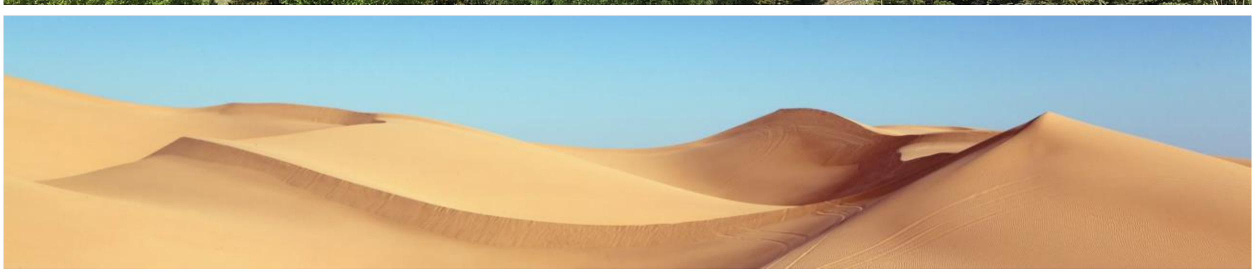
TIPPING POINTS IN THE EARTH SYSTEM

WP7 Report: State of the Art on Tipping Points: D7.2 (D32)



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Summary of Report: State of the art on Tipping Points

This report represents Deliverable 7.2 which, owing to the Covid situation, could not be based on an expert public meeting but has instead been produced on the basis of past and present science results of the partners of TiPES, as well as the available scientific literature.

The report begins with reviewing the development of climate science from first indications of non-linearities and multiple equilibrium states that were found in simplified models of the ocean's thermohaline circulation. Knowledge was boosted by new analyses of ice cores and lake sediments which corroborated that multiple climate states were assumed during the last ice age. It was shown that these events were hemispheric to global in extent. This was the foundation of indications that such events could also occur in the future as a response to the anthropogenic perturbation of the climate.

We then present the currently suggested palette of tipping points and elements and present recent analyses that range from the physical systems such as ocean circulation and ice sheets to biological and ecosystem tipping. We find that the level of understanding of the palette is highly heterogeneous, ranging from elements that have occurred in the past and have been simulated in physical models extensively to systems that have not yet experienced the stressors that are expected for the future and hence lack past analogues. Hence, confidence in tipping points and abrupt and irreversible change in general, needs to increase significantly in order to provide robust and actionable information for society and policymakers. The report also addresses the new subject of "tipping cascades", i.e. the sequence of tipping points is triggered by interactions among several unstable systems.

Recent progress in the characterization of approaches to tipping points is briefly discussed. These form the basis for the proposal of early warning systems for, e.g., a collapse of the meridional overturning circulation in the Atlantic Ocean, or mass loss in areas of polar ice sheets. This research crucially depends on the availability of high-resolution observations, both in space and time, and models that permit the comprehensive simulation of approaches to instabilities under slow external forcing.

The report ends with conclusions and an outlook.

Preamble

This report represents Deliverable 7.2 which, according to the project plan was "*A review report […] derived from an expert public meeting, focusing on tipping points that are addressed in TiPES. It will form the basis for the first policy briefs and fact sheets produced by TiPES. The document will be updated during TiPES (M30), (Task 7.2)*." Due to the Covid situation an expert public meeting could not be organized. In spite of this difficult situation, the first policy briefs and fact sheets have been produced on the basis of past and present science results of the Partners of TiPES, as well as the available scientific literature

With the document here we present a review report that should serve the originally intended purpose to serve as a basis for further policy briefs and fact sheets on tipping points. Instead of digesting information from an expert meeting, which still cannot be organized owing to the ongoing Covid situation, we have drawn on the most recent literature for this review. It is also important to recognize the scientific development that lead to the present focus on tipping points in climate science, and therefore we start this review report with a brief history on tipping points.

We regard this document only as a first version of a report which will be updated towards the end of TiPES. In the updated report we plant to present a section on the policy briefs and fact sheets produced by TiPES with "lessons learned" from the use of these outreach products. It will also include a review of the most important findings from the collective research in this project.

A brief history on Tipping Points

The notion "tipping point" came into use in climate science relatively recently [*Lindsay and Zhang*, 2005; *Meehl et al.*, 2007], and was then popularized by [*Lenton et al.*, 2008; *Lenton et al.*, 2019]. Non-linear phenomena in the Earth System, however, have fascinated researchers long before. To understand the consequence of different feedback mechanisms associated with anomalies of surface ocean temperature and salinity, the eminent physical oceanographer Henry Stommel formulated an elegant two-box model of the ocean's thermohaline circulation [*Stommel*, 1961]. He assumed a transport of warm saline water from the extra-tropics to the high latitudes where the water is cooled and freshened by the action of excess precipitation. The transport itself was assumed to depend on the north-south contrast of water density. In addition to a steady state that resembles today's conditions of the North Atlantic Ocean, the model also permitted a very different equilibrium state in which the transport was significantly smaller due to a much reduced density contrast. The origin of the non-linearity giving rise to multiple equilibrium states lies in the fact that surface temperature anomalies get eliminated rapidly due to anomalous heat fluxes while surface salinity anomalies leave precipitation unaffected. This landmark paper was recognized only more than 20 years later in an overview of simplified models of the thermohaline circulation [*Rooth*, 1982; *Welander*, 1986].

On a global scale, multiple equilibria were also found in an energy balance model that included a non-linear ice-albedo feedback [*Budyko*, 1969]. The model showed a moderate modern climate and, upon slightly reducing the solar energy flux, a much colder climate with temperatures below the freezing point. This finding has provided a credible basis for speculations about a snowball earth state in the deep past [*Hoffman et al.*, 1998]. Such multiple equilibria are now investigated to better understand climates on exoplanets. A coupled atmosphere-ocean model of reduced complexity finds as much a six equilibrium states with full, partial and absent planetary ice cover, depending on stellar irradiation and obliquity of the exoplanet's axis [*Kilic et al.*, 2017; *Kilic et al.*, 2018].

The relevance of multiple equilibria to understand Earth's climate and climate change was demonstrated by detailed analyses of various paleoclimate records, in particular the Greenland ice cores [*Dansgaard et al.*, 1984] and a sediment core of a pre-alpine lake in Switzerland [*Eicher and Siegenthaler*, 1976]. *Oeschger et al.* [1984] realized that the abrupt changes in the temperature proxy measured in the Greenland ice cores were perfectly reproduced in the carbonate isotope record in Gerzensee near Bern. This demonstrated that the millennial cooling, known to palynologists as the Younger Dryas at 12 ka BP, was indeed a climate signal of potentially hemispheric extent, if not global. They surmised that the ocean circulation in the Atlantic, particularly the movement of the polar front, was responsible for this abrupt cooling, as suggested earlier by *Ruddiman and McIntyre* [1981]. By then evidence from the paleoclimate archives has accumulated that the atmosphere-ocean system may have more than one stable mode of operation [*Broecker et al.*, 1985; *Broecker and Denton*, 1989], a paper that inspired paleoclimate scientists to search for abrupt change in other archives, and modelers to test whether physically based climate models would exhibit this new feature of climate dynamics. A key question was whether these events were hemispheric or global in extent. Robust paleoclimate evidence from high-resolution ice cores [*EPICA Community Members*, 2006] has confirmed the original hypothesis of interhemispheric connections, stated by *Crowley* [1992], coined by *Broecker* [1998] as the bipolar seesaw, and elaborated in a simple thermodynamic model [*Stocker and Johnsen*, 2003].

The first study to demonstrate that the overturning circulation could indeed switch on and off used a then state-of-the-art ocean general circulation model in a simplified rectangular basin [*Bryan*, 1986]. The change of state was associated with strong changes in meridional ocean heat transport. This confirmed that such ocean switches could trigger rapid warmings and coolings of the type observed in the Greenland ice cores. *Manabe and Stouffer* [1988] used a more complex coupled atmosphere-ocean climate model and reported two stable equilibria. One state had an active meridional overturning circulation in the North Atlantic resulting in relatively warm waters there, while the other featured a collapsed state in the North Atlantic Ocean with a much cooler climate in that region. Further research showed that the presence of multiple equilibria depended sensitively on the diffusion parameterization in the ocean model, on the basin configuration, and on the model formulation in general [*Marotzke and Willebrand*, 1991; *Schiller et al.*, 1997]. Multiple equilibria could also be a property of regional ocean circulation systems such as the subpolar gyre [*Born et al.*, 2013; *Born and Stocker*, 2014].

The basis for multiple equilibria was the fundamental physical property of hysteresis that was now found also in models of the climate system [*Stocker and Wright*, 1991]. This offered new perspectives to understand abrupt climate change [*Stocker*, 2000]. Hysteresis is a characteristic of non-linear physical systems, and best known in magnetic materials. State changes are induced by an external forcing, and when the forcing is removed, a new stable state remains. Resetting the system to the original state requires an opposite forcing. The transition between states is rapid, similar to a phase state change. Hysteresis of a ferromagnetic material was employed to store information until it has been superseded by storage using electric charge in semi-conductor layers.

Clearly, the surprises found in many paleoclimatic records had a profound impact on the discussion about possible consequences of the ongoing anthropogenic disturbance of the climate caused by the emissions of greenhouse gases. The question was whether such perturbations could trigger abrupt changes in the future [*Broecker*, 1987], and hence constitute a potentially dangerous anthropogenic interference with the climate system. Indeed, the physical understanding of the meridional overturning circulation extracted from climate model simulations pointed at the key role of the North Atlantic buoyancy balance, i.e. the density of surface water in this critical region. Three processes caused by the greenhouse gas emissions operate in concert to gradually reduce the density and move the ocean overturning circulation closer to a threshold. The global ocean heat uptake that is now robustly observed [*Johnson and Lumpkin*, 2021], reduces the ocean water density from the surface downward. The warming in the climate system accelerates the water cycle: in the extra-tropics evaporation becomes stronger and salinity increases. The additional water in the atmosphere is transported northward by the atmospheric general circulation and increases precipitation in the higher latitudes. This reduces salinity there. The large-scale changes of the salinity distribution in the ocean are a fingerprint of the accelerated water cycle [*Durack et al.*, 2012; *Silvy et al.*, 2020]. In the high latitudes ocean surface density decreases which tends to slow down deep water formation that feeds the overturning circulation. The third effect is associated with the accelerated melting of glaciers worldwide [*Zemp et al.*, 2019] and ice from Greenland [*Bevis et al.*, 2019]. These three effects act in concert to reduce the water density of the surface ocean.

These processes therefore strongly suggest that a reduction of the meridional overturning circulation is a possible response to the increase in greenhouse gas concentrations. Early climate model simulations confirmed this assertion [*Manabe and Stouffer*, 1993], with the possibility of bifurcation, depending on the rate of warming [*Stocker and Schmittner*, 1997]. Since then many modelling studies have been carried out and the fate of the meridional overturning circulation has also been investigated in successive coupled model intercomparisons [*Weijer et al.*, 2020]. A comprehensive review is provided by *Weijer et al.* [2019].

The new knowledge of a reduction in overturning circulation, and abrupt climate change in general, has already come to the attention of policymakers in 2001, when the IPCC's Third Assessment Report was published in 2001 [*IPCC*, 2001]. The Working Group I contribution considered "surprises in the climate system" and affirmed that "with a rapidly changing external forcing, the non-linear climate system may experience as yet unenvisionable, unexpected, rapid change.". The term "tipping point" first appeared in the Fourth IPCC assessment in 2007 when the possibility of "Future Abrupt Climate Change, 'Climate Surprises', and Irreversible Changes" was assessed in a separate box in the projection chapter [*Meehl et al.*, 2007]. In the Fifth Assessment Report in 2013, tipping points were addressed in several chapters and it was noted that studies report them in most components of the climate system, although the topic is generally contested and results are highly uncertain [*IPCC*, 2013]. The concept of tipping points has also taken an important place in the assessment by IPCC Working Group II in the context of regional impact and ecosystem changes. In the current sixth assessment cycle of the IPCC tipping points are addressed in various places in the two special reports SR1.5 [*IPCC*, 2018] and SROCC [*IPCC*, 2019], and in the comprehensive report of Working Group I [*IPCC*, 2021].

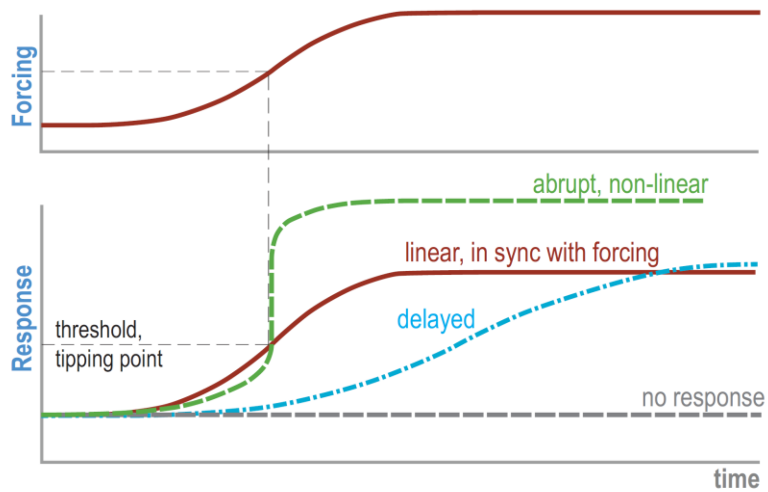

Figure 1: Qualitatively different responses to a climate forcing, both natural and anthropogenic, e.g., orbital changes in solar irradiation, or an increase in greenhouse gas concentrations. Note that this schematic figure does not provide information on the system response when the forcing returns to the original level. [Figure from IPCC [2019]].

In order to clarify the notion of large-scale tipping elements [*Lenton et al.*, 2008] and tipping points in the climate system, the qualitatively different responses to a specific forcing of a non-linear system, in our case the Earth System, are illustrated in Figure 1. A linear response evolves on the same time scale as the forcing. No "surprises" are observed in this case. If the system involves slow responding components such as ice sheets or the deep ocean, the response may be delayed and continue long after the forcing has reached a new steady level. Figure 1 does not inform about the possible evolution of the system when the perturbation has ceased. Here two possibilities must be distinguished. First, the equilibrium response may reach the original level in which case the system has only one stable equilibrium. Alternatively, the equilibrium response could remain at a different level from the original one, and the system would then reside in a new equilibrium state. The latter case would represent an irreversible change that has been caused by the transient forcing, a behavior reminiscent of hysteresis.

The two fundamentally different types of behavior of a non-linear system can be captured by considering different forcings on a hysteresis curve for the example of North Atlantic sea surface temperature and freshwater forcing (Fig. 2). Depending on the initial state and/or the magnitude of the perturbation a linear response (Fig. 2a), an abrupt reversible response involving two tipping points (Fig. 2b), or an abrupt irreversible response with one tipping point can be realized (Fig. 2c) [*Stocker and Marchal*, 2000].

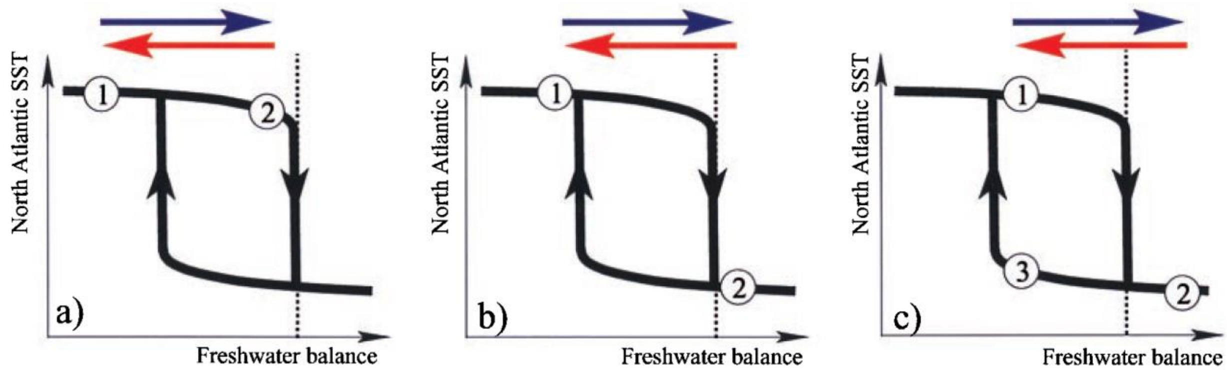

Figure 2: Hysteresis behaviour associated with the meridional overturning circulation in the Atlantic Ocean and its response to changes in the freshwater balance. Steady states are indicated by numbers on the warm (upper) and cold (lower) branch of the hysteresis. [Figure from Stocker and Marchal [2000]].

Besides potential instabilities in ocean circulation and their large-scale consequences for the climate system, the polar ice sheets and their dynamics also moved into focus decades ago. *Mercer* [1978] pointed out that the warming caused by a doubling of CO_2 in the coming 50 years could initiate rapid deglaciation of West Antarctica and estimated an additional sea level rise of 5 meters. The dynamics of the West Antarctic Ice Sheet and its response to changes in insolation was documented in lithological analyses of a sediment core underneath the Ross ice [*Naish et al.*, 2009]. These responses were found to be periodic collapses at times the global mean temperature was about 3°C warmer. Also the East Antarctic ice sheet, storing more the 50 meters of equivalent sea level, was found to have changed substantially over the past 50 million years [*Gulick et al.*, 2017]. Based on these paleoclimatic records, the early concerns about instabilities in Antarctic ice mass have been reinforced [*Pattyn and Morlighem*, 2020]. Some simulations, although still discussed controversially, exhibit very large changes when the most pessimistic scenarios of warming are assumed [*DeConto and Pollard*, 2016a], with long-term effects that profoundly impact humans and ecosystems for millennia [*Clark et al.*, 2016].

As we look ahead, we must recognize that abrupt climate change and future tipping points are an additional consequence of anthropogenic climate change. Their impact must be factored in when estimating adaptation options. Tipping could regionally amplify ongoing heating, drying, and sea level rise, or substantially modify the statistics of extreme events and weather patterns. If realized, they unequivocally constitute one aspect of "dangerous anthropogenic interference with the climate system", as referred to in Article 2 of the UN Framework Convention on Climate Change [*UNFCCC*, 1992].

The palette of tipping points

For many decades scientists have essentially limited their attention to two aspects of abrupt climate change: i) changes in meridional overturning circulation of the ocean [*Broecker*, 1997; *Stocker*, 2000; *Weijer et al.*, 2019], and ii) disintegration of the West Antarctic ice sheet [*Mercer*, 1978; *Pattyn and Morlighem*, 2020]. *Lenton et al.* [2008] widened the perspective by suggesting potential tipping points in many parts and regions of the climate system (Figure 3). This stimulated the investigation of non-linear aspects of, e.g., the Artic sea ice, instabilities of the Greenland and Antarctic ice sheets, the fate of coupled atmosphere-ocean phenomena such as ENSO and monsoon, or terrestrial systems such as the Amazon rainforest or boreal permafrost [*Good et al.*, 2018]. While Figure 3 illustrates many potential tipping points around the globe, knowledge is still evolving, and for many of these systems we do not know whether there exist at all, or if so where there are, critical thresholds. In short, the scientific understanding of tipping points is still limited and incomplete.

The amount of knowledge shrinks in lockstep with the spatial scales, and with the degree of nonlinearity of the processes. For example, changes in the statistics of extreme climate events, such as heavy precipitation or drought, are notoriously difficult to simulate with the present generation of climate models. Similarly, a possible shift or instability of monsoon systems, the life support system of more than a billion people, are insufficiently represented in the current generation of climate models. Yet this information is crucial for society and policymakers in light of the urgency of mitigation and the shrinking options for adaptation.

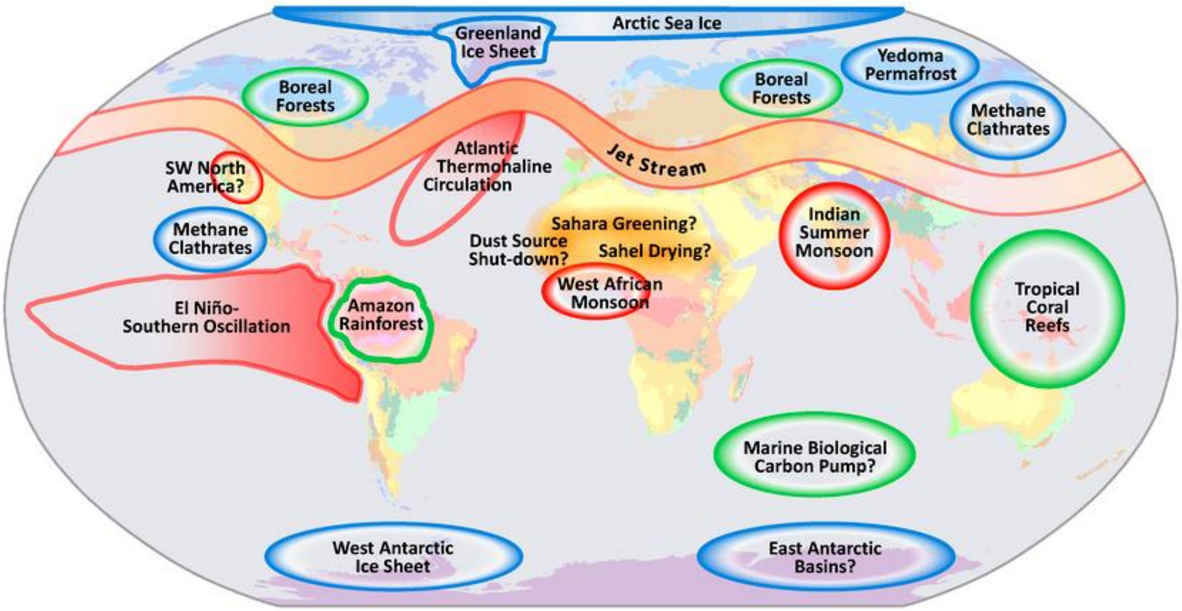

Figure 3: Global distribution of systems that may exhibit tipping points. They are grouped into three categories: atmosphere-ocean circulations (red), cryosphere (blue) and biosphere (green). [Figure from PIK Potsdam, based on Lenton et al. [2008]].

The illustrative map of Figure 3 can be substantiated by evaluating natural changes in the past, in particular during the last 30,000 years when the arguably largest perturbation of the climate system before the anthropogenic interference took place. The transition from the last ice age to the Holocene evolved against a background of slow changes in insolation, ice sheet extent and sea level. Yet the Earth system responded in a very dynamic manner if one investigates the regional and biogeochemical information at high temporal resolution as available from many paleoclimatic archives. *Brovkin et al.* [2021] review these rich changes and conclude that the slow forcing pushed these systems across various thresholds in the past.

Equally important is the critical interrogation of current coupled climate models regarding their ability to exhibit abrupt changes that point to the existence of tipping elements. *Drijfhout et al.* [2015] have analysed the previous generation of climate models (CMIP5) and found many indications of abrupt behaviour. Their focus was on the regional scale as this determines the broader impact of such events. Apart from hints at the classical process of a reduction of the Atlantic meridional overturning circulation present in all models, they find specific examples of sea ice bimodality in the Southern Ocean, winter sea ice collapse in the Arctic Ocean, local collapse of ocean convection and deep water formation in the North Atlantic, abrupt snow melt in high altitude regions, and changes in vegetation in sensitive regions, e.g., Amazon rain forest dieback or boreal forest expansion. An important finding was that in about half the reported regional abrupt changes in the ocean, sea ice, snow cover, permafrost, and terrestrial biosphere arise at global warming levels of less than 2° Celsius. Furthermore, the analysis suggested that the potential for a tendency of destabilization of the climate increases with the global mean temperature change.

The current generation of global climate models (CMIP6) simulates monsoon systems that are responding to climate change. In the context of regional impact, such changes may appear as tipping points in regional climate statistics. *Ha et al.* [2020] find that the duration of the monsoon season over East Asia and India will become longer and that extreme rainfall events will increase. The duration of the rainy season shows a large range of sensitivities to the warming from absent to nearly one month, with large uncertainties [*Moon and Ha*, 2020].

Marine ecosystems have recently come into focus in the discussion about tipping points [*Heinze et al.*, 2021]. In contrast to the global catastrophic events, traditionally associated with tipping points, changes affecting marine ecosystems may be more fragmented in time and space. In the near-surface ocean, where most of the marine life thrives, three effects conspire to potentially high impacts: warming, ocean acidification and deoxygenation [*Gruber*, 2011]. As these changes happen in the ocean, impacts will last for centuries to millennia even if climate change is stabilized, and are therefore practically irreversible. An additional stressor for marine ecosystems are marine heat waves which have been attributed to anthropogenic warming [*Laufkotter et al.*, 2020], and which will increase manifold in the coming decades [*Frolicher et al.*, 2018]. Regional responses to this forcing are likely registered as crossing thresholds, or tipping points.

Finally, the physical changes in the climate system, both naturally occurring in the past and anthropogenically forced since for the past ca. 100 years, will have impacts on ecosystems and the assemblage of organisms in them. A recent study suggests that abrupt disruption of ecosystems and consequent shifts of biodiversity will occur already in before 2030 with tropical oceans and forests being first affected and followed by ecosystems in higher latitudes [*Trisos et al.*, 2020]. Clearly, research in this area is only currently emerging and highly regionally resolved climate projections would be required for further progress.

Generally, we note that the level of understanding of the palette of tipping elements in the climate system is highly heterogeneous, ranging from elements that have occurred in the past and have been simulated in physical models extensively to systems that have not yet experienced the stressors that are expected for the future and hence lack past analogues. Hence, the level of understanding of, and confidence, in tipping points and abrupt and irreversible change in general, needs to increase significantly in order to provide robust and actionable information for society and policymakers.

Tipping cascades: a new paradigm

While earlier studies have focused on individual non-linear systems, e.g. the Atlantic meridional overturning circulation, or the Antarctic ice sheet, new research shows that a regime change of one particular system could trigger and abrupt change in a different system. This could result in a cascade of changes, an effect that has come into focus only recently [*Dekker et al.*, 2018; *Lenton et al.*, 2019], but has been studied in the context of paleoclimate changes earlier. An example is the rapid discharge of freshwater to the North Atlantic, caused by a tipping of the mass balance of the Greenland ice sheet (or the Laurentide ice sheet during the last ice age), which would push the Atlantic meridional overturning circulation to a collapse. This cascade continues by a movement of the intertropical convergence zone to the south which then tips the Amazon rainforest and finally affects the carbon stock [*Bozbiyik et al.*, 2011]. This could be described as a "domino effect", whereby the individual tipping elements do not feedback to the original trigger, here the ice sheet instability. Such one-way chains could also be responsible for step-like changes in atmospheric CO_2 concentration that have been inferred from high-resolution greenhouse gas records from polar ice cores [*Nehrbass-Ahles et al.*, 2020], but whose origin remains elusive.

Two-way interactions have also been simulated in a coupled climate model that exhibits self-sustained oscillations involving a complex interplay of the Atlantic meridional overturning circulation, Arctic sea ice, convection, and the subpolar gyre circulation [*Vettoretti and Peltier*, 2018]. While each change can be considered a tipping, the changes are evidently not irreversible. The simulation assumes that the background climatic conditions are stable and hence, this may not be a realistic scenario for the future where the transient warming may change the stability property of each of these elements.

Based on a meta-analysis of existing literature, *Rocha et al.* [2018] studied regime shifts in physical, ecological and social systems. Among the thirty physical and biological systems they found both one-way cascading, as well as two-way interactions indicating structural interdependence of tipping elements. Although this is only the starting point of future in-depth analyses, the information provides valuable insight for monitoring interconnected elements of the Earth System.

In summary, cascading events are a new research area that deserves more attention. Progress will be made with improved climate models, chiefly regarding spatial resolution and a more comprehensive consideration of interconnection, particularly with biological and human systems.

Approaching tipping and early warning signals

Ever since the ground breaking discovery of chaotic behaviour of a non-linear dynamical system that flips between different states [*Lorenz*, 1963], the question of predictability has been at the forefront of climate system research [*Shukla*, 1998; *Krishnamurthy*, 2019]. In earth science non-linear processes have been studied intensively for many decades [*Ghil*, 2019]. Rapid progress has been made both in theoretical understanding and in observations. The approach of transition points in phase space is often characterised by a slowly increasing variability superimposed on the trajectory towards the tipping point [*Scheffer et al.*, 2009]. This behaviour was already described in a dynamical model of atmospheric flow [*Lorenz*, 1963], and is a fundamental characteristic in the vicinity of the tipping point.

Evidently, the well-researched Atlantic meridional overturning circulation is a prime candidate for an assessment how close the system has moved to the critical threshold of slow down. Various methods have been proposed that base on direct and indirect observations. The direct observations [*Srokosz and Bryden*, 2015; *McCarthy et al.*, 2020] provide high-resolution time series of several elements at fixed mooring arrays. These observations quantify, for the first time, the scale of natural variability of the transport but they are not yet conclusive with respect to a a notable decrease as suggested by all coupled models as a response of the anthropogenic warming. Some estimates show little or no trend [*McCarthy et al.*, 2020], others suggest that the slowdown has brought the circulation into a reduced state [*Smeed et al.*, 2018]. Two limitations need to be mentioned: first, the time series of direct continuous observations are rather short for the slow process under investigation, and second, single quantities may not be sufficiently powerful to distinguish the signal from the noise.

Therefore, multiple indicators, so-called fingerprints, may provide additional information and more robust constraints to determine whether the overturning circulation in the North Atlantic is already weakening. By analysing sea surface temperature anomalies and trends, indications of a slowdown were reported [*Caesar et al.*, 2018]. In a more comprehensive analysis including salinity data, *Boers* [2021] proposed eight independent quantities that can be used as early warning signals. Taken together, they confirm a slowdown that has started in the last century: The overturning circulation has continually lost stability and could now be close to a threshold. How close, however, remains to be established and is the subject of further research.

Observation of transient changes in ocean circulation faces substantial logistical challenges. Another system that my exhibit tipping with serious consequences are polar ice sheets. Mass changes and the state of surface velocity of Greenland and Antarctica are now routinely surveyed by several satellite remote sensing missions. They provide a detailed picture on the response of the ice sheets to the anthropogenic warming. In Greenland both ocean warming and surface melting combine to a rapid mass loss [*Bevis et al.*, 2019; *Mouginot et al.*, 2019], while in Antarctica it is primarily caused by warming ocean waters that heat ice shelfs from below and accelerate ice discharge [*Rignot et al.*, 2019]. These observations may signal a development towards potential instabilities of the West Antarctic ice sheet [*Joughin and Alley*, 2011].

These concerns are raised by the analysis of marine sediments paleoclimate reconstructions points at frequent and large responses of Antarctica to variations in external forcing [*Naish et al.*, 2009]. The combination of detailed information on bed topography and model simulations suggests that Thwaites Glacier in West Antarctica may be on the approach of instability which may be reached in a few centuries [*Joughin et al.*, 2014], and similar findings were reported for Pine Island Glacier [*Rosier et al.*, 2021]. At this point it is not clear what the large-scale consequences of such “local” tipping may be. Could some ice streams find a new stable equilibrium rather quickly, or would the ongoing warming, primarily through ocean water delivering heat from below and destabilizing ice shelfs, initiate a domino effect with pan-Antarctic mass loss. Some extreme model scenarios suggest the latter [*DeConto and Pollard*, 2016b], which would lead to additional sea level rise over the following millennia [*Clark et al.*, 2016].

Conclusions and outlook

As is evident from this brief review, the combination of environmental information with a hierarchy of climate models is indispensable for a deeper understanding of tipping in the climate system, for the identification of tipping elements, for the assessment of risks associated with tipping, and for the development of early warning systems. Relevant information comes from direct observations and current monitoring efforts at critical locations in the climate system, as well as from high-resolution paleoclimate records by which a much longer time period and therefore a larger dynamical range of climate system behaviour becomes accessible. In order to also obtain information on impacts, paleoclimate records from different archives need to be synchronized in time. This is one focus of TiPES.

Regarding modelling, progress depends on the entire model hierarchy. A specific focus of TiPES is the systematic use of mathematical models to analyse the fundamentals of system behaviour approaching a tipping point. Improved understanding will help identify early warning signals for tipping. Most recent research on early warning signals for the Atlantic meridional overturning circulation is very promising and will serve as a template to apply the methodology to other tipping elements investigated in TiPES. Models of intermediate complexity will help build the bridge between long-term paleoclimate records, e.g. marine sediment records, and theoretical understanding. In addition to physical indicators, these models also directly simulate a palette of ocean tracers that are measured in marine sediment records. This direct comparison provides a critical framework for the analysis of tipping points found in the paleoclimatic records. In addition, model configurations with different sensitivities can be produced with these simplified models and permit a comprehensive testing of responses to perturbations that trigger transitions of threshold in the past and the future. This is a specific focus of TiPES. More complex models, such as comprehensive coupled climate models, are at the top of the model hierarchy and incorporate the most complete formulations of physical processes, in particular atmospheric and oceanic circulation.

The hierarchy of models is used to focus on two tipping elements in TiPES. First the Atlantic meridional overturning circulation is further investigated, particularly with respect to the proximity of the threshold for an irreversible reduction. This involves a test of robustness of fingerprints identified in observations which considers the joint analysis of temperature and salinity anomalies generated both by natural variability and, increasingly, by the approach to the threshold.

This review has shown that there is mounting observational evidence that some parts of the West Antarctic ice sheet may have crossed a threshold already now, and rapid decline of ice mass around the periphery is ongoing. Dedicated ice sheet models, both run offline and as coupled components of climate models, must be employed to shed more light on the effect of the various scenarios presented in the latest IPCC report. Owing to sufficient spatial resolution, these models now enable the systematic investigation of ice streams and catchment areas on Antarctica for detailed studies of their stability and the potential cascade of accelerated mass loss.

The regionalization of tipping point impacts remains a big challenge. Monsoon systems, the Amazon rain forest, and high-latitude permafrost regions count among those that have the potential to disrupt regional communities and lead to unprecedented impact. Research must therefore provide more appropriate modelling systems in order to tackle these difficult questions. TiPES will make substantial contributions to a number of these open issues.

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