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EDITORIAL

Earth system resilience and tipping behavior

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Abstract

Anthropogenic climate change, marked by unprecedented extremes, is an immediate concern. The Earth's limited ability to adapt to abrupt changes within our societal timeframe has raised global alarm. Resilience, the capacity to withstand and recover from disturbances, diminishes as disturbances intensify. For avoiding potential catastrophic changes, it is crucial to identify tipping points, where a change in part of a system becomes self-perpetuating beyond some threshold, leading to substantial, widespread, often abrupt and irreversible, impacts. This ERL focus collection has published 27 papers, which contribute novel research findings into the scientific literature in: (1) formulating theories of resilience and tipping points, (2) determining ecological resistance, resilience, and recovery, (3) examining tipping behavior of the Earth system, and (4) identifying social-ecological resilience and tipping points. Some of these results also are useful for policymakers and resource managers in addressing catastrophic disasters as a result of increasingly anthropogenic heating.

1. Introduction

Global warming is not only happening but also accelerating, leading to an increase in extreme events such as wildfires and floods occurring more frequently worldwide. Climate data (ERA5) shows that in the past 85 years (back to 1940), the global temperature measured for September and November of 2023 were the most anomalous warm months of any year (figure 1). The average sea surface temperature for September over 60 °S–60 °N reached 20.92 °C. Due to the specific heat of water being higher, sea surface temperature change is much slower than air temperature change. Warm oceans can therefore lead to prolonged warm weather conditions.

Global warming is a source of extreme weather and climate because hot air can hold more moisture (Yi *et al* 2015). Thus, global warming represents a double-edged sword, as it not only contributes to flooding but also exacerbates the occurrence of widespread wildfires due to enhancing fire weather conditions. On one hand, warming temperatures lead to an atmosphere capable of holding more moisture, increasing the likelihood of extreme precipitation events and flooding. On the other hand, elevated temperatures drive the evaporation of moisture from soils

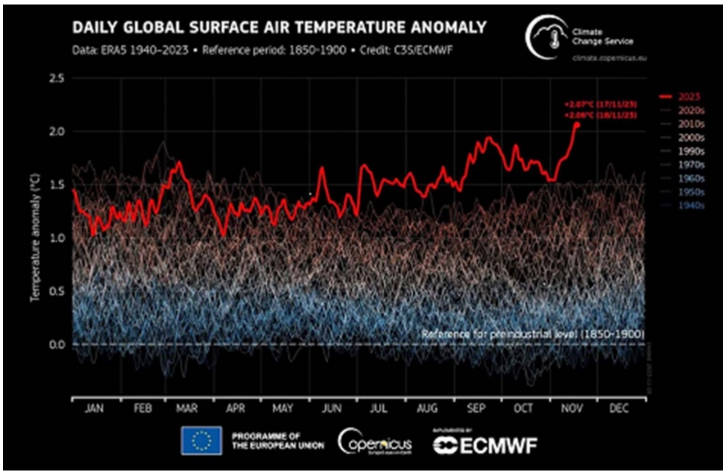

Figure 1. Global daily surface air temperature (°C) from 1 January 1940 to 17 November 2023, plotted as time series for each year. 2023 and 2016 are shown with thick lines shaded in bright red and dark red, respectively. Other years are shown with thin lines and shaded according to the decade, from blue (1940s) to brick red (2020s). The dotted line and grey envelope represent the 1.5 °C threshold above preindustrial level (1850–1900) and its uncertainty. Data source: ERA5. Credit: European Union, Copernicus Sentinel-3/ECMWF imagery (Hersbach *et al* 2018).

and vegetation, making these areas more susceptible to wildfires by reducing soil moisture, increasing surface air temperature and drying out vegetation. Global warming also fosters the conditions for wildfires by promoting droughts, heatwaves, and extreme weather events that further desiccate vegetation and elevate the risk of ignition (Yi *et al* 2022). Wildfires impact ecosystems by releasing substantial amounts of carbon dioxide into the atmosphere, exacerbating global warming in an amplifying feedback loop (Yi *et al* 2015).

One might ask, what are the effects of global warming on the overall stability and resilience of Earth's system? To conceptualise Earth's stability, Rockstrom *et al* (2009) introduced the planetary boundaries framework, which identifies nine critical processes significantly impacted by human activities. The framework aims to establish boundaries that limit human-induced disturbances, aiming to maintain Earth's state akin to the Holocene interglacial period, characterized by stable and warm planetary conditions. Human activities act as additional drivers influencing Earth's system, making the anthroposphere an integral component capable of altering the planet's state. These nine boundaries proposed by Rockstrom *et al* (2009) represent safe operating limits designed to prevent catastrophic environmental changes and to identify thresholds for environmental risks. In a recent study, Richardson *et al* (2023) quantified all nine boundaries for the first time, revealing that six of them have been surpassed (www.stockholmresilience.org/research/planetary-boundaries.html). In the face of catastrophic changes induced by anthropogenic heating, it is vitally important for policy makers and others to know the conditions at which a tipping point could be reached and exceeded. The earth system is highly nonlinear with many positive and negative feedback interactions such that the tipping behavior is complicated. The science of resilience and tipping points have made significant progress in theories (e.g. Dakos and Kéfi 2022) and applications (e.g. Yi and Jackson 2021).

The Focus Issue on 'Earth System Resilience and Tipping Behavior' presents a collection of recent advances in addressing the following questions: (1) How can we identify tipping elements? (2) What are the early-warning signals for system transitions? (3) What are the potential domino effects in tipping cascades leading to abrupt transitions? (4) Does a warming climate increase the risk of triggering tipping points?

This editorial offers a comprehensive overview of the key insights presented in each article within this Focus Issue. The focus is on research questions covering four main aspects: (1) theoretical foundations, (2) ecological resistance, resilience, and recovery, (3) Earth system tipping behavior, and (4) social-ecological resilience and tipping points. The note concludes with a summary and a glimpse into future research challenges.

2. Theory

Despite theoretical advances and a long-history of definitions in the quest of capturing resilience and tipping points, differences still remain. Dakos and Kéfi (2022) revisit the concept of resilience—a concept that has been used across multiple scientific disciplines, each with a different understanding of what resilience means—focusing on the mathematical description of resilience based on the metaphor of a stability landscape. Their review paper synthesizes what is known about resilience metrics and summarizes current approaches for measuring resilience in models and data. In particular, they clarify connections between ecological and engineering resilience metrics in simple but widely used ecological models in an attempt to identify correlations between the metrics in the two areas. Their work does not provide definitive answers but highlights a way of bridging the gap between the metaphors of stability landscapes and the quantification of ecological resilience. Meanwhile, Boers *et al* (2022) reviews the study of tipping elements in the past and the potential of tipping events in the future with a special focus on the Earth system. The authors summarize empirical evidence of abrupt climate transitions in past climates focusing on the glacial–interglacial cycles of the Pleistocene, the Dansgaard–Oeschger events of previous glacial intervals, and the Bond events of the Holocene. They also describe several components of the Earth system that have been proposed as likely candidates of tipping elements in response to ongoing anthropogenic global warming, namely the Greenland and Antarctic ice sheets, the Atlantic Ocean component of the global thermohaline circulation, the Amazon rainforest, and tropical monsoon systems. Despite recent successes in modeling abrupt climate transitions, the authors discuss the lack of a broad consensus in the climate community regarding tipping points and related instabilities, particularly under anthropogenic forcing. They conclude that the next steps should work towards a better exploration of the suspected—or even new—tipping elements in the climate system.

One major concern over present Earth system tipping elements is the risk of tipping cascades leading to domino effects. The study of Klose *et al* (2021) conceptualizes such a risk of cascading tipping events with a simple model. Tipping cascades, possibly exhibited by interacting (sub-)systems, are defined as the sequential occurrence of similar events, but their nature has been described rather roughly in the literature. Using a stylized model of two interacting tipping elements, Klose *et al* systematically identify, characterize and name patterns of cascades into a domino cascade, a two-phase cascade, and a joint cascade. They show that the potential for intervention and anticipation by common early warning indicators based on critical slowing down depends on the type of cascade, and discuss these implications for the resilience of the Earth system, as well as the need for future research. Along similar lines, Bastiaansen *et al* (2022) analyzes the dynamics of tipping in spatially extended systems, which are spatially heterogeneous. Using conceptual models, the authors illustrate the presence of additional coexistence stable equilibrium states, where part of the domain may be in one state and the other part of the domain in another state. Therefore, changing some external forcing past a critical threshold may not cause the full system to undergo tipping, but instead fragmented tipping may occur where only part of the domain experiences tipping. The spatial interfaces between tropical forests and savannah, different types of clouds, sea ice and water, and algae blooms are some examples of where these coexistence states can be observed in the real world.

A considerable effort is still dedicated to refining and developing resilience indicators. Prettyman *et al* (2022) develop the theoretical support for the use of the power spectrum (PS) scaling exponent as an indicator of critical slowing down and proxy for loss of resilience and an approach to a tipping point. The authors justify the use of the PS indicator analytically, assess the usefulness of estimating the PS scaling exponent in a tipping point context, and show that the method is robust against trends and oscillations in the time series. Thus, making it a good candidate for studying resilience of systems with periodic oscillations which are observed in ecology and geophysics. Similarly, Clarke *et al* (2023) propose an indicator utilizing the PS to detect critical slowing down, which is specifically applicable for systems not subject to additive white noise. Commonly used indicators for critical slowing down, such as increasing autocorrelation and variance, implicitly assume a stationary white noise forcing and a clear separation between forced trends and variability. However, in many applications this is not the case, such as the climate, which for example is typically forced by time-correlated processes. The authors propose ROSA, the method of considering the ratio of spectra of a state variable relative to its forcing. A conceptual model with different types of noise is used to demonstrate the applicability of ROSA compared to using the autocorrelation and variance. Furthermore, ROSA is shown to successfully identify a higher proportion, than the conventional early-warning signals, of abrupt Amazon dieback events seen in multiple state-of-the-art Earth System Models. On the other hand, more specific indicators can also prove useful in the quest of quantifying resilience. Zampieri *et al* (2021) introduce an Annual Production Resilience Indicator derived from the gross primary productivity to analyze the impact on vegetation under global warming. Using the latest generation of climate models, the authors explore if vegetation gains or loses resilience under different emission scenarios. For the lower emission scenarios, the size of regions where vegetation gains resilience far outweighs the size of regions that are predicted to lose resilience in the future. However, in the high emissions scenario the results are dramatically reversed. In particular, Brazil and consequently the Amazon rainforest is expected to be at high risk of suffering multiple years of anomalously low gross primary production.

3. Ecological resistance, resilience, and recovery

Complementing the theoretical approaches with applications to Earth system science, a number of contributions applied resilience indicators to ecological problems. Rocha (2022) studies the resilience of primary productivity in terrestrial and marine ecosystems globally by using state-of-the-art Earth system observations. He shows that ∼30% of the terrestrial biosphere and ∼25% of the marine ecosystems are showing symptoms of resilience loss. Besides the common critical slowing down indicators, he also applied indicators for critical speeding up and the fractal dimension to account for the possibility of stochastically induced transitions. An innovation of his analysis is the use of machine learning approaches and feature engineering to investigate the role of drivers in the early warnings and the time scale at which they are relevant. Similarly, Luo *et al* (2022) investigate the effect of droughts in forest recovery in China. They depart from the assumption that old forests can be more resilient to extreme events, and wonder which forests are more at risk given that the intensity and frequency of droughts is expected to increase. They find a legacy effect that lasts up to 3 years, and confirm that -as expected- forest conditions such as stock volume and forest type influence the path to recovery after droughts. For China, natural coniferous forests with high stock volumes are particularly vulnerable to droughts, which identifies opportunities for management. On a similar vein, Oddi *et al* (2022) investigate the forest transition from carbon sink to source in the Alps. Using a variety of observational datasets, the authors studied the role of the 2015 and 2017 dry spells in the region. They do not find significant evidence on the gas exchange data. However, they do report reductions of plant growth during the 2017 period. Their results suggest that dynamics of carbon sink and source can be independent.

Several contributions to the special issue developed new methods for particular problems or applications, either for particular geographies or for engaging with specific actors. For example, Lade *et al* (2022) develop an impact metric that captures the interaction between climate, the water cycle, and land use change. Their metric builds upon modeling work on the interaction of these three systems and explores how it can be used in the context of setting targets for companies and cities. They find, for example, that accounting for climate-water-land use interactions duplicate the impacts of deforestation in tropical forests. The metric development is an important step in involving companies or cities with concrete actions that they can take responsibility to avoid local to regional tipping points. Another contribution with a practical lessons for managing tipping point risks is Xu *et al* (2022) who investigate the role of canopy size on the resilience of forest to droughts in Southwestern China. They apply linear regressions and random forest to vegetation index datasets before and after the 2010 drought. They find that taller forest drought resistance has declined, and recommend taking into consideration forest structure when managing these ecosystems. Similarly, Ribeiro *et al* (2022) quantify the relationship between climate and fire propensity in two regions of the Brazilian Amazon. With intensifying climate change fire intensity is likely to increase, but the effect is relatively unknown. The work of Ribeiro *et al* contributes to answering this question by studying the features that are predictive of fires (e.g. air dryness, low precipitation). They find that fire risk has already increased 5%–10% and will continue to increase under future climate change scenarios. If warming is limited to a 1.5 C scenario, the risk will be constrained to 14%, but can go higher if climate change is unchecked.

4. Tipping behavior of the Earth system

The concept of tipping points, critical thresholds beyond which a system undergoes rapid and irreversible changes, has gained considerable attention in the study of the Earth system. In a recent study by Lux *et al* (2022), the impact of parametric uncertainty on tipping points of the Atlantic meridional overturning circulation (AMOC) was examined using a Bayesian inversion technique. This novel approach significantly reduces the uncertainty in model parameters compared to previous literature, providing a more constrained understanding of AMOC tipping points. One of the key contributions of this study is the extension of classical tipping diagrams to include probabilistic bifurcation curves. By inferring the distribution of model parameters, Lux *et al* showcase the uncertain locations of tipping points along these curves. This probabilistic framework allows for a more nuanced exploration of tipping behavior and facilitates the identification of regions with higher probabilities of tipping. Looking ahead, future research directions in the field of Earth system resilience and tipping behavior involve applying similar methodologies to other tipping elements. Lux *et al* suggest that if suitable paleo-proxy time series are available, the Bayesian inversion technique can be applied to other components of the Earth system. This expands the scope of understanding tipping points beyond the AMOC, offering insights into the likelihoods and positions of tipping points even in cases where historical data does not capture tipping events. However, several open questions remain. First, the availability of long enough paleo-proxy or observed time series (>1400 years) is crucial to apply the framework effectively. Furthermore, there is a need to assess the representativeness of the simple framework in capturing the complexities of the real world. Additionally, while modeling a larger number of uncertain parameters is desirable, the efficiency of computational cost requires further exploration.

The dynamics of sea ice and its interaction with Antarctic ice shelves is considered as another important tipping point in the Earth system. In a pioneering study, Teder *et al* (2022) employ innovative algorithms applied to daily satellite sea ice concentration data to analyze sea ice-free corridors connected to Antarctic ice shelves and the potential impact of large swell on these corridors. The key contribution of this study lies in providing the first comprehensive analysis of sea ice-free corridors and the availability of large swell that can influence the ice shelves. By tracking trends in corridor properties and sea ice extent, Teder *et al* establish a relationship and highlight the potential pathways through which large swell can reach and affect Antarctic ice shelves. To further advance our knowledge in this field, future research should focus on testing the corridor properties and available swell by utilizing different sea ice concentration and spectral wave data. By exploring alternative datasets, researchers could validate and refine the algorithms used in this study. Furthermore, the potential application of these algorithms in climate model studies can provide valuable projections of corridors and available swell, offering insights into future scenarios.

The Green Sahara during the early to mid-Holocene represents a fascinating case of an abrupt climate change event that has already happened in the past. Hopcroft and Valdes (2022) employ a coupled global climate model (HadCM3) to investigate the tipping points associated with the 'Greening' and subsequent desertification of the Sahara. A key contribution of this research is the demonstration that the climate model can reproduce abrupt climate changes comparable to real paleo-climate events. By focusing on the processes related to the Green Sahara, Hopcroft and Valdes shed light on the dynamics behind this significant climatic transition. Future research efforts should aim to refine the understanding of the response in the eastern regions of Africa and evaluate the vegetation feedback in more comprehensive models. High-resolution paleoclimate records are crucial for constraining the seasonality and decadal-to-centennial variability over several centuries, thereby improving the evaluation of climate models. However, a major challenge lies in evaluating the realism of the simulated tipping thresholds due to the lack of sufficient paleo-climate data. Acquiring more robust and extensive paleoclimate data will be vital for validating the simulated system thresholds and enhancing our understanding of tipping points in the Green Sahara.

Understanding the relationship between global warming and extreme events is crucial for assessing the impacts of climate change and potential environmental and social tipping points. Diffenbaugh and Davenport (2021) investigate whether certain extreme events would have been impossible in the absence of global warming. Using a large single-model ensemble of climate simulations, the study sheds light on the influence of historical greenhouse gas emissions and other non-greenhouse gas anthropogenic forcings on the emergence of extreme events. One of the key contributions is the demonstration that the hottest possible events in the current climate may have been nearly impossible without historical greenhouse gas emissions. However, the study also highlights that other non-greenhouse gas anthropogenic forcings (like aerosols and anthropogenic land-use changes) have muted the emergence of previously impossible events, emphasizing the complexity of the climate system. To expand on these findings, future research should explore additional large single-model ensemble experiments to enhance our understanding of the role of different climate models. Investigating the role of ocean variability in shaping the emergence of previously impossible temperature thresholds is an important area for further investigation, which could involve analyzing atmospheric initial-condition large ensembles and benchmark simulations with prescribed ocean conditions. While this study primarily focuses on temperature-related extremes, future research efforts can extend the methodology to other types of extreme events. However, the emergence of previously impossible thresholds and the underlying physical ingredients would require in-depth analysis specific to each event type. Several open questions remain, such as the influence of climate model biases related to internal climate variability and external climate forcing on the calculation of impossible event thresholds. Robustly isolating the influence of individual human forcings on the most extreme hot events in different regions necessitates large single-model ensembles.

Lucarini *et al* (2023) focus on a particular heatwave event, the 2021 Western North America summer heatwave (WNAHW), that captured global attention due to its unprecedented severity. They employ a methodological framework based on large deviation theory and simulations from a state-of-the-art Earth system model to investigate the typicality of this extreme event. Their findings reveal that while the event is rare and unusual in the overall statistics of weather variability, it becomes typical when considering specific constraints, such as the occurrence of a large and persistent summer temperature anomaly at a specific location. A significant contribution of this research is the demonstration that the 2021 WNAHW can be seen as an unlikely manifestation of climate variability, yet its probability of occurrence is greatly amplified by ongoing climate change. This understanding provides insights into the complex interplay between natural climate variability and anthropogenic influences. Future research directions should explore whether similar results can be obtained using other climate models within the CMIP6 framework. It is important to note that Earth system models tend to globally underestimate the duration, intensity, and frequency of heatwaves. Additionally, further investigations are needed to characterize the features of the studied event, such as the separate contributions of dynamical and thermodynamical factors, preconditioning effects, and the role of teleconnections. Complementing the current study, an approach that examines atmospheric circulation compounds, as described in Faranda *et al* (2021), could provide a deeper understanding of the dynamical properties responsible for exacerbating dry conditions in the region. By combining multiple approaches, researchers can unravel the complex mechanisms driving extreme events and their interactions with the broader climate system.

The sea surface temperature (SST)—atmospheric convection relationship in the Indo-Pacific warm pool (IPWP) is non-monotonic, with studies indicating intensified convection up to a certain SST threshold, beyond which the relationship breaks down. Kim *et al* (2023) investigate shifts in the SST-precipitation relationship and the SST threshold for deep convection under a warming climate in the IPWP, addressing the gaps in understanding the non-continuous increase in precipitation with SST warming.

5. Social-ecological resilience and tipping points

Special issue contributions focusing on resilience and tipping points in social-ecological systems addressed a number of different themes, especially current modeling challenges and ways to advance modeling efforts, the value of a long-time perspective, including the use of palaeoenvironmental data, adaptation to climate change risks, and the concept of social metabolism.

In their paper, Franzke *et al* (2022) emphasize the urgent need for modeling the multiple interactions between human societies and Earth systems that create tipping dynamics and cascades. This is an inter- and transdisciplinary challenge of knowledge development that can support decision making and governance in response to tipping threats. The authors review different disciplinary perspectives of tipping dynamics (e.g. bifurcations, phase transitions, social change processes), and discuss cascading effects and telecoupling. Based on these discussions, Franzke *et al* argue that new integrated climate economy models are needed that are capable of reflecting the interactions between social and Earth systems to better understand and assess tipping risks. They discuss a range of challenges to advance such modeling efforts, both regarding biophysical and social system dynamics. Summarizing critiques of the damage functions in existing Integrated Assessment Models (IAMs), the authors caution that modeling efforts of future impacts of tipping points in the Earth system will be challenging due to lack of observations. They make the case that urgent efforts are needed to tackle these obstacles in the development of Human-Earth system models.

In response to the urgent need highlighted by Franzke *et al* (2022) for integrated modeling of tipping dynamics and cascades within social-ecological systems, further contributions by researchers like Tamberg *et al* (2022) have also delved into modeling challenges pertinent to resilience, particularly focusing on climate tipping points. Reflecting the arguments made by Dakos and Kéfi (2022), the authors are concerned with the persistence of multiple definitions and understandings of resilience, which can undermine modeling efforts and impede communication across research programs. To alleviate these problems, Tamberg *et al* (2022) provide guidelines for resilience modelers that can work in very diverse modeling contexts. Their guideline consists of four questions: (1) Resilience of what?, (2) Resilience regarding what?, (3) Resilience against what?, and (4) Resilience how? The answers to these questions (the system, the 'sustainant', the adverse influence, and the response options) enable the 'translation' of models and model results across domains, potentially advancing systematic knowledge development through comparability and synthesis. The authors illustrate the power of their guidelines with an application to modeling the resilience of the Amazon rainforest to dieback.

Adding to the discourse on modeling resilience within complex systems, Anderies *et al* (2023) contribute a third paper focusing on the long-term resilience of the World-Earth System (WES). Bringing together resilience theory and world systems theory, they develop a simplified two-region model with linkages between the natural and social system components. The objective of this model is to provide an extensible framework that balances complexity and accessibility to enable deeper understanding of resilience dynamics at large scales, especially the risk of tipping points. Based on the assumption that the world is currently in a transitional (i.e, unstable) state, Anderies *et al* focus on the availability of transition pathways towards future sustainable states (safe and just operating space) of the WES. Their multi-century model demonstrates the importance of social variables for pathway resilience, especially perceptions of fairness and inequality between the modeled regions.

Expanding upon the examination of long-term global land-use dynamics, Taylor and Rising (2021) undertake a comprehensive analysis spanning from 1780 to 2010. They found evidence for a tipping point in land-use intensification tied to income levels (economic development). Treating land-use and the economy as a coupled social-environmental system, the analysis reveals income levels as a key driver of complex change dynamics, strengthening arguments that economic development will be key driver of land-use change in the future.

In alignment with the call for a long-term perspective on resilience analysis, Allen *et al* (2022) underscore the significance of considering historical and paleo-environmental data. They discuss the utility of paleo-environmental and historical data not only for research on resilience and sustainability, but decision making related to the sustainable development goals (SDGs) and climate change policy. They argue that archival records emphasize themes that are relevant to the SDGs, including diversity, inclusion, innovation and connectivity. Hence, Allen *et al* make the case that a long-term historical perspective is valuable when considering what social-ecological resilience means and how it can be achieved, i.e. drawing on the 'long-term memory encoded in historical, archaeological and related "paleo-data"'. The authors also point out issues with SDG baselines and indicators that are rooted in too short time perspectives and corresponding misunderstandings of ecosystems variability.

In their study, Raymond *et al* (2022) underscore the critical importance of considering the compounding effects of heat and precipitation extremes when examining tipping points in socio-environmental systems. By utilizing a large single model ensemble, they quantitatively demonstrate the increasing spatiotemporal proximity of such compound events in a warming world. A key contribution of this research is the revelation that concurrent heat and drought conditions leading to simultaneous crop failures become more prevalent across multiple breadbasket regions. The study also indicates an increased likelihood of interannual wet-dry oscillations in subtropical regions. These compound events, with their potential high-end impacts, underscore the potential for crossing tipping points in socio-environmental systems, thus amplifying the social, political, and economic crises at the regional scale. Future research endeavors should aim to incorporate compounding interactions, both from physical and societal perspectives, in extreme event analysis and projections. While the thermodynamic effects of global-mean warming dominate the changes in extreme heat and precipitation, regionally varying nonlinear contributions may vary substantially across different models and regional aggregations. It is essential to consider these regional nuances and explore their model dependencies. Future research should also consider other multivariate events, such as storms or humid heat, to develop comprehensive risk assessments. Furthermore, predicting periods with an increased likelihood of compound events at sub-seasonal and longer timescales, particularly for heat and precipitation/drought, could be possible through the use of multi-member ensemble prediction systems. While using a large single model ensemble, such as the Max Planck Institute Grand Ensemble (MPI-GE), uncertainties related to internal climate variability can be estimated, but it relies on the timing of extremes in a single model. A comprehensive uncertainty analysis should encompass multiple models, parameterizations, and sensitivity tests to capture a broader range of possibilities and provide a more comprehensive understanding of compound climate extremes.

In their comprehensive review, Hagen *et al* (2022) meticulously analyze climate change risks and the corresponding adaptation potential in Central and South America. They differentiate eight topical risk clusters, including food and water insecurity, and tipping point risks in the Amazon, arguing that climate risks in all of these eight could become severe during this century. Risks are heterogenous throughout the region, which is characterized by low adaptive capacity. The insights provided by Hagen *et al* (2022) can help guide future adaptation policies for Central and South America, especially efforts at strengthening adaptive capacity.

Considering the specific context of small island developing states, Singh *et al* (2022) analyze the potential for tipping points on small islands using the framework of socio-metabolic risk (SMR)—a subset of systemic risk. The social-metabolic risk framework applied to social-ecological systems refers to the availability of critical resources, the integrity of material circulation, and the distribution of products and services, making SMR a type of social-ecological coupling. The sectoral focus of the analysis (water, waste, infrastructure) allows the authors to identify strategies for fostering adaptation and resilience, e.g. resource localization and increases in resource circularity rates. Like other papers in this category, it makes a conceptual contribution and uses an illustrative case study in the absence of data for all relevant variables.

6. Concluding remarks and outlook

Here, we highlight the reliance on extensive numerical simulation models to understand the cascading tipping dynamics of the climate system or the stability of social-ecological systems. Within these systems, the stability of one element is often intertwined with another through complex multiple feedback interactions. The nature of feedback is crucial for system stability: positive feedbacks act as driving forces for perturbation growth, while negative feedbacks act as driving forces for perturbation decay. The resilience and tipping behavior of a system are determined by the competition and cooperation between positive and negative feedback loops included in the models (Yi and Jackson 2021). However, the current generation of climate-economy models generally do not take these feedbacks into account

(Franzke et al 2022). Anderies et al (2023) pointed out that existing Earth system models are typically too complex, lack transparency, and are difficult to access. Meanwhile, more accessible dynamic models used for resilience analysis are too simple to capture the key feedback interactions of social-ecological systems. Anderies et al (2023) proposed a modeling framework for World-Earth System resilience. The idea is to use the ball-in-cup heuristic model as a principle to merge ideas from Earth system models and social-economic theory and capture feedbacks between global biophysical and global social and economic processes that co-determine development pathways, World Earth Resilience, and tipping points. While we may be able to describe physical and ecosystem tipping points with Earth System models and mathematical equations as derived in the previous section, the complexity of cascading physical and social tipping precludes a 'one-fits-all' modeling approach and ask for novel research approaches embracing qualitative and quantitative information within a systemic risk framing (Sillmann et al 2021).

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