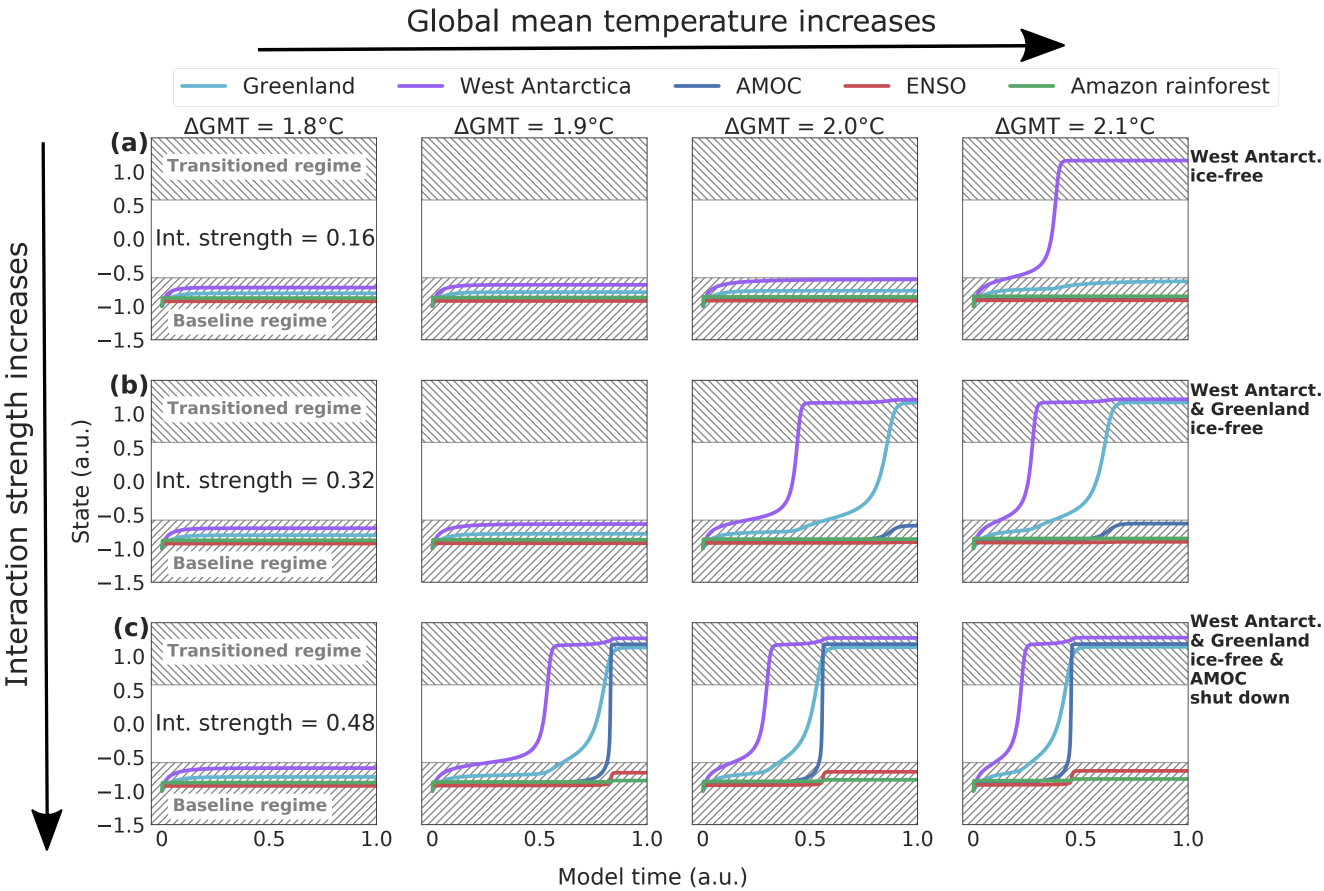

Figure 3. Time series of tipping cascades. Exemplary time series of states for each of the five investigated tipping elements, here simulated until equilibrium is reached. For comparability reasons, the initial conditions for the time series are the same (see Table S1) and all time series are computed for ΔGMT increases of 1.8, 1.9, 2.0 and 2.1 °C above pre-industrial (columns). Couplings are constant for each row. Tipping cascades as shown here are defined as the number of transitioned elements at a fixed interaction strength and ΔGMT compared to the simulation with a slightly higher ΔGMT (ΔGMT increase by 0.1 °C), but same interaction strength. If, between these two simulations, some of the tipping elements alter their equilibrium state, then a tipping cascade of the respective size occurred and is counted as such. **(a)** Singular tipping event for an interaction strength of 0.16. Tipping occurs at 2.1 °C. **(b)** Tipping cascade of size two for an interaction strength of 0.32. The cascade occurs at 2.0 °C. **(c)** Tipping cascade of size three for an interaction strength of 0.48, where tipping occurs at 1.9 °C. For other initial conditions, interaction strengths and global mean temperatures (ΔGMT) tipping cascades of size four and five can occur, too. Additionally, we marked the baseline and the transitioned regime as grey hatched areas. Between the hatched areas, the value of the time series is not stable and a critical state transition occurs. In the lower grey area, the element is called to be in the *baseline* regime and in the *transitioned* regime in the upper grey region.

2400, 300, 300 and 50 years at 4 °C above pre-industrial. The tipping time scale is calibrated at this one point in the case of no interaction between the elements. After calibration, the tipping time is allowed to scale freely with changes in the GMT and the interaction strength d.

Since this model is a conceptual model and we are running equilibrium experiments only, we are only interested in the difference (and not the absolute value) between the tipping times as they can be decisive if a cascade emerges or not. The time each experiment is run is more than eight times the tipping time of the slowest tipping element which is until the equilibrium is reached in our experiments. In turn, the actual *absolute* number of the tipping time value is difficult to interpret and should not be taken as a prognosis of how long a potential tipping cascade takes. Therefore, the figures show model years in arbitrary units.

2.5 Model initialisation and uncertainties

Since the absolute strength of interactions between the tipping elements is highly uncertain, a dimensionless interaction strength is varied over a wide range in our network approach to cover a multitude of possible scenarios (see Chapt. 2 for detailed methods). To cope with the uncertainties in the critical temperatures and in the link strengths between pairs of tipping elements (see Eq. 2, Tables 1 and 2), we set up a Monte-Carlo ensemble with approximately 11 million members in total.

This Monte Carlo ensemble is set up a follows: we use a sample of 100 starting conditions of critical temperatures and link strengths s_{ij} from the uncertainty ranges given in literature (see Tables 1 and 2) (Schellnhuber et al., 2016; Kriegler et al., 2009). We model the uncertainty in the critical temperatures and the link strengths by drawing values randomly from a uniform distribution with a latin-hypercube algorithm (Baudin, 2013). Note that in the expert elicitation (Kriegler et al., 2009), there has been an estimation of the maximum increase or decrease of the tipping probability in case the element which starts the interaction is already in the transitioned state. For example, the link between Greenland and AMOC is given as [1; 10] in Kriegler et al. (2009) and is here modelled as a randomly drawn variable between 1 and 10 for s_{ij}. An example for an unclear coupling would be the link between West Antarctica and AMOC which is given as [0.3; 3] in Kriegler et al. (2009) which we translate into an s_{ij} between -3 and 3. In general, the values are drawn between 1 and the respective maximum value s_{ij} if the interaction between i and j is positive or between -1 and the negative maximum value s_{ij} if the interaction between i and j is negative (see Table 2). Since our model has 17 parameters with uncertainties, we use a latin-hypercube sampling to construct a set of starting conditions for the Monte Carlo simulation such that the space of starting conditions is covered better than with a usual random sample generation (Baudin, 2013). With this set of 100 starting conditions, we simulate the state for each pair of global mean temperatures and interaction strengths d.

We also simulate all 27 different network types which arise when we permute all possibilities (negative, zero, positive) from the three unclear links AMOC $\rightarrow$ Amazon rainforest, West Antarctica $\rightarrow$ AMOC and Amazon rainforest $\rightarrow$ ENSO (see Table 2 and Fig. 1). For each of these 27 network types, we compute the same 100 starting conditions that we received from our latin-hypercube sampling. Thus, in total, we compute 2700 samples for each GMT ($0.0 - 8.0$ °C, step width: 0.1 °C) and interaction strength ($0.0 - 1.0$, step width: 0.02) ending up a large ensemble of 11 million members overall.

3 Results

3.1 Critical temperature ranges

For each individual tipping element, global mean temperature thresholds have been identified (Schellnhuber et al., 2016), showing that Greenland and West Antarctica might already be at risk within the Paris range while AMOC, ENSO and the Amazon rainforest have a higher critical temperature range (Fig. 4(a)). Assuming a uniform distribution, we draw random values from these individual temperature ranges as initial conditions for our Monte-Carlo ensemble.

Owing to the interactions between the tipping elements, the critical temperatures are generally shifted to lower values (Figs. 4(b) and (c)). This lowering of the temperature thresholds is almost linear for the Amazon rainforest and ENSO with increasing interaction strength, while for West Antarctica and AMOC, we find a sharp decline for interaction strengths up to 0.2 and an approximately constant critical temperature range afterwards.

In particular, the mean critical temperature for these four tipping elements is lowered by about 1.4 °C (45%) for West Antarctica, 2.75 °C (55%) for AMOC, 2.75 °C (50%) for ENSO and 2.1 °C (55%) the Amazon rainforest, respectively (Fig. 5). This is likely due to the predominantly positive links between these tipping elements (see Fig. 1).

In contrast, the critical temperature range for the Greenland Ice Sheet can in fact be raised due to the interaction with the other tipping elements, accompanied by significantly increasing uncertainty. This can be explained by the strong positive-negative interaction loop between Greenland and the AMOC (see Table 2): On the one hand, enhanced meltwater influx into the North Atlantic might dampen the AMOC (positive feedback), while on the other hand, a weakened overturning circulation would lead to a net-cooling effect around Greenland (negative feedback). Thus, the state of Greenland strongly depends on the specific initial conditions in critical temperature and interaction strength of the respective Monte-Carlo ensemble member.

Overall, the interactions do not lead to a stabilisation for all components in the network except for the Greenland Ice Sheet.

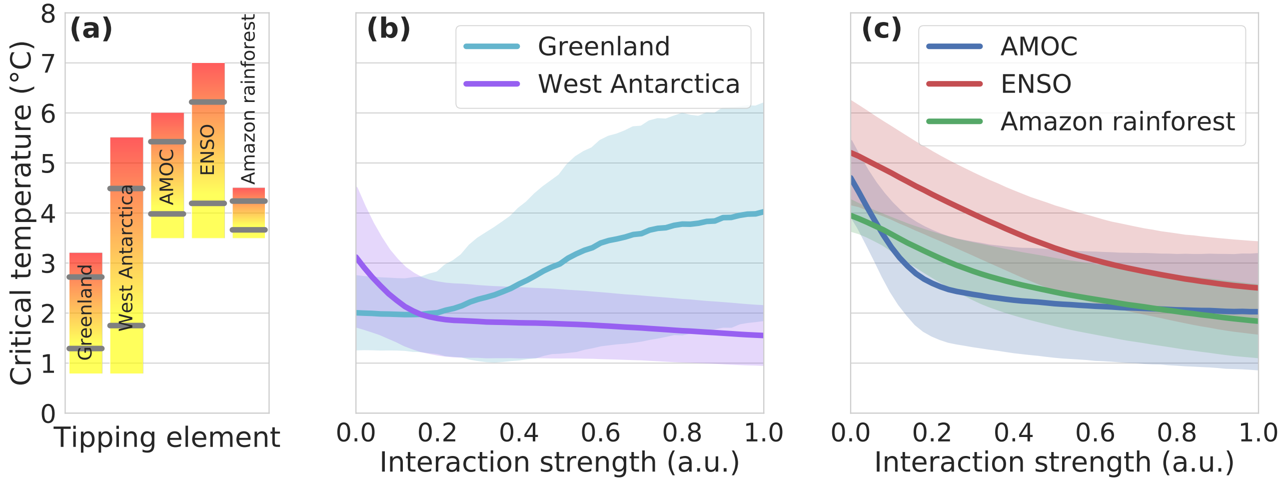

Figure 4. Shift of critical temperature ranges due to interactions. **(a)** Critical global mean temperatures for each of the five investigated tipping elements, without taking interactions into account (as reproduced from literature (Schellnhuber et al., 2016)). The grey bars indicate the standard deviation 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), El-Niño Southern Oscillation (ENSO) 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.

3.2 Risk of tipping cascades

Tipping cascades occur when two or more tipping elements transgress their critical thresholds for a given temperature level (see Sect. 2.3: *time series and evaluation of tipping cascades*). We evaluate the associated risk as the number of ensemble representations in which such tipping cascades are detected. For global warming up to 2.0 °C, tipping occurs in 63% of all simulations (Fig. 6(a)). This comprises the tipping of individual elements (23%) as well as cascades including 2 elements (15%), 3 elements (13%), 4 elements (10%) and all 5 elements (3%; see Fig. 6(b)).

Since the coupling between the tipping elements is highly uncertain, we introduce an upper limit of the maximum interaction strength and vary it from 0.0 to 1.0 (see Table 3). The highest value of 1.0 implies that the interaction between the elements is as important as the nonlinear threshold behaviour of an individual element. For lower values, the interaction plays a less dominant role. We find that the occurrence of tipping events does not depend significantly on the maximum interaction strength - however, the cascade size decreases for lower values.

Tipping cascades are first induced at warming levels around 1 °C above pre-industrial, where the lower critical temperature threshold of the Greenland Ice Sheet is exceeded. The bulk of tipping cascades, however, is found between 1 and 3 °C GMT increase. This is true for all cascade sizes (see Figs. 6(c, d) and Figs. S2(a, b)).

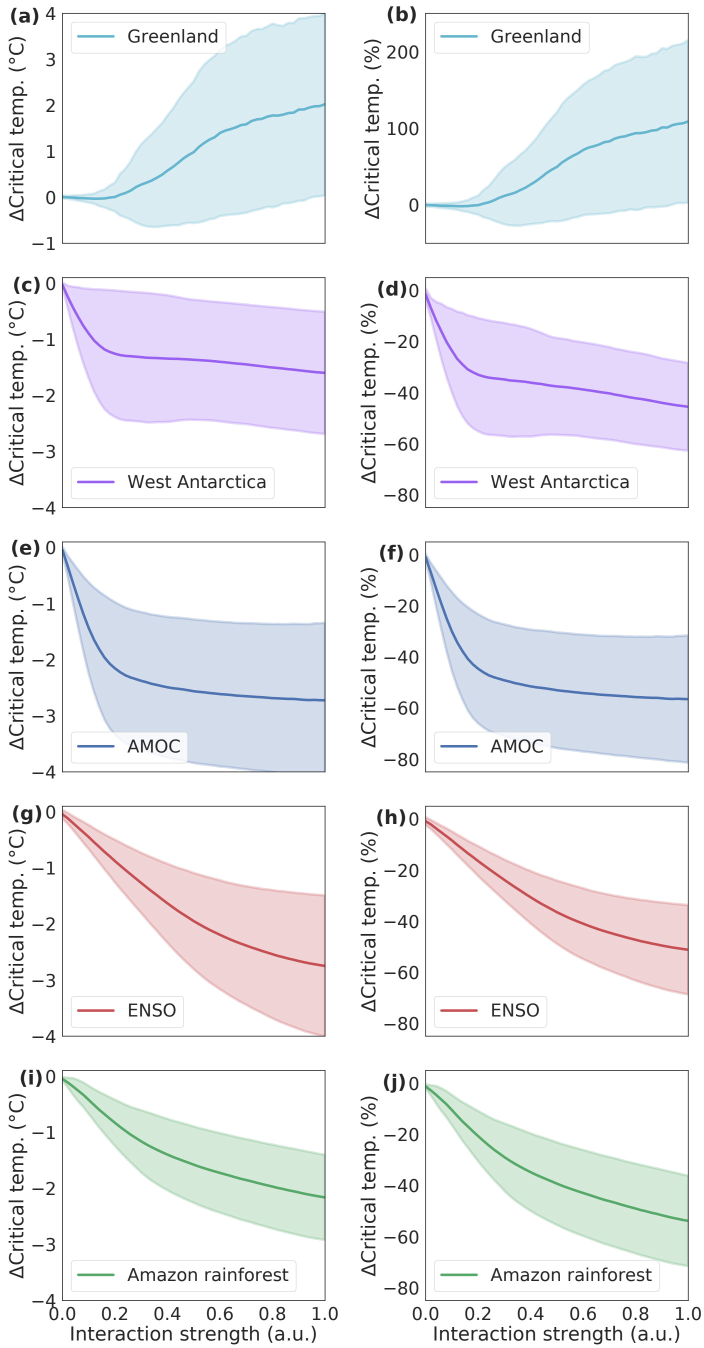

Figure 5. Difference in critical temperatures with respect to the interaction strength. Difference of critical temperatures in °C (left panels) and % (right panels) compared to the respective initially drawn critical temperature for the five investigated tipping elements: **(a, b)** Greenland Ice Sheet, **(c, d)** West Antarctic Ice Sheet, **(e, f)** AMOC, **(g, h)** ENSO and **(i, j)** Amazon rainforest. The standard deviation from the ensemble members is shown as respective colour shading.

Maximum interaction strength d	No tipping (%)	Tipping (%)	Cascade sizes (%) 1	2	3	4	5
1.0	37	63	23	15	13	10	3
0.75	39	61	27	14	12	7	1
0.50	40	60	33	13	11	4	0
0.25	40	60	45	12	4	0	0
0.10	41	59	55	4	0	0	0

Table 3. Fraction of tipping events. For different maximum values of the interaction strength d (first column), the fraction of networks is shown that have a tipping event or cascade (third column) within the Paris limit until the global mean temperature increase reaches 2.0 °C above pre-industrial. This means that 63% of all networks posses a tipping event or cascade, while 37% do not (second column) if all interaction strengths until 1.0 are considered (see Figs. 6(a, b)). Overall, the fraction of tipping events rather stays the same and only slightly goes down for lower limits of maximum interaction strengths. However, the distribution of tipping events and cascade sizes changes, i.e., the number of large cascade sizes decrease with lower limits of interaction strengths. This is shown in the last column that is split up between the percentage of cascades of size one, two, three, four and five.

For temperatures above 3 °C GMT increase, cascades occur less frequently since most of the tipping elements already transgress their threshold before this temperature is reached.

This analysis reveals that the five tipping elements can be grouped into two clusters, one comprising Greenland, West Antarctica and the AMOC, the other ENSO and the Amazon rainforest. The latter cluster is shifted towards higher temperature thresholds, where tipping cascades can still be triggered above 3.0 °C (Fig. S1(c)).

The most prevalent tipping pairs, as simulated in our network approach, consist of cascading transitions between the ice sheets and/or the AMOC, summing up to 60% of all tipping pairs (Fig. 6(e)), which supports the hypothesis of a polar ice-ocean and an equatorial ENSO-Amazon cluster.

While ENSO together with the Amazon rainforest makes for 30% of the tipping pairs due to their strong interlinkage via changes in moisture supply that exist in all network representations (compare Fig. 1 and Table 2), its role in tipping triplets is much smaller, with the most frequent combination together with AMOC and the Amazon around 15% (Fig. 6(f)).

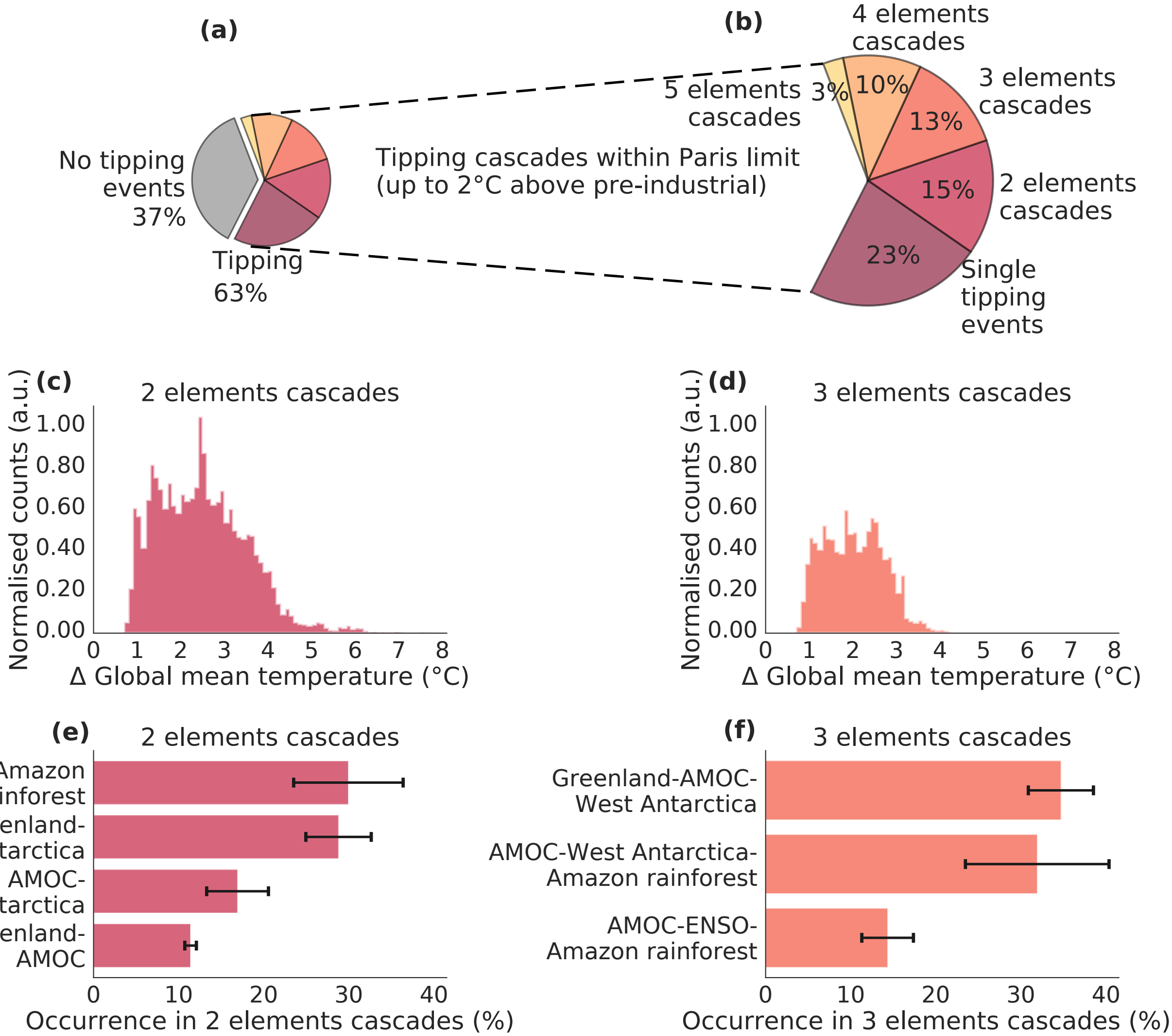

Figure 6. Tipping cascades. **(a, b)** For global warming up to 2.0 °C above pre-industrial, the colour shading illustrates the fraction of model representations in the Monte-Carlo ensemble without tipping events (grey), with a singular tipping event (purple) and with cascades including two (red), three (dark orange), four (orange) and five (yellow) elements. **(c, d)** Occurrence of tipping cascades of size two and three 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, four and five (Figs. S2(a, b)) are set to the same scale to secure comparability. **(e)**, Dominant cascades of size two for temperature increases from $0-8$ °C above pre-industrial. **(f)**, Dominant cascades of size three for temperature increases from $0-8$ °C above pre-industrial. Other cascades are not shown, since their relative occurrence is comparably much smaller. The standard deviation represents the difference between the network settings (see Sect. 2.2: *model initialisation and uncertainty*). It is larger for network representations where unclear links are involved, e.g., for the ENSO-Amazon rainforest tipping pair (compare Fig. 1 and Table 2).

3.3 Different roles of tipping elements

For each of the five tipping elements, we systematically assess their role within the climate network, generally distinguishing between initiators (triggering a cascade), followers (last element in a tipping chain) and mediators (elements in-between).

We find that in up to 40% of cases, the Greenland Ice Sheet appears to trigger tipping cascades. At the same time, it is among the elements which occur least frequently in cascades (around 16% of all cases, see Fig. 1). Thus, we call Greenland a *dominant initiator* of cascades. Following this argument for Greenland, the West Antarctic Ice Sheet is both an *initiator and mediator* of cascades, since it occurs more often in cascades (24%) compared to other tipping elements and, likewise, often acts as the initiator (28%). Although the frequency of occurrence and initiation of cascades is very similar for the AMOC and Amazon rainforest, their role can be clearly distinguished via the network structure. While the AMOC is a *dominant mediator* of cascades, the Amazon rainforest mainly is a *follower*. The Amazon rainforest follows critical transitions of other tipping elements out of two reasons: First, its critical temperature is small (3.5−4.5 °C) which makes it vulnerable to be drawn over its critical threshold by other elements.

Second, as argued above, it is strongly influenced by ENSO through the changes in moisture supply (Fig. 1). Keeping this in mind, the role of ENSO can be described as in-between mediator and initiator. Apart from the Amazon rainforest, other elements are far less influenced by ENSO. This can be observed when looking at the most frequent tipping cascade of size two and at temperatures above 3 °C (Fig. 6(e)), which almost exclusively consist of cascades between ENSO and the Amazon rainforest, which in turn are almost only triggered by ENSO at this temperature range (Fig. S1(c, d)).
The ice sheets are initiators of tipping cascades because their critical threshold ranges are partly lower than for the other tipping elements (see Fig. 4a). Many cascades are then passed on to other tipping elements, especially the AMOC. Thus, the role of the AMOC as the main transmitter of cascades can be understood from a topological point of view since the AMOC is the network element with most connections. As such, the AMOC connects the two poles and can be influenced by both, the Greenland Ice Sheet and the (West) Antarctic Ice Sheet as is also suggested by literature (Wood et al., 2019; Ivanovic et al., 2018; Hu et al., 2013; Swingedouw et al., 2009; Rahmstorf et al., 2005).

3.4 Structural robustness analysis excluding ENSO

As mentioned in the beginning, we performed a structural robustness analysis without taking into account ENSO as a tipping element (see supplement). We find that the roles of the tipping elements remain qualitatively the same: the ice sheets remain strong initiators, the Greenland Ice Sheet dominates as an initiator with 65% compared to 23% of the West Antarctic Ice Sheet. The AMOC initiates 12% of all cascades. Among AMOC and the West Antarctic Ice Sheet, the West Antarctic Ice Sheet initiates more cascades, but both elements transmit cascades to a similar extent (see Fig. S3). We find that the interactions still destabilise the overall network of tipping elements apart from the Greenland Ice Sheet as in the simulations including ENSO (Figs. S4 and S5). The change in the critical temperature range for the Amazon rainforest is smaller and reduces less than in our previous experiments, where the influence of ENSO strongly impacted the state of the Amazon rainforest. The reason is that there is now only one interaction link from the AMOC to the Amazon rainforest, but no further connection. Results regarding the risk of tipping cascades remain robust keeping in mind that tipping cascades that include ENSO are not possible anymore (see Fig. S6). Overall the results remain robust excluding ENSO, suggesting a certain degree of structural stability of our analysis.

4 Conclusion and Discussion

It has been shown in previous studies that all of the five integral components of the Earth's climate system considered here, are at risk of transgressing into undesired states when critical thresholds are crossed (Schellnhuber et al., 2016; Lenton et al., 2008) and some of them have already been proposed as examples where a starting transition might be observable (Lenton et al., 2019). This may affect the stability of the current climate even in intermediate global warming scenarios consistent with the Paris Agreement (Steffen et al., 2018).

Here, we show that this risk increases significantly when considering interactions between these climate tipping elements. Altogether, with the exception of the Greenland Ice Sheet, interactions effectively push the critical threshold temperatures to lower warming levels, thus reducing the overall stability of the climate system. The domino-like interactions also foster cascading, nonlinear responses. Under these circumstances, our model indicates that the climate system generally decomposes into a polar and an equatorial tipping cluster. Cascades are predominantly initiated by the polar ice sheets and mediated by the AMOC. This also implies that the negative feedback loop between Greenland and the AMOC might not be able to stabilise the climate system, a possibility that was raised in earlier work using a binary model approach (Gaucherel & Moron, 2017).

While our conceptual model evidently does not resemble the full complexity of the Earth system and is not intended to simulate the multitude of biogeophysical processes or make predictions of any kind, it allows us to systematically assess the qualitative role of the different interactions of some of the most critical sub-regions of the climate system. The large-scale Monte Carlo approach further enables us to systematically take into account and propagate the uncertainties associated with the interaction strengths, interaction directions and the individual temperature thresholds. This comprehensive assessment indicates structurally robust results that allow qualitative conclusions, despite all these uncertainties.

This work could form the basis for a more detailed investigation using more process-detailed Earth system models which can represent the full dynamics of each tipping element, but where computational constraints yet prohibit such a detailed analysis as presented here. Some possible examples of relevant processes that could be investigated with more complex models are: the changing precipitation patterns over Amazonia due to a tipped AMOC, i.e., whether rainfall patterns will increase or decrease and whether this would be sufficient to induce a tipping cascade in (parts of) the Amazon rainforest. This would shed light on the interaction pair AMOC-Amazon rainforest. 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 similar to experiments that have been performed for the Greenland Ice Sheet (Rahmstorf et al., 2005; Hawkins et al., 2011; Wood et al., 2019). Here, some studies suggest that freshwater input into the Southern Ocean at a modest rate would not impact the AMOC as much as from the northern hemisphere (Ivanovic et al., 2018; Hu et al., 2013; Swingedouw et al., 2009), while higher melt rates could have more severe impacts on the AMOC (Swingedouw et al., 2009). With a carefully calibrated ice-ocean model, potentially including dynamic ice sheets, tipping cascades that include the ice and ocean tipping elements could be examined better. Also in particular, the time-scales for potential tipping dynamics need to be rigorously explored in contrast to the conceptual approach used here, considering that these might only manifest over multiple centuries or even millennia, as for instance for the continental ice sheets (Winkelmann et al., 2015; Robinson et al., 2012; Lenton et al., 2008). Furthermore, it might be worthwhile to perform an updated expert elicitation, where other interactions, tipping elements or a better understanding of the interaction strength would help to narrow down on the vast space of possible scenarios that have been investigated here.

Code and data availability. The data that support the findings of this study are available from the corresponding author upon reasonable request. The code and the python software package "pycascades" that support the findings of this study are available from the corresponding author.

Author contributions. R.W., J.F.D. and N.W. designed the study. N.W. conducted the model simulation runs and prepared the figures. All authors discussed the results and wrote the manuscript.

Competing interests. The authors declare no competing interests.

Acknowledgements. We are thankful to Anders Levermann, Marc Wiedermann and Jobst Heitzig for fruitful discussions. We are also grateful for further discussions with Julius Garbe as well as to Jonathan Krönke for support with the software package "pycascades". This work has been carried out within the framework of the IRTG 1740/TRP 2015/50122-0 funded by DFG and FAPESP. N.W., J.K. and R.W. acknowledge their support. N.W. is grateful for a scholarship from the Studienstiftung des Deutschen Volkes. J.F.D. is grateful for financial support by the Stordalen Foundation via the Planetary Boundary Research Network (PB.net), the Earth League's EarthDoc program, and the European Research Council Advanced Grant project ERA (Earth Resilience in the Anthropocene). R.W. acknowledges support by the European Union's Horizon 2020 research and innovation programme under grant agreement no. 820575 (TiPACCs). We are thankful for support by the Leibniz Association project DominoES. The authors gratefully acknowledge the European Regional Development Fund (ERDF), the German Federal Ministry of Education and Research and the Land Brandenburg for supporting this project by providing resources on the high performance computer system at the Potsdam Institute for Climate Impact Research.

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