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Tipping Points in the Earth System in the context of the NGFS physical risk assessment

A short note

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Authors list

Carl-Friedrich Schleussner[1], Annika Hoegner[1], Tessa Moeller[1], Anne Zimmer[2], Kai Kornhuber[1].

1 International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria.
2 Climate Analytics, Berlin, Germany.

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Introduction

Climate tipping points represent critical thresholds of elements of the Earth System that, once crossed, can lead to irreversible and potentially catastrophic environmental changes with far reaching consequences for societies and economies globally. Tipping point impacts may unfold on timescales of centuries and thus often well beyond the time horizon of the NGFS long-term scenarios[i]*. The scenarios do not explicitly model tipping point impacts due to their long timescales and high uncertainty. Yet, the Earth System Models informing the NGFS physical risk representation represent dynamical responses of atmosphere and ocean circulations (such as the Atlantic Overturning or Arctic Sea Ice loss). This short note provides an overview of the state of scientific knowledge on tipping points and suggests avenues for future work to enhance the representation of tipping point risks in NGFS Scenarios.*

What is a tipping point?

In climate science, tipping points are commonly understood as *critical thresholds beyond which a system reorganizes, often abruptly and/or irreversibly*[ii, 1]. This reorganization is driven by self-amplifying feedback dynamics that are triggered when a critical threshold is crossed, and therefore typically unfolds in a nonlinear and potentially irreversible way. A wide range of tipping elements has been identified in the Earth System[2], which include elements in the Earth's cryosphere[iii], the biosphere, as well as in relation to ocean and atmospheric circulation dynamics. Besides tipping points of global importance, i.e. in relation to the Amazon rainforest, polar ice sheets or ocean circulation patterns, a growing number of regional tipping points have been identified[3]. Here, we focus on a selection of the key tipping elements of particular relevance to the global climate system that are summarised in Table 1.

Table 1 **Selected Global Tipping points of the Earth System**

Domain	Tipping element	Critical long-term global warming level above pre-industrial (°C)	Tipping timescale (years)	Key biophysical impacts
Biosphere	Tropical Coral Reefs	1.2 [1.0-1.5]	10 [~]	• Tropical marine biodiversity loss • Coastal protection reduction • Loss of commercial and artisanal fisheries
Biosphere	Amazon Rainforest	3.5 [2.0-6.0]	100 [50-200]	• Biodiversity loss • Changes in global and regional rainfall patterns in Latin America • Loss of a major carbon sink, contributing to additional global warming
Ocean	Atlantic Meridional Overturning Circulation (AMOC)	4.0 [1.4-8.0]	50 [15-300]	• Rapid regional temperature and sea level changes of up to 10 °C cooling in western Europe with trends of exceeding 3 °C/decade • Far reaching global changes in precipitation and weather patterns • Reduced ocean carbon uptake • Related circulation systems like the North Atlantic subpolar gyre may potentially show abrupt changes at lower levels of warming and shorter timescales with far-reaching consequences for regional climates

i An important exception are nature risks including the loss of tropical coral reefs that are already observed and will intensify with ongoing warming. Yet, the NGFS modelling framework is not suitable at this stage to account for nature-related risk.

ii While *social* tipping points are relevant in the context of NGFS scenarios and the financial system, this note focusses on the *climate* tipping points in the Earth System with relevance for physical climate risk assessments.

iii The cryosphere is the part of Earth's surface where water exists in solid form, including glaciers, the Greenland and Antarctic ice sheets, sea ice, and permafrost.

Cryosphere	Greenland Ice Sheet	1.5 [0.8-3.0]	10k [1k-15k]	• Multi-meter sea level rise affecting coastal regions globally • Risk of disruption of global ocean circulation due to large amounts of meltwater being dispersed into the surrounding oceans • Shifts in atmospheric circulation patterns
	West Antarctic Ice Sheet	1.5 [1.0-3.0]	2k [500-13k]	
	East Antarctic Ice Sheet	7.5 [5.0-10.0]	unknown[iv] [10k-unknown]	
	Arctic Winter Sea Ice	6.3 [4.5-8.7]	20 [10-100]	• Amplified regional and global warming • Ecosystem changes • Impacts on ocean circulation
	Boreal Permafrost (Collapse)	4.0 [3.0-6.0]	50 [10-300]	• Additional greenhouse gas emissions potentially amplifying global warming • Rapid landscape changes for terrestrial permafrost • Widespread regional permafrost thaw will occur at lower levels of warming and faster timescales

Note: For the critical long-term temperature and tipping timescales, the best estimate and the min-max range in brackets are provided.

References: Armstrong Mckay *et al.* (2022), The Global Tipping Points Report (2023), Van Westen *et al.* (2024).

As highlighted in Table 1, tipping points are associated with major physical risks that can result in asymmetrical and severe impacts on economic prosperity globally.

Response timescales and uncertainties

There is **strong scientific consensus around the existence of tipping points** of global relevance and the related risks[ii]. However, large uncertainties remain in relation to the precise global warming thresholds past which irreversible tipping dynamics would be triggered and with regards to the timescales over which the consequences would unfold (compare Table 1).

The critical long-term global warming level specifies the level of sustained global mean surface air temperature increase (over decades to millennia) above which tipping may occur. The tipping timescale indicates the transition time from the baseline to the transitioned (tipped) regime for an individual climate tipping element under a sustained forcing[19]. This includes the duration of sustained warming that is required to trigger an irreversible response as well as the time over which the tipping will unfold. Depending on the tipping point at question, there remains **deep uncertainty in relation to the duration of sustained warming above a critical long-term threshold that would be required to trigger a tipping element**.

This leads to important considerations regarding the risks posed by tipping elements:

1. **Tipping points may be triggered if current levels of global warming of around 1.3 °C[4] were sustained for centuries**, for example the West Antarctic ice sheet. In the long run, bringing temperatures down to levels well below 1.5 °C may be required to limit tipping point risks[5]. Yet, it cannot be ruled out that irreversible dynamics in some tipping points may have already been set in motion[2].
2. Tipping point timescales span decades to millennia, implying that temporarily **transgressing a specific global warming level assessed as the long-term (millennial) threshold does not result in the tipping point being instantaneously triggered**. Specifically, an exceedance of the 1.5 °C warming limit does not automatically imply that several climate tipping points are imminent. Bringing temperatures back down below 1.5 °C, i.e. in a climate overshoot scenario, may potentially still avoid an irreversible response.
3. Irreversible dynamics of tipping points may be triggered by crossing critical warming thresholds in the 21st century, but many impacts may only unfold beyond 2100. For example, triggering an irreversible ice sheet disintegration would commit multi-meter sea level rise for centuries to millennia. The temporal delay between reaching critical warming thresholds and the dynamical responses of tipping elements implies considerable **legacy risks of 21st century climate action.**

iv The scientific understanding of the potential response time scales of the East Antarctic Ice Sheet is not yet mature enough to support a best estimate.

The scientific uncertainties in relation to system dynamics remain considerable, which can lead to confusion about the characteristics of the risks involved and adequate policy responses. This can be exemplified for the Atlantic Meridional Overturning Circulation (AMOC). The **weakening of the Overturning Circulation** under ongoing climate change is well established and represented in climate models, yet **large uncertainties remain** with regards to the likelihood of an **irreversible shutdown**. The scientific consensus, as reflected in the latest report by the Intergovernmental Panel on Climate Change (IPCC), states that "There is medium confidence that there will not be an abrupt collapse before 2100"[ii]. Some recent studies have challenged that conclusion[6, 7] suggesting much more immediate risks of AMOC cessation. However, other scholars point out methodological shortcomings in the analysis[8, 9]. This underscores the **potential pitfalls of basing policy responses on individual studies**, and the need for comprehensive scientific assessments such as conducted by the IPCC.

Despite the broad agreement about the importance of tipping points, there is also an emerging **critique of an overemphasis of tipping points** in climate risk assessments[10]. Focusing on tipping points tends to highlight extreme, long-term events that need to be thoroughly considered in climate risk assessments. However, an over-emphasis can result in a diversion of focus from very **immediate, and substantial climate risks** which are scientifically well understood, projected with high confidence, and require urgent attention. Furthermore, uncertainties about tipping points can be exploited to justify climate inaction or extreme responses, amplifying discourse polarization.

Tipping points at risk to materialise in the 21st century

A range of tipping points have been identified across earth system components, that each might carry a specific set of risks. Tipping points in the biosphere, **highlight the interconnection of climate and nature risks** and the potential for irreversible biodiversity and socio-economic losses. A potential **loss of the Amazon rainforest ecosystem,** for instance, would come with far reaching consequences for global biodiversity, the carbon cycle and the global and regional Latin American climate[11] playing out over decades to centuries. Even if an irreversible dynamic was triggered, the loss would not be instantaneous but unfold until well beyond the 21st century. In addition to global warming, ongoing deforestation contributes significantly to undermining the resilience of the Amazon rainforest[12] and increasing Amazon carbon emissions as consequence of forest degradation and deforestation are already observed[13]. Halting Amazon deforestation and forest degradation is critical to minimize the risks of Amazon tipping and would come with substantial economic benefits. The **cost of an Amazon tipping** for the Latin American economies alone is estimated to be in the **order of several hundred billion to several trillion USD[14, 15]**.

Crossing the tipping point for tropical coral reefs due to coral bleaching linked to marine heatwaves is one of the fastest responding tipping points and will on decadal timescales result in irreversible ecosystem shifts, massive biodiversity loss, and the disappearance of critical ecosystem services such as coastal protection, tourism and fishery productivity[16]. The economic damages of coral reef losses are estimated to be in the order of **multiple billions of USD annually**, even without accounting for biodiversity loss[17].

Crossing major ocean and cryosphere tipping points (compare Table 1) can have **far reaching and potentially catastrophic consequences which would unfold over the coming centuries to millennia**. For example, a collapse of the Atlantic Meridional Overturning Circulation would have a profound cooling effect on Europe, in particular during winter months, and increase seasonality[18]. Similarly, irreversible, multi-meter sea level rise because of ice sheet tipping would put the global coastal infrastructure and hundreds of millions of people at risk of displacement. The high impact nature of tipping points requires careful consideration in climate risk assessments. Furthermore, interactions between tipping points can lead to **cascading and amplified risks**[19], but also potentially stabilizing interactions[20], and lead to additional global warming[2].

Risks of crossing tipping points under a current policy scenario

Continuation of current climate policies is estimated to lead to a warming between 2.5 °C and 3 °C by the end of the century. Using a probabilistic model representing four tipping elements, the Amazon Rainforest, the Atlantic Overturning and the Greenland and West Antarctic ice sheet and their interactions, Moeller *et al.* (2024)[21], estimate **an almost 1-in-2 probability for triggering at least one of those tipping points by 2300 if current policies are followed** in this century. This is the case even if subsequently global mean temperatures would be reversed back to 1.5 °C until 2300. An illustrative application of this methodology for tipping probabilities under NGFS scenarios is provided in Annex I.

The probability of **triggering tipping points by 2300 increases with every additional 0.1 °C of overshoot** above 1.5 °C and strongly accelerates for peak warming above 2.0 °C. Assessing the risks of triggering tipping points requires consideration of the potential for high risk warming outcomes under different emission scenarios. **Achieving and maintaining at least net zero greenhouse gas emissions in the 21st century and beyond,** and thereby (partial) reversal of global warming, **is required to minimize tipping risk**.

Options for representing tipping point dynamics in NGFS climate scenarios

The Earth System Models informing the NGFS physical risk representation also **include dynamical responses of atmosphere and ocean circulations** (such as the Atlantic Overturning or Arctic Winter Sea Ice loss). Others, such as the nature related risks of coral reef loss and Amazon dieback, or risks related to sea level rise, are currently not represented in the modelling framework. The exploration of specific tipping points would therefore need to be mindful of **potential double counting** beyond the already incorporated dynamics in the physical risk assessment.

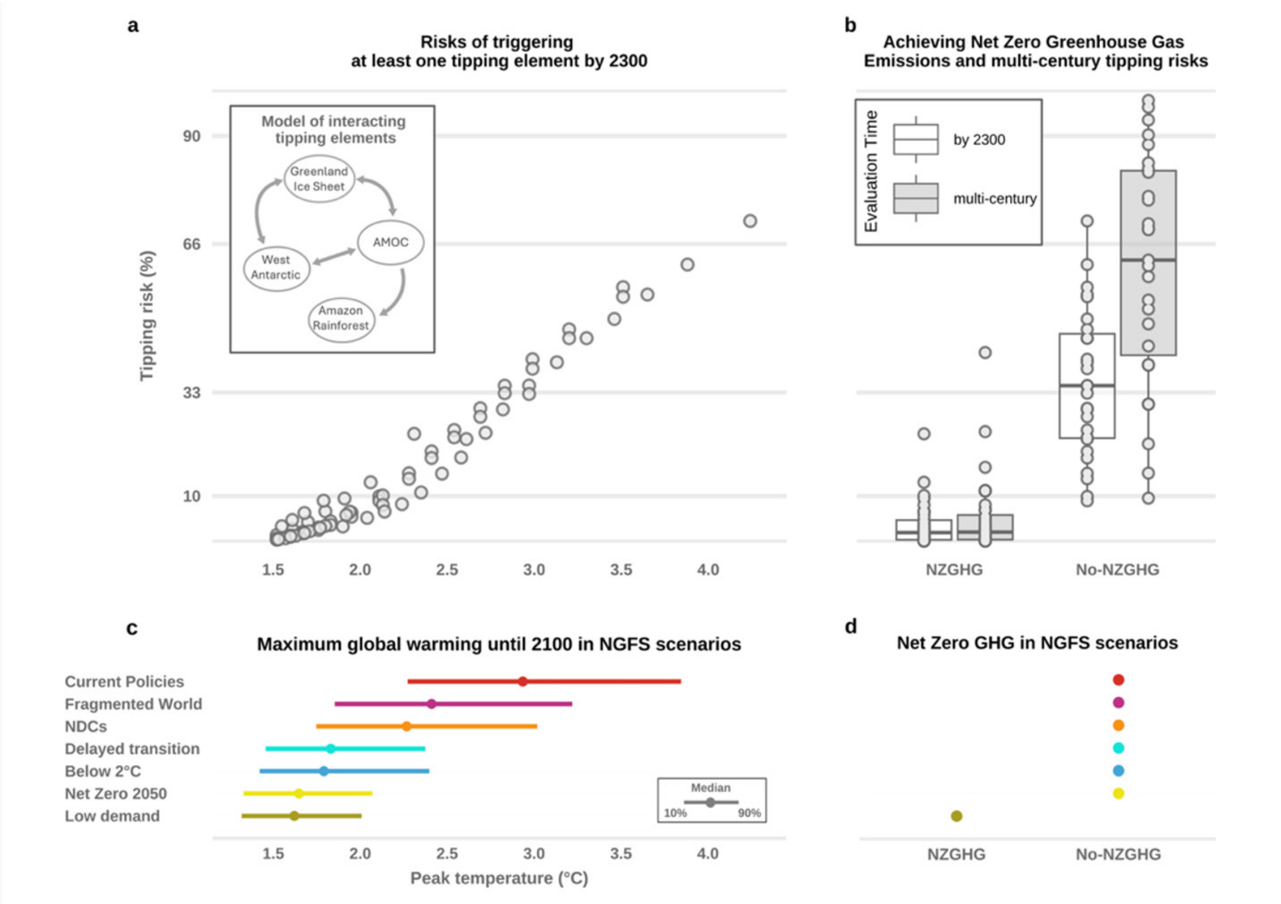
The NGFS focusses on transition and physical risks in the near-term, mid-century and for selected indicators up to 2100. Consideration of the **timescales of tipping dynamics** which can be considerably longer is therefore of central relevance when considering their importance for the NGFS scenarios (compare Table 1). Risks posed by Earth System tipping points are profound and are expected to emerge over decades to centuries. But their direct impacts on shorter timescales, i.e. until mid-century, are subject to high uncertainty. Climate-related economic tail risks up to mid-century and beyond will likely be dominated by high warming and regional high climate risk outcomes, including extreme weather and compound event risks from non-linear climate responses on the regional scale. An important exception are nature risks including the **loss of tropical coral reefs** that are already observed and will intensify with ongoing warming. Representing the consequences for the marine economy of the imminent crossing of a tipping point for tropical coral reefs would be of particular importance for economies around the equator. Similarly, the consequences of severe degradation and potential tipping of the **Amazon rainforest** in the 21st century due to combined climate- and deforestation-related stressors could be explored. Doing so would help capture the systemic nature, irreversibility, and potentially cascading economic and financial effects of tipping dynamics, which are not currently represented in existing NGFS risk quantifications. Including climate-related perils such as **sea level rise** in the NGFS physical risk modelling would be a first step towards a representation of cryosphere related tipping points.

Today's actions will have far reaching, irreversible consequences for future climate risks for centuries to come and a comprehensive consideration of tipping points would need to extend beyond the end-of-century time horizon of the NGFS scenarios**. Although most of the economic impacts deriving from crossing tipping points are likely to materialise beyond 2100, the consequences of crossing tipping points may unfold already sooner, bringing their economic consequences closer to the NGFS scenarios timeline.** Avenues to enhance the consideration of tipping point risks within the NGFS risk assessment could include the use of a **storyline-based approach** and could provide for an innovative avenue to incorporate uncertainties and provide actionable risk estimates from tipping points, accelerated sea-level rise, glacier and biodiversity loss. The wide uncertainty regarding the triggering and consequences of tipping points calls for a precautionary approach. Only stringent emission reductions in the near-term will be effective in limiting climate risks.

Annex 1 – Probabilistic modelling of cascading tipping point risks

The following figure is adapted from work presented in a study by Moeller *et al.* (2024)[21]. This study explores the risk of triggering tipping points under a subset of policy-relevant future emission pathways and the uncertainty of the climate system in response to increasing emissions, using PyCascades, a stylized Earth System model of four interacting tipping elements, including the Greenland Ice Sheet, the West Antarctic Ice Sheet, the Atlantic Meridional Overturning Circulation and the Amazon Rainforest[19]. We note that this model only includes a subset of tipping points, and the inclusion of other tipping elements as discussed above may further increase the risks. The emission pathways span from pathways following current policies and pledges to pathways consistent with the climate objectives of the Paris Agreement by 2100. All considered pathways reverse global warming to 1.5 °C or lower by 2300. The probabilistic range of tipping risks in 2300 and in long-term (after 50.000 years, well beyond the tipping timescales of all elements) are studied by considering the full range of potential global mean temperature outcomes for each pathway and propagating uncertainties in tipping timescales, critical long-term tipping temperature and the interaction of the four tipping elements. The figure presented below shows results based on the scenario set from Moeller *et al.* (2024), including the associated tipping risks by peak temperature and the achievement of net-zero greenhouse gas emissions. The NGFS scenario ranges are shown for comparison, focusing on their respective maximum warming levels in the 21st century and the achievement of net-zero greenhouse gas emissions. The scenarios are categorised according to their outcomes until 2100. On the higher end, further warming beyond 2100 may additionally increase tipping risks by 2300. On the lower end, the Net Zero 2050 and Below 2 °C and Delayed 2 °C scenarios are close to net zero greenhouse gases by 2100. If they were extended to achieve and maintain at least net zero greenhouse gases in the 22nd century, and thereby global temperature reversal, long-term tipping risks in those scenarios would be substantially lower.

Figure 1 **Illustrative risks of triggering tipping points in a model of interaction tipping elements as a function of (a) peak temperature and (b) long-term emission outcomes based on Moeller *et al.* (2024)**



Notes: For comparison, the maximum global warming until 2100 in NGFS and the long-term emission outcome until 2100 is shown. Note tha t this comparison is incomplete as NGFS scenarios only cover the timeframe up to 2100 and assumptions beyond 2100 crucially shape the outcomes.

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