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Reflecting on the Science of Climate Tipping Points to Inform and Assist Policy Making and Address the Risks they Pose to Society

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Abstract

There is a diverging perception of climate tipping points, abrupt changes and surprises in the scientific community and the public. While such dynamics have been observed in the past, e.g., frequent reductions of the Atlantic meridional overturning circulation during the last ice age, or ice sheet collapses, tipping points might also be a possibility in an anthropogenically perturbed climate. In this context, high impact—low likelihood events, both in the physical realm as well as in ecosystems, will be potentially dangerous. Here we argue that a formalized assessment of the state of science is needed in order to establish a consensus on this issue and to reconcile diverging views. This has been the approach taken by the Intergovernmental Panel on Climate Change (IPCC). Since 1990, the IPCC has consistently generated robust consensus on several complex issues, ranging from the detection and attribution of climate change, the global carbon budget and climate sensitivity, to the projection of extreme events and their impact. Here, we suggest that a scientific assessment on tipping points, conducted collaboratively by the IPCC and the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services, would represent an ambitious yet necessary goal to be accomplished within the next decade.

Keywords Tipping points · HILL events · IPCC assessment · Scientific consensus

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Article Highlights

- A scientific consensus regarding tipping points, abrupt changes and surprises in the climate system will address diverging perceptions in the scientific community and the public, and accelerate scientific progress
- The Intergovernmental Panel on Climate Change (IPCC) has a successful history of generating consensus through a formalized process across a wide range of topics, from the physical science basis to mitigation of climate change
- A broader view on tipping points, including high impact—low likelihood events, provided more comprehensive information for policymakers and the public

1 Introduction

With a flurry of high-profile papers in the past few years (Boers et al. 2017; Lenton et al. 2019; Pattyn and Morlighem 2020; Boers 2021; Boers and Rypdal 2021; Caesar et al. 2020; DeConto et al. 2021; Armstrong McKay et al. 2022; Ditlevsen and Ditlevsen 2023) the conversation on tipping points, abrupt changes and surprises (terms defined in (IPCC 2021a)) has been picked up by the media. The Global Tipping Points Report (Lenton et al. 2023), an interdisciplinary status report written by a group of scientists, was published during COP28 in December 2023 and received much media coverage worldwide. This is just the most recent example where media regularly amplify such potentially catastrophic consequences of anthropogenic climate change to "doomsday" scenarios. This contrasts starkly with the more detailed presentations in scientific publications (Weijer et al. 2019; Heinze et al. 2021; Wang et al. 2023) and the more nuanced, perhaps even conservative, assessments of this highly policy-relevant topic presented in successive reports of the Intergovernmental Panel on Climate Change (IPCC) since 1990. Furthermore, some authors criticize the overly narrow tipping point framing and argue in an opinion paper that focusing on them would distract from urgent action (Kopp et al. 2023). Given the potential risks from tipping points, we argue that this topic now requires focused attention and a formalized process to achieve a scientific consensus where possible.

The purpose of this paper is therefore to discuss ways to reduce the widely diverging perception among the public, policymakers, and even scientists, of tipping points, abrupt changes and surprises in the climate system that appears to have grown in recent years. This divergence was also enhanced by social movements engaged in climate action when the urgent need for action was argued with the approach of a threshold beyond which irreversible changes would be unleashed (Hagedorn et al. 2019). The concern regarding the approach of the Earth System toward tipping points or thresholds is real and scientifically fully justified, all the more since recent research has identified nonlinear transitions that may occur earlier than previously suggested (Ditlevsen and Ditlevsen 2023), or that involve interactions not considered in previous work such as vegetation dieback (Bochow and Boers 2023) and its impacts on regional climate (Nepstad et al. 2008). Nevertheless, we advise not to neglect the consensus finding process in the scientific community in this hotly debated topic in order to better quantify the probability of reaching tipping points, and identify early warning signs, increasingly using space-based Earth observations (Boulton et al. 2022) and employing the most advanced climate models (Schär et al. 2020). Consensus processes have been applied successfully to other low probability outcomes, such as extreme events. This has led to a widely shared awareness about the growing risk of extreme weather and climate events in the coming decades.

Scientific consensus finding is the starting point of effective and coherent communication. It is essential for the maintenance of the credibility of science, robust policy advice, and long-term implementation of mitigation. There is ample experience in the scientific community and the policymaker arena on how to successfully pave the way to scientific consensus, and there is strong appreciation for the value of a scientific consensus that emerges from a formalized process. A case in point is the global carbon budget. This concept was first presented in the scientific literature around 2009 (Allen et al. 2009; Matthews et al. 2009). By 2013 the scientific consensus had solidified to the point that the concept could be defended against strong resistance by some policymakers (IPCC 2013b). Without the formalized assessment process carried out by the IPCC, which has been applied since its inception in 1988, the scientific basis of important milestones to protect the climate system, such as the UN Framework Convention on Climate Change (UNFCCC), the Kyoto Protocol, and the historic Paris Agreement, could not have been achieved.

This paper is organized as follows. First, we consider the Earth System as a dynamical system with a range of possible behaviors, in particular abrupt changes. A well-documented and simulated example of a climate tipping point is then discussed. Key gaps in the understanding of climate surprises are identified, and an impact-oriented approach is advocated. Four examples of scientific progress enabled by consensus finding in a formalized assessment process are presented. Finally, it is argued that clear statements and simple language, firmly rooted in the science, render communication effective. In conclusion, a combined, interdisciplinary assessment process involving both the IPCC and the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) is proposed. Inclusion of the latter is important as both climate and biodiversity are tightly linked.

2 The Complex Climate System as a Dynamical System

The climate system can be understood as a dynamical system that is modeled by a set of nonlinear partial differential equations and parameterizations, including state equations. As such, the climate system is expected to exhibit, in principle, at least some features of the wide range of behavior documented by the mathematical analysis of such dynamical systems (Ghil and Lucarini 2020). These involve multiple equilibrium states, both stable and unstable, damped and self-sustained oscillations, attractors, limit cycles and chaotic behavior. This applies for the individual components of the climate system, such as the atmosphere, ocean, cryosphere, and biosphere, as well as for the fully coupled system. Early examples are multiple equilibria in the ocean's deep circulation (Stommel 1961), the complexity of the meridional atmospheric circulation that evolves from thermal instabilities (Lorenz 1963), the planetary energy balance (Sellers 1969) which shows multiple equilibria caused by the nonlinear dependence of planetary albedo on surface temperature, the El Niño-Southern Oscillation variability in the equatorial Pacific caused by ocean-atmosphere instabilities (Zebiak and Cane 1987), or glacial–interglacial cycles (Saltzman and Maasch 1991).

The Lorenz model has revolutionized the science of dynamical systems and provoked a paradigm shift in our understanding of the climate system. Although the model is entirely deterministic, predictability of the internal structure of the circulation is fundamentally limited. This is because the system can abruptly change from one mode of variability to another which is characterized by different amplitude and frequency. For an observer, such a change may come as a surprise, if warning signals are unknown, inconclusive, or ignored. Loss of predictability does not imply the absence of predictive power to estimate some global properties and their changes in the system. For instance, the preference of one mode over another, when some external forcing is applied to the system (Palmer 1999), is an example of predictability in the presence of chaos. Furthermore, depending on the specific parameter values the behavior may change from stable to oscillatory to chaotic, suggesting that external forcing resulting in different climate states may also lead to different dynamical characteristics. The Lorenz model teaches us that such different regimes may lie very close to one another and therefore, slight changes in the background state could, in principle, lead to completely different dynamical behavior.

Abrupt shifts, surprises, and irreversibility are not just characteristics of simplified models (Weijer et al. 2019). Indeed, there is now a wide range of such dynamical behavior that can be found in the currently most comprehensive coupled climate models (Drijfhout et al. 2015). In their survey of the coupled models assessed by the IPCC in 2013, they found many regional climate indicators that exhibited abrupt change in response to future warming, even for global warming levels below 2°C. The model generation at that time, however, did not yield a consistent picture across different models. The next generation of coupled models was analyzed with respect to the stability of the ocean circulation to freshwater perturbations and showed a wide range of response (Baker et al. 2023; Jackson et al. 2023).

Not only the warming, but also small stochastic fluctuations at the ocean's surface could destabilize ocean circulation and result in large changes, as earlier demonstrated in models of reduced complexity (Knutti and Stocker 2002), and most recently in state-of-the-art coupled models (Romanou et al. 2023), with consequent impacts on atmospheric circulation and regional climate (Orbe et al. 2023). The coupled ocean-atmosphere system may thus be less stable than previously assessed. Another possibility of dynamical behavior are self-sustained oscillations under current and past climate states (Kuniyoshi et al. 2022; Vettoretti et al. 2022; Izumi et al. 2023). As such, complex dynamics are found in the entire hierarchy of climate models; thus we argue that such, behavior is an intrinsic part of the functioning of the Earth System (Weijer et al. 2019; Malmierca-Vallet et al. 2023). Ongoing modeling intercomparison projects, e.g., TipMIP (Loriani et al. 2023), will help in elucidating the dynamical behavior of the current climate models much more systematically and provide new insight into which of the many tipping elements in Lenton et al. (2023) may be likely or plausible and hence need to be monitored.

3 The Atlantic Meridional Overturning Circulation: An Iconic Tipping Element

3.1 Combining Evidence from the Paleoclimatic Records and Models

Based on the general mathematical knowledge of nonlinear dynamical systems, it is no surprise that the paleoclimatic record, in particular reconstructions at decadal, annual and sub-annual resolutions, has been interpreted through the lens of dynamical systems. An early example is the interpretation of an abrupt millennial cooling during the transition from the last ice age to the current Holocene, about 12,900 years ago, found both in a Greenland ice core (Dansgaard et al. 1993) and in lake sediments in Switzerland (Oeschger et al. 1984). These authors suggested that an ocean flip-flop system would be the origin of these climate swings and thus revived an elegant, almost forgotten idea involving two stable equilibria of the meridional overturning circulation (Stommel 1961). One circulation state, typical for the modern Atlantic Ocean, shows strong meridional overturning and an associated substantial meridional heat flux. The other stable state has no overturning and, hence, the northward heat flux is absent. The iconic view of the deep ocean circulation as a heat "conveyor belt" as devised by Broecker (1987a), motivated researchers to seek further evidence for an unstable ocean circulation in the past (Broecker et al. 1985), and potential implications for the future (Broecker 1987b).

Strong initial support for ocean-mediated abrupt climate change was given by idealized model simulations that exhibited multiple equilibria (Bryan 1986; Stocker and Wright 1991; Stocker et al. 1992). Since then, it has been recognized that such abrupt coolings and warmings are a common feature of climate variability during ice ages. They were identified in high-resolution records of marine sediments, polar ice cores, lake sediments, speleothems, and tree rings throughout the entire northern hemisphere (Li and Born 2019; Rousseau et al. 2022). The important role of the ocean in these abrupt temperature swings registered in Greenland ice cores was further evidenced in the characteristic century-to-millennial scale, more gradual warmings and coolings found in ice cores from Antarctica for each of the abrupt changes in the north (EPICA Community Members 2006). This has been interpreted as the fingerprint of a thermal bipolar seesaw mediated by the Atlantic meridional overturning circulation (AMOC) (Crowley 1992; Stocker and Johnsen 2003; Pedro et al. 2018). Taken together, the past 40 years of paleoclimate analysis and modeling have demonstrated the important role of ocean circulation in limiting the stability of the global climate system (Clark et al. 2002; Weijer et al. 2019). They also emphasize the value of paleoclimatic evidence for identifying possible tipping points, and the need to interpret these considering the global system (e.g., Brovkin et al. 2021).

What is valid for the past is also relevant for the future, in particular in an anthropogenically forced future. If the climate system has exhibited limited stability to perturbations and responded with abrupt changes in the past, it would be no surprise if such behavior were to develop in the future. In fact, it would be quite remarkable if this same physical system were to behave strictly linearly and reversibly despite the potentially very large and rapid anthropogenic perturbations. Indeed, early model simulations based on idealized scenarios suggested that the AMOC would reduce in response to the warming (Stouffer et al. 1989). In the most recent family of scenarios (Riahi et al. 2017), business-as-usual would result in global mean heating of 3.3–5.7°C relative to pre-industrial levels by the end of this century (IPCC 2021b). This approaches the size of a typical glacial-to-interglacial warming of 5–7°C. The evident difference is the speed of change: The natural global mean warming out of the last ice age took about 10,000 years, whereas the ongoing anthropogenic heating would reach the same magnitude in just 200 years in a business-as-usual scenario, appearing like a shock compared to the gentler evolution of the climate system during the last several million years. But even lower scenarios are problematic since so-called temporary overshoots are now also considered to be compatible with the goals of the Paris Agreement, at least in the long-term (Tokarska et al. 2019). Such overshoots can generate hysteresis (Jeltsch-Thömmes et al. 2020; Wunderling et al. 2023), and hence surprises after time of larger forcing has ended.

By the end of the 1980s the paleoclimatic evidence for large-scale changes in AMOC was well established, and early model simulations demonstrated the relevance of such

Table 1 Occurrence of terms relevant to "tipping points" in the six assessment reports of IPCC Working Group I (WGI) since 1990. The definitions of the terms can be found in the respective IPCC glossaries

Term in WGI	FAR (1990)		SAR (1995)			TAR (2001)			AR4 (2007)			AR5 (2013)			AR6 (2021)		
	SPM	*AR*	*SPM*	*TS*	*AR*	*SPM*	*TS*	*AR*	*SPM*	*TS*	*AR*	*SPM*	*TS*	*AR*	*SPM*	*TS*	*AR*
Multiple equilibria		✓			✓			✓			✓			✓			
Abrupt change[1]		✓		✓				✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Irreversibility[2]		✓			✓		✓	✓		✓	✓	✓	✓	✓	✓	✓	✓
Surprise[3]		✓		✓			✓	✓			✓			✓		✓	✓
Tipping point[4]											✓		✓	✓	✓	✓	✓
HILL[5]							✓				✓			✓	✓	✓	✓

[1]abrupt change, or abrupt climate change

[2]irreversibility or irreversible change

[3]surprise, or unexpected [event, change]

[4]tipping point, or tipping element

[5]high impact event, low likelihood-high impact [event, outcome], or vice versa

reorganizations for future climate change (Stouffer et al. 1989). Consequently, this has aroused policy makers' interest, as it would have grave consequences for regional climate, both in the atmosphere and in the ocean in the North Atlantic regions with potentially global repercussions. Already the first assessment report of the IPCC reflected this (Table 1), as relevant terms entered the main report (IPCC 1990). Although a reduction or possible shutdown of the AMOC was already a consensus finding in the in the Summary for Policymakers of Working Group I (WG I) in the Third Assessment Report (IPCC 2001b), the terms listed in Table 1 have not yet made it into this top-level, government approved document. The projection chapter of the 4th Assessment Report featured a box that explained the different dynamical behaviors that were loosely referred to as "climate surprises" (Meehl et al. 2007). The box also pointed to additional elements in the climate system that may be prone to exhibit "surprises" in response to anthropogenic forcing. In addition to the AMOC, Arctic sea ice, glaciers and ice caps, the polar ice sheets, vegetation and atmosphere, and atmosphere-ocean regimes were mentioned. The overview has motivated the coinage of the terms "tipping elements" and "tipping points" in the climate system that were featured in the inaugural article by Lenton et al. (2008). These terms have since been widely used in science, by the media and in the public, and finally in 2021, found their way into the Summary for Policymakers (Table 1).

The recent IPCC 6th Assessment Report (IPCC 2021b) concluded that there was *medium confidence* that an AMOC collapse will not occur before 2100. The medium confidence, despite widespread model agreement, results from a number of missing processes in current climate model projections, and some evidence of a bias toward excessive AMOC stability in the models. Beyond 2100, the IPCC Special Report on Oceans, Cryosphere and Climate Change (IPCC 2019) concluded that an AMOC collapse was *about as likely as not* by 2300, for high emissions scenarios. Some model simulations also suggest the possibility of a temporary, multi-decadal to century scale AMOC reduction, followed by a recovery (Stocker and Schmittner 1997; Hu et al. 2013; Koven et al. 2022; Pöppelmeier et al. 2023). These assessments and recent studies emphasize the still incomplete nature of current scientific understanding of the relevant processes.

3.2 Five Reasons for Patchy Knowledge of the Future Evolution of AMOC and its Impact

The current state of knowledge on tipping points and their climatic impact on regional to global scales is patchy for five reasons. These include a lack of comprehensive observational data, the incomplete physical understanding of trigger factors, the limitations of models and scenarios, and the complexity of impacts of tipping points. This is best illustrated by considering the AMOC, which has been studied extensively, but it essentially applies to all systems that may exhibit tipping potential (Wang et al. 2023).

First, patchiness arises from the fact that two monitoring campaigns (Rapid-AMOC since 2004, and Overturning in the Subpolar North Atlantic Program (OSNAP) since 2014) with direct oceanographic measurements only cover a relatively short time period. They show an unexpected high variability but no trend (Li et al. 2021; Worthington et al. 2021; Jackson et al. 2022). This contrasts with long-term, paleoclimatic records that are indicators of surface temperature, deep ocean temperature, water mass distribution, and deep currents (Broecker 1997). However, as these are proxy records, evidence remains circumstantial. A selection of such marine records covering the last millennium suggests that a decline of AMOC is well underway and that today's strength is the lowest (Caesar et al. 2021a). However, there are several open issues. A number of locations in the North Atlantic, where additional records exist, have not been considered in this study and remain to be analyzed and confronted with the suggestion of AMOC weakening (Halimeda et al. 2022). Then, climate signals from, for example, the southern hemisphere could provide independent evidence for an AMOC evolution and eventual reduction during the last millennium, via a teleconnection (Stocker and Johnsen 2003; Pedro et al. 2018), with no indication so far. Finally, some argue that the observed North Atlantic cooling is instead caused by local heat loss due to a changing large-scale atmospheric circulation (Li et al. 2022), or by remote influences not directly reflecting the AMOC (Hu and Fedorov 2020; Keil et al. 2020). Hence the paleoclimatic evidence for an ongoing AMOC slow-down remains debated and a consensus is not yet reached.

Second, theory and simple models suggest that critical AMOC thresholds can arise when temperature and salinity anomalies generate different atmospheric responses that result in surface buoyancy anomalies leading to instabilities. However, it is not established how vertical and horizontal mixing in the ocean interior, the wind-driven circulations of the sub-tropical and sub-polar gyres, and high-latitude deep water formation would modify the overall stability of the circulation system. In fact, some models show a preponderance toward instability in very narrow windows of parameter space, particularly with respect to vertical mixing (Vettoretti et al. 2022; Malmierca-Vallet et al. 2023). This shows that there are gaps in the process understanding and quantification that must be closed before a consensus for the long-term fate of AMOC is reached.

Third, the currently most complete climate models show a very wide spread of the response of the AMOC to anthropogenic warming and to changes in the meridional water transport through the atmosphere by the end of the 21st century (IPCC 2021b). While some decrease in the AMOC is simulated consistently, the amount of reduction is very uncertain (Weijer et al. 2019). Furthermore, the observational record is still too short to constrain these model simulations meaningfully. None of the models shows an abrupt reduction or a collapse during this century which would be one of the characteristics of crossing a tipping point.

Fourth, commonly reported multi-model means are inadequate to investigate the consequences of threshold crossings of the AMOC. Impact models forced with multi-model output, or regional analyses of multi-model output would not be appropriate to inform about risks and regional consequences associated with an AMOC collapse. Therefore, regional surprises may go unnoticed in such products if not specifically and systematically searched for. Here, the analysis of apparent "outlier members" of multi-model ensembles might be worthwhile, a path similar to what has been followed recently in the analysis of heat waves (Fischer et al. 2021).

Fifth, current IPCC scenarios used to assess impacts are incomplete with respect to the possible crossing of thresholds in the climate system. IPCC WGII and WGIII base their assessment on projections which often use multi-model mean outcomes from CMIP efforts. For a comprehensive risk analysis, individual global simulations showing tipping behavior should be used for regional model projections or impact studies. The ongoing comparison project TIPMIP will likely provide such simulations that could generate new input to impact models (Loriani et al. 2023).

4 A Broader View on Climate Tipping: High Impact—Low Likelihood (HILL) Events

To clarify the discussion, it is worthwhile to recall the common definition of "tipping point" according to IPCC's WG I (IPCC 2021a): "A critical threshold beyond which a system reorganizes, often abruptly and/or irreversibly." WG II gives a somewhat more detailed definition: "A level of change in system properties beyond which a system reorganizes, often abruptly, and does not return to the initial state even if the drivers of the change are abated" (IPCC 2022). In terms of impacts, these definitions seem to be too restrictive and do not comprehensively cover the relevant climate system behaviors that could occur and that are not simply a linear response to an anthropogenic perturbation. Recently, a new term has been proposed for such behavior: High impact—low likelihood (HILL) events (Wood et al. 2023). This term shifts the focus and emphasizes the impact rather than the dynamical behavior of abrupt events, irreversible changes, surprises, etc. It is useful to visually clarify the perspective that underlies the notions of "tipping" and "HILL." This is illustrated in Fig. 1 which compares the dynamical or time perspective with the impact perspective. The relationship between forcing and response in the time perspective provides a basis for "tipping," which denotes a change that is more rapid than the forcing causing the change. In the impact perspective, the relationship between forcing and impact determines whether the system responds in a resilient way or whether a high impact—low likelihood (HILL) event results. Obviously, many quantities may also show linear behavior for a large range of forcing speeds and levels, respectively.

Focusing on the impacts of HILL events directs the attention to the regional consequences of large-scale events such as the reduction or collapse of the AMOC, the gradual decrease in mass of the polar ice sheets with potentially irreversible melting, the shift of atmospheric circulation systems, or the possible large-scale decline of the Amazon rainforest. This calls for a new generation of atmosphere and ocean models (Hewitt et al. 2022; Slingo et al. 2022) featuring much higher resolution and more realistic coupling, commensurate with the physical processes that trigger HILL events. It requires realistic inclusion, in Earth System models, of interactive processes such as fire and vegetation disturbance and loss. Some events previously considered to occur with low likelihood have already become more likely, as illustrated by increased vulnerability of some tropical forests (e.g.,

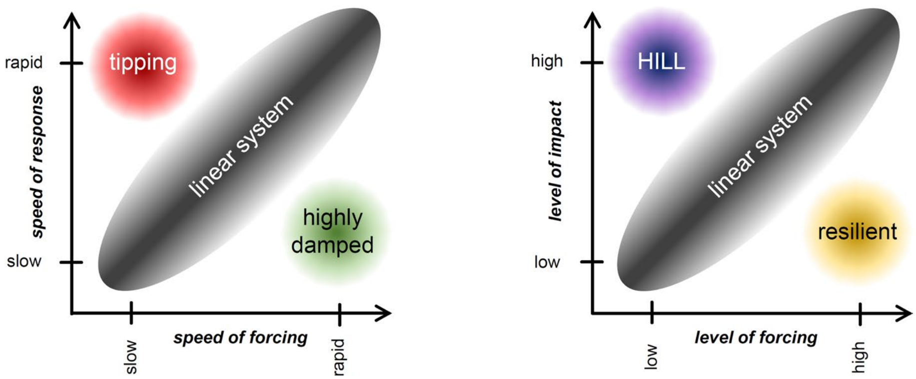

Fig. 1 Two alternative views on nonlinear behavior in the Earth System, the dynamical view (left) and the impact view (right), respectively. HILL denotes high impact—low likelihood event

Saatchi et al. 2021), observations of severe coral bleaching (Hughes et al. 2017), and the occurrence of unprecedented extreme events (e.g., Thompson et al. 2022). With models that can resolve processes and scales relevant for HILL events and tipping points, a fresh look must be taken at the question of the existence of thresholds and their location, the sensitivity of large-scale and regional-scale atmosphere, coupled atmosphere-ocean, and coupled ocean–cryosphere systems to the ongoing global heating.

HILL events go far beyond the physical science basis, they occur in geochemical and biological systems (Bastos et al. 2023), and they are relevant for impacts on ecosystems (Dakos et al. 2019; Willcock et al. 2023). Generally, evaluating HILL events requires dense sampling of extreme events, and coverage of long enough timescales to capture the statistics of rare events and to address slower processes such as ice sheet melting. At the same time, new high-resolution simulations should be carried out to gain a more detailed understanding of the dynamics that can generate HILL events.

Deep uncertainties are generally associated with tipping elements. The process and timing of boreal forest recovery after drought and fire is poorly understood. Land surface and vegetation models still do not capture the full complexity of the coupled Earth System (Fisher and Koven 2020). Amazon drying in response to climate change varies between climate models (Parry et al. 2022), and is affected by uncertainties in vegetation response and societal choices such as deforestation (Nobre et al. 2016). For other potential tipping points, such as Amazon forest loss or boreal forest shifts, observations are still relatively short and uncertain. Finally, current understanding of ice sheet tipping points is largely based on offline modeling (Pattyn et al. 2018), as are the effects of permafrost melting and methane releases in the high latitudes of the northern hemisphere (Kleinen et al. 2021).

In summary, taking a broader view on surprises in the climate system, combining tipping points, HILL events and irreversible change, would accelerate the understanding of the Earth System and the responses, from global to regional and local, to the ongoing anthropogenic perturbation.

5 Consensus Finding Process Promotes Scientific Progress

Anthropogenic climate change has been a topic of scientific attention since the late 1960s (Manabe and Wetherald 1967; Broecker 1975). To the wider public, the topic was known through the landmark report of the Club of Rome (Meadows et al. 1972), and later it was covered by the media worldwide. Public awareness of the greenhouse effect has increased steadily since the mid-1980s (Nisbet and Myers 2007). Many different aspects of anthropogenic climate change have featured in the news media and innovative ways of analyzing the growing corpus of media coverage are being applied (Hase et al. 2021; Schäfer and Hase 2023). Regarding climate tipping points, the media coverage has steeply increased since about 2017, when also digital news media showed an accelerating mention of this and related terms (Bellamy 2023). Often, more dramatic terms, such as “climate emergency” and “climate breakdown” were used when reporting on climate tipping points.

Generally, disasters are prone to distortion in media reports, possible future disasters even more. It is important to emphasize that the distortion can go both ways. Reporting could exaggerate the consequences and invoke doomsday scenarios, but it could equally downplay the gradually increasing preponderance of disasters. Society sometimes ‘discounts’ future risk in their decision-making, particularly in regions and situations when domestic pressures are high. While this is common practice in classical cost-benefit analyses of measures to counter anthropogenic climate change, research shows that this is inappropriate when it comes to climate surprises (Dasgupta 2008; Weitzman 2011). We feel that the same mechanism is at play in the current discussion on tipping points in the climate system and on climate change projections. Some media inflate scientific results in order to generate attention, others regularly ignore such findings despite their potential humanitarian and economic consequences. “Catastrophizing” science can lead to despair and hopelessness which eventually leads to inaction. In the scientific community, when it comes to climate surprises, we observe the development of groups with diverging views, here loosely termed as “tippists” and “linearists.”

“Tippists” argue that tipping points are ubiquitous in the nonlinear climate system and that there is unequivocal evidence for an approach to tipping points in a number of climate system components, such as the AMOC, the Greenland ice sheet, and the Amazon rainforest. Some even suggest that one tipping point could trigger another one or unleash an entire cascade (Steffen et al. 2018; Lenton et al. 2019; Brovkin et al. 2021; Wunderling et al. 2021; Wunderling et al. 2024). Currently, these arguments rest on very simple nonlinear mathematical models; thus, it is not yet clear whether a consensus will emerge on this issue. Tipping cascades are often used to invoke a state of emergency of the climate which requires swift action of mitigation, or some even advocate geoengineering to avoid disaster (Heutel et al. 2016; Helwegen et al. 2019). Evidently, this view generates media coverage and high attention. Looking beyond the physical climate system, thresholds seem to be abundant, e.g., physiological limits in vegetation and the biosphere (Scheffer et al. 2001; Higgins and Scheiter 2012; Biggs et al. 2015; IPBES 2018), including for humans (Vecellio et al. 2023), or in snow and ice cover which exhibit nonlinear responses to a change in ambient conditions or in forcing.

“Linearists,” on the other hand, emphasize the complexity of the climate system that has many dissipative elements that would prevent large-scale instabilities from unfolding. Some hold the view that tipping points are artifacts of simplified or incomplete climate models, and comprehensive models would not show such behavior (Stouffer and Manabe 2003; Wunsch 2006). The argument of absence of tipping is often connected with the equilibrium response of the system long-term fate of the climate system, e.g., when an initially reduced AMOC has recovered (Stouffer and Manabe 2003; Dijkstra et al. 2004; Stouffer et al. 2006), or the bifurcation occurs for only very large warming (Hu et al. 2013; Hu et al. 2023). Others argue that the concept of tipping is employed too liberally, may not be dynamically accurate, and often confuses the issues of climate system response (Kopp et al. 2023). Clearly, such a view would be readily taken by some others to call off the urgency for mitigation and stress that anthropogenic perturbations would merely cause some manageable impacts.

Diverging views in the scientific community, framed, and amplified by the media as controversies, must be viewed critically. They should not be confused with indispensable scientific discussion and debate without which knowledge gain is impossible. Controversy generally bears the potential for progress and deeper insight. However, any controversy must follow the scientific approach, i.e., the production of reproducible facts, observations, and theoretical foundation. This is precisely the reason why consensus building in a formalized process has a special value. Within the agreed framework this process brings about facts and findings more sharply and allows a transparent exposition of the arguments of both tippists, linearists, and all in between.

One successful model is the IPCC process in which a diverse group of elected authors assesses a topic comprehensively and submits drafts of their report to multiple stages of open review. This raises awareness of questions, gaps, and controversies which need to be addressed in the course of revision. This process has a high chance of convergence because the selection process of the topics happens at the juncture of two different departure points: bottom-up from the scientific community, and top-down as requested by policymakers. Since the first IPCC report in 1990 the scientific community has found robust consensus in many difficult issues of climate science. If this happens, very strong and robust messages emerge. On the other hand, some topics may not yet have reached maturity for consensus. This is then presented as a finding of low confidence, or the absence of consensus is declared, and gaps of knowledge are explicitly enumerated. Often, this has stimulated further research. The community of climate scientists looks back on more than 35 years of experience in formalized IPCC assessments of complex climate science. We just mention four representative examples.

The first example concerns the detection and attribution of climate change. The question to what extent the increase in greenhouse gas concentrations is responsible for the observed changes in the climate system, has found a robust consensus over several successive assessments. After a few seminal studies in the early 1990s, the first cautious statements on global mean temperature increase were formulated for top-level documents, identifying a discernible human influence (IPCC 1996; Santer et al. 1996). With an increasing number of scientific findings and studies using multiple datasets and methods, longer and better observations, and improved climate models, the statements could be quantified, first for global mean temperature increase (IPCC 2001a), and subsequently for a growing number of observed variables–examples are large-scale precipitation, polar sea ice extent, worldwide glacier reduction, heat wave statistics and other extreme events (IPCC 2013a; 2021b).

The second example is the global carbon budget that is now accepted as a scientific fact owing to a deep understanding and detailed observations of the global carbon cycle, specifically the continued monitoring of atmospheric CO_2 increase and the uptake of anthropogenic CO_2 in the ocean. The global carbon budget was presented by scientists of IPCC WGI in the 5th Assessment Report in 2013 (IPCC 2013a). It met fierce opposition by some policymakers but was finally approved in consensus thanks to multiple lines of independent evidence, the bar that science sets for robust findings. As a result, the global carbon budget was included for the first time in AR5 and was accompanied by a compelling figure in the WGI Summary for Policymakers (IPCC 2013b). This result has stood the test of time: Since then, each successive report has included the updated carbon budget with the latest estimates in their highest-level documents (IPCC 2014; 2021b; 2023). The concept has thus become the most policy-relevant scientific finding for the Paris Agreement. It is the basis for estimating the required emissions pathways toward climate stabilization (e.g., Stocker 2013), and for assessing the stocktaking of emissions reductions by the UNFCCC.

The third example revolves around equilibrium climate sensitivity, i.e., the increase in global mean temperature upon a doubling of the atmospheric CO_2 concentration and equilibration of the climate system. It was first assessed in 1979 by a small group of scientists who were tasked by the US National Academy of Science (Charney et al. 1979). Equilibrium climate sensitivity has been at center stage in both the scientific and public debate ever since. The formalized consensus finding process of the IPCC has forced the scientific community to periodically revisit this issue and comprehensively assess the range based on the latest findings. This process has been going on since the beginning of the IPCC. Successive cycles could narrow the likely range of climate sensitivity, but in the 5th Assessment Report, the range had to be widened again, and a best estimate could not be delivered. This was due to the advent of new quantitative estimates from early instrumental records that yielded lower estimates than those from climate modeling, and other lines of evidence, such as paleoclimatic archives. At the same time, the consensus building process also fostered collaboration across usually separate communities such as paleoclimate science, cloud physics and climate modeling, attribution analysis and analysis of feedbacks. It was discovered that the pattern of warming matters, and that feedbacks evolve with the warming, rendering a constant feedback estimate from the observed warming uncertain (Sherwood et al. 2020). Overall, this significantly increased understanding, in particular, of the multiple sources of uncertainties, and of how to combine results across multiple lines of evidence and resulted, again, in a narrower range of climate sensitivity (IPCC 2021b). In the scientific debate, more pertinent metrics for global warming were developed to better inform policymakers such as transient climate response, and transient climate response to cumulative emissions (IPCC 2013a).

As the fourth example we mention the science of extreme events. In 2008 when the IPCC Special Report on Extreme Events was proposed, knowledge and understanding were patchy, and the relationship to anthropogenic warming was poorly explored. It was recognized that the impacts caused by extreme climate events created high losses and damages, and policymakers needed more scientific knowledge about projected changes in intensity, frequency, and regional expression of extreme events. The mere announcement of the forthcoming Special Report, carried out by two IPCC Working Groups jointly, accelerated research significantly, notably through internationally coordinated research initiatives such as the World Climate Research Programme, or Future Earth. It led to new collaborations across disciplines, and the new risk framing, proposed in this report, helped communicate the findings and their uncertainties more effectively (IPCC 2012). Since then, the science has evolved rapidly to the extent that individual extreme events can now be attributed to anthropogenic climate change (Otto 2017), and that the tight links between physical climate science and impacts are recognized for extreme events. The synergy of assessment and production of new science is evident in this example. A similar effect also resulted from IPCC (2018), where the scientific literature rapidly expanded to address the questions posed in response to the government request via the UNFCCC for the IPCC Special Report on 1.5°C warming to which the Paris Agreement aims to limit global warming. In both cases, this rapid advance has led to a step change in the scientific understanding of important and policy-relevant questions. The recent joint IPBES-IPCC workshop is a further important step toward cross-discipline assessments (Pörtner et al. 2021).

In summary, these four examples demonstrate that formal assessments play an important role beyond informing the policymakers and the public. Scientists focusing their attention on a specific topic, that is unresolved, has substantial uncertainties, or generates diverging views, with the clear goal to arrive at a consensus, or map out where there is none, is a healthy process that stimulates further research to address the open issues. We have seen in numerous examples that the consensus finding process also brings together scientists from diverse fields, when it becomes clear that a comprehensive understanding is only possible beyond the individual silos. While cumbersome and intensive, assessments have accelerated the progress of scientific knowledge generation in these issues by bringing on board funding agencies and policymakers.

6 Effective Communication in Support of Understanding and Action

Communication is central to making the results of a scientific assessment available to policymakers and to the broader public. In past IPCC Assessment Reports the Summary for Policymakers generated criticism due to the complexity of the language used (Barkemeyer et al. 2016). Likewise, the scientific diagrams of these documents have been found not to deliver on the promise of assisting and illustrating assessment findings (Harold et al. 2016; 2020). A significant improvement in the accessibility of language was introduced with "headline statements" (Stocker and Plattner 2016). These are short and succinct summaries of complex findings presented in the top-level documents of the IPCC. They use plain language without jargon, and in most cases without numbers. In short, they should be statements that could be quoted directly by newspapers, radio, TV, and in social media. These headline statements form part of the approved text and have therefore been elevated from statements by the scientists to statements of the entire panel, i.e., the 195 governments participating in the IPCC. The improvement in readability was demonstrated by simple metrics of text analysis (Stocker and Plattner 2016). IPCC has recognized the value of "headline statements" in the top-level documents and has adopted this instrument as an integral element of their products (IPCC 2016).

An example of a particularly effective headline statement that was approved by the panel in 2013 was the affirmation that "Human influence on the climate system is clear." We do not go into the details of how the authors deliberated for an hour in a closed preparatory meeting ahead of the approval plenary about the most suitable and appropriate adjective describing human influence. Along with "clear" about ten alternative adjectives were proposed, debated and pondered before "clear" was the preferred choice. This concise statement is the one-sentence summary of the complete detection and attribution science assessed in the WG I contribution to the 5th assessment cycle. An entire chapter of 87 pages was dedicated to detection and attribution, then condensed to 19 pages in the Technical Summary, and afterward summarized in one section of 2 pages and one figure in the Summary for Policymakers. In this one section, three groups of headlines summarized up to 12 bulleted paragraphs each, containing all the complexities, numbers, and uncertainties. The three headline groups were finally distilled into two overarching headline statements of which the opening statement is the quoted one above. The successive hierarchical approval, from full complexity to super-distillation, eventually permitted the consensus approval of a statement that seemed unapprovable at first. Such headline statements would be most useful for HILL events, but this would first require a robust scientific consensus.

Taken together, a well nuanced assessment of nonlinearities, thresholds and tipping points must be carried out across all three IPCC working groups, i.e., from the physical climate science to ecological tipping and social tipping in decarbonization. In order to be comprehensive, such an assessment would include social tipping points, often considered as "positive" (Tàbara et al. 2018; Lenton et al. 2022), but would also critically address aspects of climate justice (Pereira et al. 2024). This could accelerate scientific understanding, converge into clear communication and help avoid the most dangerous aspects of climate change.

7 Conclusions

Based on scientific evidence HILL events, which include many of the 'traditional' climate tipping points but emphasize their impact rather than the dynamics, are a plausible outcome of continued anthropogenic forcing. Therefore, they must be factored into the development of strategies to adapt to or prevent impacts. Currently, their effect is largely missing in analyses of the widely used IPCC scenarios; and hence, the associated risks are poorly quantified. Moreover, there are significant gaps in our knowledge of the impacts of HILL events at the regional level. This is due to the limited resolution of climate models, the incompleteness of small-scale and coupled processes in the atmosphere, ocean, cryosphere and land surface, as well as limitations in observational data records. Proper consideration of these in a new generation of climate models, along with new long-term Earth Observations that are becoming available through a rapidly expanding space sector, will refine, and in some cases revise, the assessment of the stability of the climate system and the possibility of nonlinear behavior and surprises. Further, evaluation of the impacts of climate change has to date focused largely on the most likely ranges of climate drivers, resulting in incomplete knowledge of the consequences of HILL climate outcomes. These gaps in knowledge could be closed by implementing strong and enhanced research programs focusing on tipping points. A step increase in understanding will come from related projects, e.g., within EC's Horizon 2020 and Horizon Europe programs, continued monitoring efforts in the ocean (ARGO, RAPID and OSNAP, and future campaigns), in the atmosphere (GCOS and GAW, and future campaigns), satellite observations of land surface properties and ocean status, and the development of the next generation of global climate models (Schär et al. 2020; Jungclaus et al. 2022). Targeted global programs under the auspices of WCRP and ESA, which plans work on tipping points in its new climate program "Climate-Space," as well as Future Earth, could significantly boost the scientific understanding of this critical feature of the earth system.

However, a broad consensus on tipping elements, tipping points, HILL events, and climate surprises in general, in short "tipping points (*sensu lato*)," is not yet present in the scientific community. This is due to the absence of a comprehensive and formalized assessment of the peer-reviewed literature in this topic. In the past 20 years the relevant scientific literature has grown rapidly but only a few individual studies have dominated the public discussion and perception on tipping points. It seems to us that the time is mature to commission a focused assessment following a procedure that is time-tested by IPCC. Clearly, a cross-working group Special Report on Tipping Points (*sensu lato*), would provide the most effective process for a comprehensive assessment and the building of a robust scientific consensus. However, at its 60th plenary in January 2024 negotiating the work program, IPCC decided not to prepare more than the special report on cities that was already decided in 2016. In a survey carried out by the IPCC in preparation of that plenary (IPCC-LX/Doc.4), tipping points ranked top of the list for additional IPCC products, calling for a response in the forthcoming scoping process. This offers the opportunity for each working group to scope a dedicated chapter on tipping points (*sensu lato*) and combine the findings and consensus in the synthesis report.

As we have argued, HILL events go far beyond the physical science basis. They are most relevant for impacts and even more in the area of ecosystems and biodiversity. We therefore suggest that a joint IPCC/IPBES assessment could be envisaged as an ambitious goal to be achieved within the next decade. Furthermore, rapid changes and nonlinearities can also occur in the area of climate mitigation, from rapid acceptance of new technologies to political instability derailing agreements; and some tipping points such as Amazon or boreal rapid forest change would have implications on the carbon budgets ultimately affecting mitigation pathways. This cross-working group/cross-panel process could be assisted by a series of workshops, similar to that hosted by ISSI, the International Space Science Institute in Bern, in October 2022. These workshops should be convened jointly by the three working groups of the IPCC and IPBES. For the IPCC this could be an innovative new element for its forthcoming 7th assessment cycle.

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Declarations

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