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COMMENTARY

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Key Points:

- Climate science needs to adjust to account systematically for low-likelihood, high-impact risks and comprehensive pathway interactions
- Achieving this requires new strategies; several are outlined here, including increased model coupling and scenario exploration
- Success will require collaboration between physical sciences and other disciplines

Correspondence to:

S. C. Sherwood,
s.sherwood@unsw.edu.au

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Author Contributions:











Conceptualization: G. Hegerl, P. Braconnot, P. Friedlingstein, H. Goelzer, N. R. P. Harris, E. Holland, H. Kim, M. Mitchell, T. Naish, P. Nobre, B. L. Otto-Bliesner, K. A. Reed, J. Renwick

Writing – original draft: G. Hegerl, P. Braconnot, P. Friedlingstein, H. Goelzer, N. R. P. Harris, E. Holland, H. Kim, M. Mitchell, T. Naish, P. Nobre, B. L. Otto-Bliesner, K. A. Reed, J. Renwick, N. P. M. van der Wel

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Uncertain Pathways to a Future Safe Climate

S. C. Sherwood¹ , G. Hegerl² , P. Braconnot³, P. Friedlingstein^{4,5}, H. Goelzer⁶ , N. R. P. Harris⁷ , E. Holland⁸, H. Kim^{9,10,11} , M. Mitchell¹² , T. Naish¹³ , P. Nobre¹⁴, B. L. Otto-Bliesner¹⁵ , K. A. Reed¹⁶ , J. Renwick¹⁷ , and N. P. M. van der Wel¹⁸

¹Climate Change Research Centre, UNSW Sydney, Sydney, NSW, Australia, ²School of Geosciences, the University of Edinburgh, Edinburgh, UK, ³Laboratoire des sciences du climat et de l'Environnement (LSCE-IPSL), Gif-sur-Yvette cedex, France, ⁴Faculty of Environment, Science and Economy, University of Exeter, Exeter, UK, ⁵Laboratoire de Météorologie Dynamique, Institut Pierre-Simon Laplace, CNRS, École Normale Supérieure, Université PSL, Paris, France, ⁶NORCE Norwegian Research Centre, Bjerknes Centre for Climate Research, Bergen, Norway, ⁷Cranfield Environment Centre, Cranfield University, Cranfield, UK, ⁸Institute for Strategy, Resilience and Security, University College London, London, UK, ⁹Moon Soul Graduate School of Future Strategy, Korea Advanced Institute of Science and Technology, Daejeon, Korea, ¹⁰Department of Civil and Environmental Engineering, Korea Advanced Institute of Science and Technology, Daejeon, Korea, ¹¹Institute of Industrial Science, The University of Tokyo, Tokyo, Japan, ¹²Virginia Institute of Marine Science, William & Mary, Gloucester Point, VA, USA, ¹³Antarctic Research Centre, Victoria University of Wellington | Te Herenga Waka PO Box 600, Wellington, New Zealand, ¹⁴National Institute for Space Research - INPE, São José dos Campos, Brazil, ¹⁵Climate and Global Dynamics Laboratory, National Center for Atmospheric Research, Boulder, CO, USA, ¹⁶School of Marine and Atmospheric Sciences, Stony Brook University, Stony Brook, NY, USA, ¹⁷School of Geography, Environment and Earth Sciences, Victoria University of Wellington, Wellington, New Zealand, ¹⁸World Climate Research Programme Secretariat and WMO, Geneva, Switzerland

Abstract Global climate change is often thought of as a steady and approximately predictable physical response to increasing forcings, which then requires commensurate adaptation. But adaptation has practical, cultural and biological limits, and climate change may pose unanticipated global hazards, sudden changes or other surprises—as may societal adaptation and mitigation responses. These poorly known factors could substantially affect the urgency of mitigation as well as adaptation decisions. We outline a strategy for better accommodating these challenges by making climate science more integrative, in order to identify and quantify known and novel physical risks including those arising from interactions with ecosystems and society. We need to do this even—or especially—when they are highly uncertain, and to explore risks and opportunities associated with mitigation and adaptation responses by engaging across disciplines. We argue that upcoming climate assessments need to be more risk-aware, and suggest ways of achieving this. These strategies improve the chances of anticipating potential surprises and identifying and communicating “safe landing” pathways that meet UN Sustainable Development Goals and guide humanity toward a better future.

Plain Language Summary Global risks may arise from many places, not all of which are being considered at the moment in the usual projections of future climate. Some risks are being overlooked, sometimes by most of the physical science community itself, or else by others who need information about future climate. We think physical climate sciences can do a lot to remedy this situation by looking more systematically at a broader array of risks and possible futures, narrowing them down, and collaboratively seeking better ways to express them. In this perspective we argue why this is important and explain a few ways it can be done.

1. Introduction

A common metaphor for global warming is that rather than causing disasters directly, it “loads the dice,” changing the probability of high-impact weather events such as extreme rains, droughts and storm surges (NAS, 2016). But increasingly events occur that appear unprecedented, even previously considered virtually impossible—we are playing with a new set of dice. Australian bushfires more intense than any since European settlement and Canadian ones setting new burned-area records, record downpours in China and Libya, unprecedented Amazon droughts completely drying the Negro and Solimoes rivers, and other extreme events have produced shocking headlines and countless human tragedies. Can climate science anticipate such extraordinary events and their consequences? In some cases it has: for example, unprecedented heat waves and heavy rains have been predicted (e.g., Fischer et al., 2021) and are now evident on several continents. However, consequences such as record-breaking fires and floods and their associated fatality and damage tolls have often come as surprises. It is

unclear where adaptation will reach limits, such as those already faced by coral atoll communities (IPCC, 2019), especially as events continue to recur more frequently.

Climate and environmental change may bring global-scale changes that have not been previously experienced. While the geologic record reveals possibilities such as rapid ice sheet loss or different ocean overturning regimes, some changes are hard to anticipate. The emergence of the “ozone hole” in the 1980's, for example, was unexpected even though scientists had foreseen gradual thinning of the ozone layer by CFC gases (Solomon, 1999). Moreover, if bromine-based compounds had been used and escaped into the atmosphere rather than chlorine-based ones, the consequences for humanity would have been cataclysmic (Crutzen, 1996). It would be naive to assume that greenhouse gas buildup to levels unprecedented in at least 2.7 million years, and warming unprecedented in at least the last 2000 years (IPCC, 2021) and probably much longer, would not also bring unexpected challenges.

One concern is climate “tipping points” or regime shifts where regional or global systems could change rapidly and perhaps irreversibly on human timescales (Solomon et al., 2009) to an unfamiliar state if the global temperature crosses some threshold (Armstrong McKay et al., 2022). These include dieback of the Amazon or other forests (Wang et al., 2023), shutdown of the Atlantic thermohaline circulation (Weijer et al., 2019), changes in ocean chemistry that affect marine life (e.g., Heinze et al., 2021), ice shelf collapse or rapid ice sheet melt (Pattyn et al., 2018), and many other risks. Concern about such climate surprises among the science community has been increasing since the first Intergovernmental Panel on Climate Change (IPCC) assessment report (Lenton et al., 2019). These alarming possibilities embody a broader problem: how can society be sure that it is adequately prepared, not just for what is expected, but for “*high-impact, low-likelihood*” (HILL) occurrences a warming planet might throw at us (see Wood et al., 2023)? Are we missing risks by working in silos rather than considering risks of the coupled and highly interactive earth/human system?

Adding to the challenge, climate change is not happening in isolation but is part of a broader spectrum of human influences on the environment. In addition to climate change, native forests are affected by deforestation and fires; groundwater by irrigation and other water use; coastal erosion by development; ice retreat by air pollutants that darken the ice surface; disease propagation by human travel; and species extinctions by habitat destruction (IPBES, 2019). Future changes in human well-being, as encapsulated by the United Nations Sustainable Development Goals (SDGs, <https://sdgs.un.org/2030agenda>), will therefore depend on how (or whether) human and natural systems can adapt to many stressors including the new climate. These changes will have widely varying impacts across diverse communities around the globe, and efforts to mitigate one problem will rebound on other problems. Issues of equity and multi-dimensional approaches to vulnerability underpin decades of negotiations leading to the operationalization of a loss and damage framework at COP28 in 2023. Limits to the adaptability to climate change, or substantial unexpected costs, would clearly bear on the urgency of mitigation.

Is climate science up to the challenge of assessing this uncertain future and preparing decision makers at all levels? This paper discusses two overarching and challenging questions that climate science must now strive to answer. First: *what potential high-impact climate hazards, surprises or irreversible changes should society be genuinely worried about and how can the associated risks be usefully quantified and communicated?* And second: *what do achievable, internally consistent and safe pathways to a future climate look like that also meet broader human needs, and how can we identify them?* These questions are interrelated, and answering them will require the climate science community to work across disciplines to identify risks arising within the entire earth/human system, and to connect with all aspects of society.

2. An Interdisciplinary Challenge

These concerns are not new. Economists have long noted for example, that the upper tail on the probability distribution of climate sensitivity dominates risk rather than the central value, due to the highly nonlinear increase of damages with warming (Ackerman & Stanton, 2012; Nordhaus, 2011; Weitzman, 2009, 2012). Observers and climate scientists have more recently highlighted “missing risks” of climate change that are poorly understood and hard to quantify; the importance of including them somehow in economic evaluations and decision making processes (Calel et al., 2020; Rising et al., 2022; Simpson et al., 2021); and the need for a risk-based framing for climate change (Sutton, 2019). Frameworks such as “planetary boundaries” (Rockström et al., 2009) have been proposed to cope with the multiple problem dimensions and needs (including for multiple communities) encapsulated in UN SDGs particularly relating to climate, water and food security and protection of biodiversity,

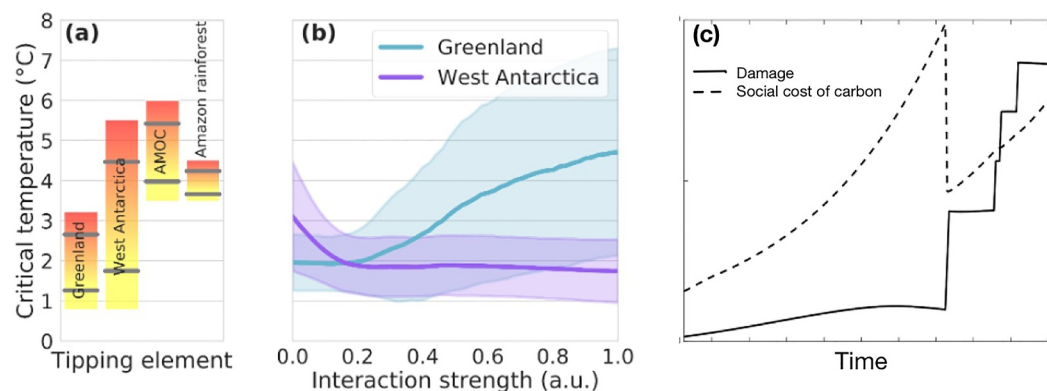


Figure 1. Transition thresholds for important geophysical system transitions remain highly uncertain. (a) Warming thresholds estimated for a few isolated tipping point transitions. (b) If the two systems interact strongly (higher values of interaction strength), most such interactions are expected to reduce tipping thresholds such as shown for WAIS although a collapse of the WAIS may increase the threshold for Greenland depending on relative strengths of feedbacks on Greenland. (c) The threat of uncertain tipping point occurrence and damage (solid line) increases benefits of early mitigation (dashed line) in economic cost-benefit model due to the risk premium brought by tipping uncertainty. Panels (a, b) from Wunderling et al. (2021), (c) from Cai and Lontzek (2019).

yet still struggle with the inter-relatedness of individual boundaries. “Storylines” of possible futures are a simple hence useful way of dealing with deep uncertainty (Shepherd et al., 2018), and expert elicitation can make progress on problems that are hard to quantify (Dessai et al., 2018).

Yet in spite of these tools and awareness, assessment of climate risk has been limited by a traditional disciplinary focus on incomplete modeling tools and “linear thinking” rather than thinking more broadly about rare events and possibly nonlinear and cascading consequences and network effects. The most recent IPCC report, while acknowledging a few high-profile tail risks, still focuses on likely outcomes, and frames them as deviations from today's climate while thresholds might be crossed that lead to very different impacts. New emphases and transdisciplinary tools are needed.

Tipping points are one example of where science needs to focus. A recent overview (Armstrong McKay et al., 2022) gives global tipping temperatures for a range of systems, identifying 1.5°C above preindustrial as a potential trigger for multiple tipping points, but a look behind the best estimates reveals wide ranges and considerable uncertainty, as also illustrated in the “burning embers” diagrams of IPCC (IPCC, 2022). It has been suggested that multiple system transitions could interact leading to “tipping cascades” where one event increases the likelihood of others (Wunderling et al., 2021; Figure 1b) although potential mechanisms need much more careful exploration. While risk-analysis frameworks ideally start with hazard probabilities and damages, climate science currently struggles to quantify either of these in a useful way, which leaves room for risk perception to vary between unhelpful extremes of complacency and fatalism (see Davidson & Kemp, 2023; Figueres, 2024).

Most of the science gaps involve coupling between physical climate and subsystems such as vegetation, ocean biochemistry, ice sheets, or human responses that are typically treated individually or coupled only rudimentarily in present modeling tools. A sobering example of the problem is the US “Dust Bowl” of the 1930's, where rapid land cover change contributed to unprecedented temperature extremes; these lay well outside the envelope of retrospective climate-model predictions (Figure 2) because models lacked land-use feedbacks and realistic land cover forcing. Such model errors, further suggested by the failure to explain other climate variations such as the mid-Holocene “green Sahara” (e.g., Hoppert & Valdes, 2021) and increases during recent decades in Pacific trade winds and surface temperature gradients (Kajtar et al., 2018), compromise prediction of possible tipping of Boreal and tropical forests (see Wang et al., 2023), bushfire risk, rapid ice sheet and sea level change and many others. These concerns add to more traditional ones about processes like mixing, clouds and convection that affect HILLS such as extreme climate sensitivity or atmosphere/ocean circulation shifts (Bjorndal et al., 2020; Carlson & Caballero, 2016). In general, multi-model ensembles therefore cannot be relied upon to fully characterize uncertainty and physical risk as often assumed, let alone outcomes of unprecedented situations or changes that involve strong coupling between Earth and Human system components.

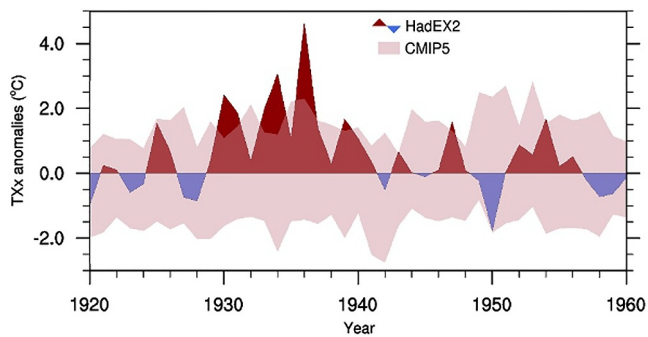


Figure 2. Dust bowl extreme temperature anomalies exceeded worst model hindcasts. 90% range of CMIP5 model historical simulations shown by light shading, observed values shown by dark red/blue shading. The extreme high values are likely due to land surface changes not represented in the models. Adapted from Cowan et al. (2020).

The extreme Dust Bowl drought, together with dust and crop loss, led to mass human migration; similar coupling has affected Lake Chad (Franzke et al., 2022) and may lead to human conflicts (IMCCS, 2021). This highlights the role of human responses, an even more challenging modeling problem. They can exhibit tipping behavior apparently analogous to that in physical systems (Winkelmann et al., 2022), and can provide positive or negative feedbacks on climate change and mitigation through adaptation behavior. Modeling of these interactions remains in its infancy even compared to Earth System Models, but studies are beginning to project global-mean economy-climate interactions (e.g., Moore et al., 2022; Ramanathan et al., 2022).

In spite of the expected coupling across climate, biosphere and society, current endeavors to identify future impacts and possible societal pathways are largely independent, even though strong coupling is expected among impacts, mitigations, and adaptations for climate change and other UN SDGs. For example, scenarios for IPCC reports begin with exogenous assumptions about future trends in populations, economies and technologies, though these

will be influenced by climate change. In IPCC (2021), Shared Socioeconomic Pathways (SSPs, Riahi et al., 2017), defined by five narratives about future global directions concerning energy use, population, etc., were loosely constrained to fit with five warming trajectories set by a separate and backward-looking analysis based on the concept of a carbon budget of allowable GHG emissions for a given warming target. The fact that the uncertainties associated with the underlying, detailed assumptions were not well quantified made it impossible to properly assess the risks or internal consistency of each scenario. If, for example, a climate mitigation strategy such as biofuel development leads to increased pressure on a land or water resource, unintended consequences may affect the ability to mitigate climate change or reach other UN SDGs. Such an approach may also reduce the capacity to address biodiversity loss.

Understanding extreme events and limits to biophysical and societal adaptation is crucial in assessing whether a given climate trajectory is safe or dangerous, and impacts can be hard to quantify based on today's observations as future adaptations may differ from those today (see IPCC, 2022). Future climate damages are usually estimated by extrapolation from the impact of observed natural climate variations. In some cases, the inferred damages would be muted by adaptations on longer time scales, for example, crop substitution (White et al., 2011). But in other cases, the opposite is true, for example, human heat stress where adaptations implicit in the empirical data would eventually reach biophysical limits and fail with sufficient warming (Sherwood & Huber, 2010) leading to a dramatic escalation of impacts. Plants including crops (Bokszczanin & Fragkostefanakis, 2013), wildlife (Ratnayake et al., 2019) and marine species can all reach temperature or carbon-dioxide tolerance limits (Heinze et al., 2021). This requires accurately calibrated modeling rather than just precision in simulating changes over time. Moreover, the breaching of tolerance thresholds and hence significant impacts typically result from very rare, unprecedented or compound events (Kotz et al., 2022; Zscheischler et al., 2018) whereas most climate studies report on relatively common events such as annual maxima (e.g., Kim et al., 2020).

The above discussion highlights where climate science needs to focus on new research questions or techniques, and on better knowledge integration. First, the substantial limitations in our current physical modeling and scenario development need to be better recognized, reduced if possible, and supplemented with other methods to cope with system coupling and deep uncertainty. We also need more attention to absolute thresholds or limits to adaptation and their interaction with extremes and compounding risks. Uncertainties around HILLs of all kinds need to be understood and, if possible, reduced. Finally, all of the above issues need to be supported by trans-disciplinary approaches and better communication of uncertainty as part of climate information.

3. A Strategy for Integrative Climate Science

We now present a strategic program of more integrative climate science to address these challenges. Many of these approaches, even if not new, are not yet widely adopted; we argue that expanding them would lead to greater progress toward answering the questions posed in the Introduction and improve the decision-relevance of climate science.

3.1. Safe Landing Pathways Exploration

Identifying safe trajectories requires a highly interdisciplinary and whole-of-system approach to explore the effect of interacting mitigation and adaptations (Zommers et al., 2020), accounting for climate risk along the entire trajectory particularly for nonlinearities and tipping points. Treating such quantitative aspects requires stochastic thinking (Sutton, 2019) so that future scenarios consider tail risks and a full range of possible events such as tipping point crossings, temporary disruptions by large volcanic eruptions (Sharkov, 2020), natural climate variations, societal responses, and responses of the biosphere (Natali et al., 2021). This involves a far greater range of possible futures than the handful of SSP and RCP pathways considered by the IPCC, and associated risks to the SDGs such as food and water supply.

One particular science need is to better understand the human perturbation of the global carbon cycle. There is for example, an opportunity to reassess the Transient Climate Response to Emissions (TCRE) by combining multiple lines of evidence similar to a recent effort for the “Charney” sensitivity (Sherwood et al., 2020), consolidating past research on understanding the land and ocean carbon fluxes and pools, and how they respond to observed and future rises in atmospheric CO₂ and changing climate (e.g., Canadell et al., 2021; Turetsky et al., 2020). Direct interventions such as large-scale afforestation or other biologically based carbon dioxide removal options, however, may pose new challenges to safe pathways for food, water, and biodiversity, and expose gaps in current research.

Recent ambitious goals of the UNFCCC framework such as the Net Zero objective or the Global Methane Pledge now open the possibility of declines in CH₄ and CO₂ concentrations well before the end of the century, that is, an “overshoot” scenario. The unique impacts that such forcing reversals would have on the Earth system need to be investigated. In particular better quantification of the key relevant carbon turnover times, both in the ocean and land continuum, will be key to assess the response of the carbon cycle to zero or even negative emissions (MacDougall et al., 2022). Understanding of potential hysteresis and irreversibility or potential transition from carbon sinks to sources under such conditions is largely uncharted territory, and understanding the behavior of tipping systems is clearly of concern if thresholds are crossed even temporarily. This requires growing a research emphasis on high-mitigation pathways and what the consequences would be on the carbon cycle, climate responses, SDGs and associated impacts.

Current strong-mitigation scenarios such as the SSP1-1.9 (Riahi et al., 2017) assume substantial capture and sequestration of carbon, primarily on land, with bioenergy with carbon capture and storage (BECCS) being one of the most heralded options. Typical Earth System Model (ESM) simulations such as those performed under CMIP6 (Eyring et al., 2016), simply assume “external” negative emissions without representing in the model the biogeochemical processes responsible for them or their impact on land resources (Figure 3). Potential trade-offs and limitations to land-based or ocean-based mitigation now need to be considered, moving to comprehensive ESMs that include interactions among climate system, land and ocean biogeochemical cycles, and other biological processes (discussed further below). Better understanding of carbon cycle interactions with food resources, water availability, and biodiversity, in the context of a changing climate with increased risks of climatic (e.g., droughts) or ecologic (e.g., wildfires) extremes, is crucial if carbon dioxide removal is to come anywhere near fulfilling current hopes on future mitigation pathways.

Similarly, future methane concentrations will be determined not by emissions alone but by the overall Earth system response to climate change. The recent rapid increase in atmospheric methane could be due to increased anthropogenic emissions or a change in natural emissions and sinks (McNorton et al., 2018). This requires improved understanding of how the removal processes respond to different rainfall patterns, soil moisture, and temperatures. The impact of future atmospheric composition changes, including for example, those from a hydrogen economy (Ocko & Hamburg, 2022), on the oxidizing capacity of the atmosphere and hence methane lifetimes must be considered.

The complexity of the system demands new types of integrative and exploratory models and new types of data (Figures 3 and 4). Paleoclimate data can provide valuable constraints on physical and biological responses to climate (Armstrong McKay et al., 2022; Salvatecchi et al., 2022), insights into tipping point thresholds (De Conto et al., 2021; Golledge et al., 2015, 2017; Lau et al., 2023), slow feedbacks and the committed equilibrium response (Grant et al., 2019), rates of change (Deschamps et al., 2012), and case studies for model benchmarking, such as changes in boreal forest in warmer climates (e.g., Thomas et al., 2020) or the African humid period (e.g., Pausata

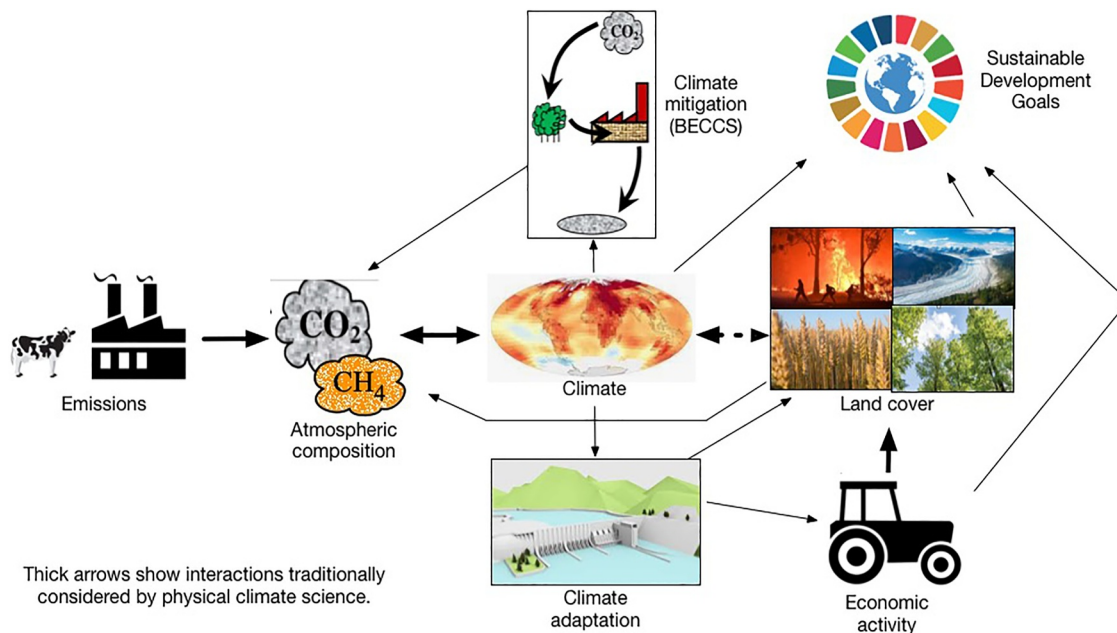


Figure 3. System interconnections for the example problem of land-cover change. Thick arrows show interactions that are considered by physical climate scientists so far, yet may not be fully coupled (e.g., land cover response to climate as indicated by dashed fat arrows); thin arrows show additional interactions that may be crucial in governing final outcomes for society, and will require broadening the scope of modeling as well as novel ways of addressing deep uncertainty.

et al., 2020). However, because no past scenario is analogous to our current situation, models of broad scope are necessary to translate this understanding from past to future. These tools can together enable us to explore and identify safe landing pathways that stay within the planetary boundaries for a resilient and stable Earth system.

The Paris agreement targets are one example of a science-informed boundary for climate, which is complemented by Earth system boundaries (ESBs) to identify just and safe limits for other components or measures of the Earth-human system (Rockstrom et al., 2023). The global biodiversity goals for 2030 and 2050 provide another framework (COP15 outcome, <https://www.cbd.int/gbf>). While these do not in themselves ensure that all the SDGs are achieved, they help identify societal actions necessary to remain within planetary boundaries from the viewpoint of all UN SDGs. Ideally this would be supported by quantitative modeling of the physical-human interface (see discussion below), but the difficulty of doing this reliably means the goal must be the illumination of possible hazards, cascades, and trade-offs rather than reliable prediction. In addition to capturing more interactions, this type of modeling becomes inherently more relevant to decision makers, who are trying to anticipate all types of important hazards, synergies, or efficiencies in an uncertain and complex environment. A clearer picture is needed of impacts as adaptation limits are approached and how they depend on other factors (e.g., for heat stress, the availability of water and power), to help anticipate failures of coping mechanisms.

Various modern industries and academics have turned to serious “games” to simulate hypothetical yet plausible future scenarios (Bartels, 2020; Bontoux et al., 2020). Gaming exercises in complex scenario planning can illuminate the intricacies and feedbacks that lead to unexpected outcomes, and the decision (or tipping) points that led to them—potentially helping to avoid adverse scenarios. Such activities involving sectoral experts would throw light on the issues and times at which a dynamic adaptation of policy pathways (DAPP, Haasnoot et al., 2013) is needed. The development and implementation of regularly scheduled climate “pathways” gaming workshops could allow for frequent assessments of ever-evolving possible pathways on decadal and century timescales. A successful approach must be inclusive of scientific expertise, stakeholders, industry partners, community groups and policymakers to include input on recent geopolitical, societal, technological, and sustainable advances. The results of these exercises could inform new and nimble scenarios for climate modeling efforts, international and local policies, and communication of climate risks, and could provide an understanding of the range of plausible and timely pathways to safe landing climates.

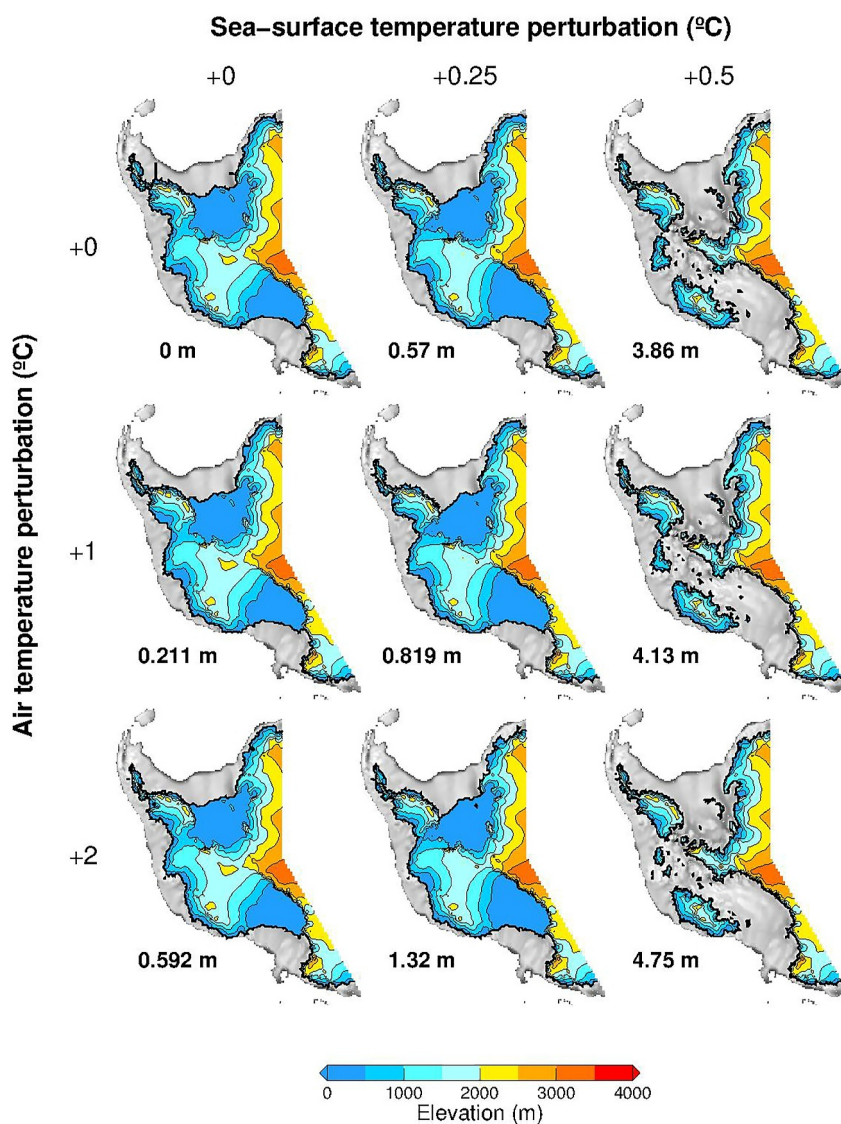


Figure 4. Models and paleoclimate evidence suggest irreversible loss of the WAIS if global surface temperature is maintained at 1.5–2C above preindustrial levels. Panels show modeled WAIS surface elevations (colors) and sea-level equivalent Antarctic ice loss after 10 kyr (numbers) for a range (0C–+2C) of perturbations to regional air and sea-surface temperature (SST). Projected ice loss is most sensitive to ocean temperatures with a threshold at +0.25C to +0.5C. Quantifying ice loss rates is crucial for coastal communities. Reprinted from Golledge et al. (2017).

3.2. Signposts of Change for Adaptation

Adaptation is a crucial element of these future pathways, but adaptation responses are complex and can be hard to foresee. Societal adaptation planning has proven challenging in part because it requires proactive decision-making on uncertain futures, and in part because it hinges on local cultural understanding. Cultural factors can inhibit what might otherwise seem like obvious strategies, for example, relocation. Indigenous cultures who, while they might embrace an understanding of the impermanence of particular conditions at a location, still value their connection to the location (Lambert et al., 2021) favoring in situ adaptation (or possibly, failure to adapt) rather than relocation. Such issues are also debated in developed countries, for example, in Australia some mayors have suggested relocating entire towns due to flood risk from heavy precipitation, but this idea understandably encounters resistance. The expense and difficulty of proactive adaptations, superimposed on the possibility that worst-case outcomes may not be realized, can be strong disincentives to engage any kind of anticipatory response even if it yields the “safest landing.”

How can the science community assess risk and calibrate responses in a way that is (a) geographically and culturally aware, (b) can be incorporated into a flexible management strategy (such as DAPP; Haasnoot et al., 2013), and (c) recognizes the risk of compound and cascading threats? We propose that a key strategy be the development of a suite of geographically aware sentinel signals (“signposts” Hermans et al., 2017) of changes in threat drivers that would foreshadow the need to alter a regional planning pathway, particularly when exceedance of a relevant tipping point in some global process essentially rules out lower projections. In concept, regional adaptation plans can be made for multiple projections, with a strategy for moving from one plan to the next as a particular projection becomes more likely. By anchoring adaptation plans to such signposts of physical change, we can simultaneously guide adaptations to better manage the greatest risks, while also making adaptation more predictable so that it can be incorporated into projected future global pathways.

Sea level rise offers one clear opportunity to apply a regionally tailored approach. The phenomenon is highly heterogeneous globally: increased rates of ice sheet melting contribute unequally to sea level acceleration across the globe (Kopp et al., 2015) and AMOC slowing is connected to shifts in the Gulf Stream (Caesar et al., 2018) that specifically affect sea level in the Mid-Atlantic region of the United States. Therefore the risk of rapid sea level rise in that region, over a multidecadal planning horizon, is strongly influenced by tipping point indicators associated with the Atlantic circulation as well as ice sheets, and will not be noticeable in time for adaptive action by only monitoring sea level itself (Houston, 2021; Wenzel & Schroter, 2010). A regionally targeted “signposts” approach would escalate local responses based on specific changes in remote drivers, for example, Atlantic meridional overturning, Antarctic sea ice (Purich & Doddridge, 2023), Antarctic surface temperature, and Antarctic ice shelf integrity (Orr et al., 2023). This can mitigate the difficulties that communities often face to coalesce around similar perspectives of the future (Jackson et al., 2015; Mitrovica et al., 2009; Sallenger et al., 2012), and can allow regionally differentiated adaptations to be better supported by evidence and more predictable enabling them to be anticipated in modeling.

Complications in selecting adaptation scenarios are exacerbated by significant uncertainty in global projections, particularly under high emissions scenarios (Sithara et al., 2024), which in the case of sea level rise is mainly due to uncertainty about change in the West Antarctic and Greenland ice sheets (DeConto et al., 2021; Edwards et al., 2021; Figure 4). Improved global modeling is needed, while the heterogeneity of impacts and desire to identify quantitative signposts calls for the complementary development of global and regional models that resolve the relevant processes and enable risk assessment (Scambos et al., 2017). These should ideally include compounding stressors such as changes in weather systems and resulting storm surges. On the other hand a signpost-like approach can mitigate against modeling limitations by identifying observable indicators of risk. One example is that sea ice losses (Purich & Doddridge, 2023), Antarctic surface warming (Casado et al., 2023) ice shelf hydrofracture (Lai et al., 2020), and/or warm water incursions into ice shelf cavities (Lauber et al., 2023) would be precursors to accelerated ice-sheet loss and global sea-level rise. As a different example concerning a flood-prone region, different-than-expected increases in the most extreme rainfall events collectively across other regions may become evident long before a signal clearly emerges in that particular region itself; these would inform the local risk because prediction uncertainty arising from atmospheric model process errors is correlated geographically (Bador et al., 2018). For both cases better observations (of tropical rainfall and polar ice processes) would be needed to fully exploit them. The signpost strategy can also inform improvements to the observational network and physical models (Haasnoot et al., 2018).

To incorporate cultural understanding into the adaptation planning, a more holistic and thoughtful perspective is needed that includes and respects local and indigenous knowledge, women and youth, and develops long-term relationships between the community and development partners. Flexible, multi-pathway planning has been recognized as critical to balancing investment with long-term resilience under uncertainty (e.g., Dewulf & Termeer, 2015; Wilby & Dessai, 2010; Zevenbergen et al., 2018). Conversations between scientists and stakeholders, focused on signposts as a connection point, can identify realistic adaptations and situations where adaptations may be impractical or unacceptable.

3.3. Characterizing High-Impact, Low-Likelihood (HILL) Risks

The discussion so far indicates that the traditional approach of considering (and presenting in reports like those of the IPCC) only anomalies and likely ranges (see Figure 2) needs to be supplemented by a risk-oriented framework that focuses on high impact, lower likelihood possibilities, extreme events, and exceedance of absolute adaptation

thresholds. For example, exceeding extreme heat thresholds (e.g., Freychet et al., 2022; Henry et al., 2022) due to any combination of the above factors would lead to dramatically greater impact on humans, the biosphere and/or crops. Predicting the impacts of threshold crossing requires managing model biases, considering microclimates such as coastal humid regions or urban effects, and aggregating across many threshold crossing events under varying vulnerability. This is a paradigm shift from analyzing large-scale anomalies and requires different analysis strategies.

Given that climate risk is strongly influenced (if not dominated) by HILL possibilities, how do we anticipate and characterize these scientifically when, by definition, they involve events for which there will be few if any direct past analogs? There are a few options. The first is to draw on relevant cases from prior observations and paleoclimate archives to better understand possible events and their consequences, and then evaluate how these would change in a warmer world. Events could include record-breaking observed extremes and rapid changes (involving the cryosphere and ocean) in paleo records. The second is to improve modeling tools to be able to better represent HILL events, including tipping points, irreversible events and event cascades; this is part of an overall modeling strategy discussed in the next subsection. The third is to change the way we use existing models and analyze Earth system data (simulated and observed), to focus more on climate risk and to break it down onto hazard and probability components for estimating what events are possible, their probabilities, impacts, degree of reversibility (e.g., Nobre et al., 2023), and interaction with pathways to a mitigated climate.

Observed case studies of the most severe events from instrumental or paleoclimate proxy data can challenge models and show storylines of how the most extreme events unfold. This applies particularly to past cases that have taken society and the scientific community by surprise, such as the record-shattering 2021 Pacific heatwave (McKinnon & Simpson, 2022; Thompson et al., 2023) and other recent drought and extreme heat events, many of which have been followed by severe wildfires across continents in the Western US, Australia, the Mediterranean, Siberia, and Canada. Wildfire seasons and ranges have extended on every fire-prone continent and intense fires appear to be damaging even fire-adapted ecosystems (e.g., Williams et al., 2019) suggesting a rapidly growing risk. Fire and drought can lead to substantial changes in carbon uptake or release (Humphrey et al., 2021), affect air quality over wide regions, and when compounded heat and drought events can lead to failures of multiple breadbaskets (Zscheischler et al., 2018) potentially affecting the global food supply (Kornhuber et al., 2020). Although worsening heat and stronger evaporation exacerbating drought are features of global warming (IPCC, 2021), paleo records show the potential for very severe drought in the last millennium (Cook et al., 2007). These records are crucial for testing our understanding and modeling of regional rare climate extremes and tipping points (Braconnot et al., 2019; Hopcroft & Valdes, 2021), and show changes that might have contributed to civilization collapse such as the end of the Indus Valley Civilization ~4.2 kyr BP (e.g., Staubwasser et al., 2003). The same arguments apply to risks from rising sea level and severe rainfall, where recent events have led to surprisingly severe consequences such as the Ahrtal floods of 2022 in Germany. We need to learn how the most severe events unfold physically, even if future events will not be identical to them. This can be done using analog methods or process studies (see Yiou et al., 2014), and benefits from storyline approaches to specific events (Shepherd et al., 2018). Ensemble boosting methods (Gessner, 2022; Leach et al., 2022) and the UNSEEN method (Thompson et al., 2017) can simulate feasible events similar to, but more severe than those which occurred in reality or in a conventional simulation.

To generalize, we can use the model types and observations currently available but analyze them in a more risk-facing way, focusing on thresholds, near-term irreversibility and the potential for impacts to cascade. The design of the next modeling exercise (CMIP7 and beyond) is an opportunity to go further to explore the potential for breaching tipping points within the coupled Earth system using more complete models. An assessment and critical review of climate risk, large-scale cascading events, tipping and irreversibility is needed (e.g., Stocker et al., 2024).

To get a better handle on HILL events, we advocate a “what-if” strategy: first identify potentially important event scenarios, then address their associated risks by separating the objectives of estimating their probability versus estimating their consequences. These two objectives can be met with different modeling setups or observations; for example, consequences can be estimated by imposing a scenario in an ensemble of ESM simulations (e.g., Amazon dieback in LUMIP) to build a more complete picture, including for different scenario variants. Some tipping points, for example, might lead to cascading impacts while others are less challenging. Separate approaches (perhaps combining model and long or paleo data sets) may be able to estimate scenario probability (or

plausibility). This strategy can be widely applied; for example, in the expert elicitation case of Dessai et al. (2018), impacts were expressed conditional on (unknown) changes in moisture advection into a the study region, the probabilities of which could in turn be estimated given other global-change scenarios. This approach of separating impact from probability could also be useful for some compound events and event cascades, where the conditional probability of one event given another can be estimated, although uncertainties inflate when estimating chains of events.

Quantifying HILL probabilities has been a serious challenge. For example, although some individual studies proposed quantitative probabilities for extreme sea level rise this century (Bamber et al., 2021; DeConto et al., 2021) this has not yet been attempted by WGI, who from AR4-AR6 tried various other strategies to convey uncertainty (e.g., via caveats) and tail risks as relevant to different stakeholders (Kopp et al., 2023). Quantifying a PDF of climate sensitivity was likewise contentious in assessments, but was eventually done with broad community support (Sherwood et al., 2020). Even if challenging, a rough idea of the informed probability of HILL events would be extremely useful even if this involves transparently subjective judgments, since even careful and well-intentioned qualitative explanations often end up misinterpreted or their caveats overlooked (Kopp et al., 2023). Efforts must also recognize that some HILL risks are relevant to mitigation but not adaptation for many communities, because they would be too hard for these communities to prepare for. Interdisciplinary work across all IPCC working groups is needed to address HILL challenges.

3.4. More Complete Earth-System Modeling Approaches

While imperfect model skill is a well-known issue affecting all of climate science, the challenges discussed here also call for new modeling approaches to tackle three additional needs. First, current modeling approaches need the scope (i.e., coupling) to assess large-scale irreversible change, proximity to tipping points, and other unprecedented events that involve multiple Earth system components. For example, to address possibilities such as Amazon dieback or continued growth of fire hazards, Earth system models would need to interactively and realistically simulate fire and its emissions, vegetation loss and regrowth, crop impacts, and vegetation change under changing climate conditions in addition to carbon emissions and the local water cycle (see Figure 3). Many climate models have suitable land surface and fire models, yet interactions among climate, vegetation, carbon cycle and fire are either absent, limited in scope or not well tested in current ESMs. Human actions such as deforestation play a significant role as well. Fully exploring these issues with models will require advances in model coupling, and in understanding the role of societal choices and pressures that drive deforestation. Similarly, to address future sea level rise requires dynamic ice-sheet models that can be tested on past climates, but modelers are only beginning to simulate the last deglaciation dynamically (e.g., Quiquet et al., 2021). At the same time these more comprehensive models must still represent extreme weather events, which significantly contribute to economic risk (see e.g. Calel et al., 2020; Chen et al., 2021).

The second need is long runs and/or large ensembles, in order to assess tail risks, especially the most extreme and rare (hence consequential) hazards or cascading events. While ensemble sizes of ESM runs are growing, they remain far from being able to capture the more extreme events, although new methods such as ensemble boosting may help (see above). Analogously, large model design ensembles such as CMIP remain as valuable as ever, but only to the extent that the models are physically independent and can simulate the most impactful Earth system hazards.

Third, we need innovative ways of coupling the physical and human systems that capture weather and climate impacts currently missing in Integrated Assessment Models (IAMs). Many questions about pathways require this, for example, how adaptation actions will be affected by climate change. Human responses can exhibit tipping behaviors apparently analogous to those in physical systems (Winkelmann et al., 2022) but so far this is only illustrated with toy models. An obvious limitation is that much human behavior is challenging if not unfeasible to model quantitatively. Efforts to couple tipping points into economic models (e.g., Lontzek et al., 2015) are useful but need better information on tipping point likelihoods, consequences and interactions.

These needs for holism and large ensembles for risk assessment are in tension with the current push for large-scale, ultra high-resolution (km-scale) atmosphere/ocean models, for example, with “digital twin” initiatives (Bauer et al., 2021). Such models are clearly of scientific value due to their ability to simulate a great range of scale interactions in the atmosphere and ocean, which may address long-standing biases and uncertainties, for example, in circulation variability and change (Hewitt et al., 2022; Palmer & Stevens, 2022; Slingo et al., 2022). However, these high resolution models are too unwieldy to be used for broad exploration of pathways or climate transitions

(Stainforth & Calel, 2021), to include and resolve earth system feedbacks on their relevant timescales, or for more than a small number of them to be developed. They therefore need to be complemented by simpler, faster models that can for example, accommodate feedbacks from the cryosphere or biosphere within many possible climate trajectories, while acknowledging the limitations of such models (e.g., Steinacher et al., 2013).

There are at least two ways to enable such holism in practice. First, advanced computing and artificial intelligence/machine learning approaches can be used to link different types of model together, or build emulators of one that can efficiently run within the other. This strategy is already being explored to expand the range of spatial scales effectively represented in numerical atmosphere models (Rasp et al., 2018) but could be used more broadly to emulate IAMs within ESMs, for example, or build efficient hybrid models of such a coupled system that could more quickly identify potentially important feedback behavior, where extreme events are represented by emulators. Such models (especially the latter) may lack reliability but could be used to explore possible risks that could then be explored further, as a strategy to anticipate possible surprises.

Unfortunately, coupling components of Earth system models often amplifies biases (e.g., Cohen-Solal & Le Treut, 1999), such as the Amazon rainfall dry bias (e.g., Monteverde et al., 2022) or the eastern equatorial Atlantic warm bias (e.g., Exarchou et al., 2018). These biases are a problem for regional rainfall simulation, for nonlinear or threshold impacts like heat stress, and for coupling to dynamic vegetation or ice sheets which are sensitive to absolute temperatures. Innovative ways of correcting or compensating model biases rather than usual tuning approaches (Dommenget & Rezny, 2018) could mitigate these problems. Overall, novel process diagnostics need to be deployed in atmosphere-ocean models and also ESMs that are more relevant to climate change (Eyring et al., 2019).

The other way to enable holism is to recognize limits of predictability and work within them. No matter how resources are expended, some climate uncertainties are likely to be irreducible, analogous to the chaos-imposed limit on weather forecasting. To be effective, rather than wait for models that can predict everything we must establish strategies to assess and communicate that which is known, expected, and possible given current knowledge (Lemos & Rood, 2010). It is also important to recognize which uncertainties actually affect decisions: for example, detailed regional climate simulations may not be helpful if the key uncertainty comes down to whether or not some tipping point is crossed that isn't represented in that modeling system. This synergizes with “pathways” options discussed earlier, where the focus shifts from deterministic prediction to probabilistic, or beyond this to identifying plausibilities (Shepherd et al., 2018). Co-design of pathways between scientists, social scientists, users/practitioners, facilitated by communication expertise is essential.

3.5. Communication

Achieving many of the goals above will be impossible without better communication among disciplines. This may require long-term, interactive in-person collaboration to educate physical and social scientists about one-anothers' conceptual approaches, methods, and terminology. It may be valuable to develop educational resources targeted at this application. We also need to learn how scientific understanding can be best used to inform effective decision making, recognizing that models are but one source of information and guidance. These goals will require ongoing iteration between the physical science community and climate information users, as well as the development of a community of science practitioners who can apply scientific knowledge to thorny complex problems. The communication of climate information to stakeholders, via for example, climate services, is still underdeveloped (e.g., Hansen et al., 2019).

Communicating climate risk to the public, meanwhile, is as important as ever. Uncertainty has always complicated this already-difficult task; our strategies may offer help. Climate games that can be used for research can also be used for education and outreach. Communicating plausible and timely pathways to a safe landing climate is crucial for better decision making at the nation, city, and individual level. Policy changes, no matter how well supported by objective reasoning or science, will not be enacted without public support. It is now clear that the “information deficit model”—that providing sufficient information about climate change will lead to understanding and support for appropriate action—is not sufficient (Centre for Public Impact, 2021). Concrete scenarios are more easily grasped than abstractions. We aim to illustrate realistic possible pathways and their implications as well as possible, acknowledging the uncertainties, to inform debate on solutions.

Communication needs to distinguish between genuinely unlikely and more probable events. Some challenging high-impact possibilities are not even HILLS because they are increasingly likely. New signs are emerging that the

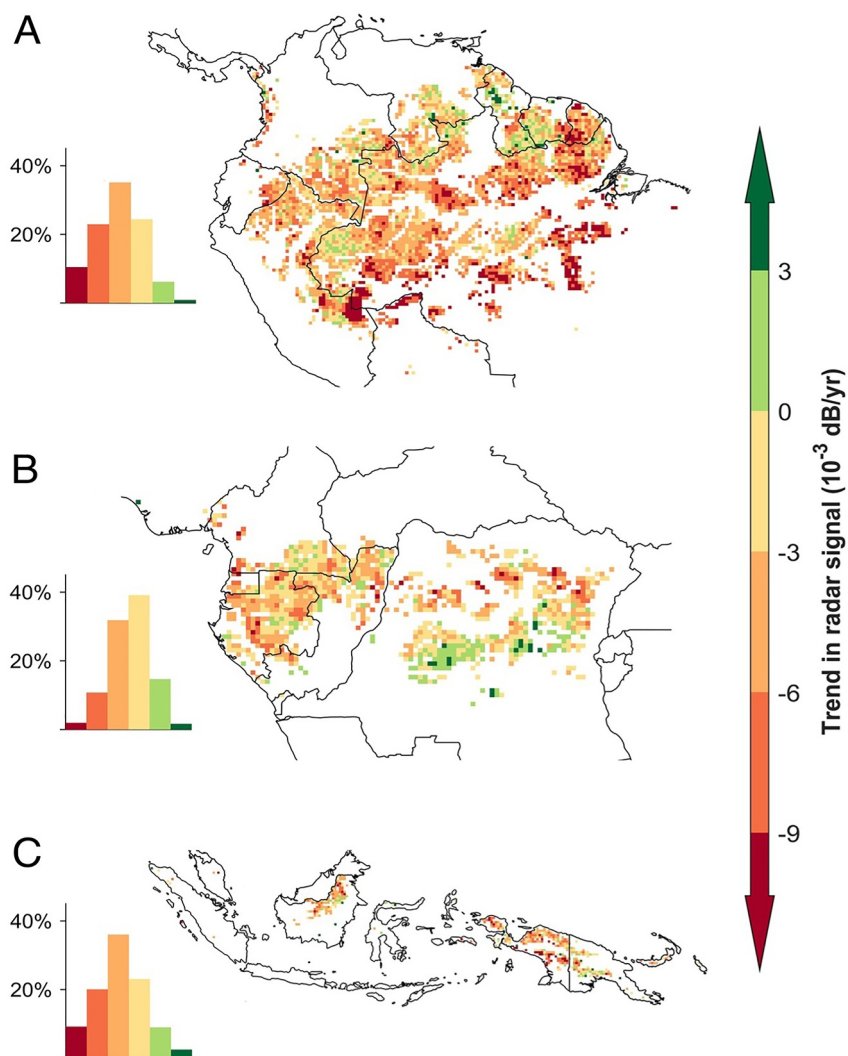


Figure 5. Many tropical land biomes are already under existential threat from climate change and land use. Radar-retrieved forest canopy moisture has been declining since 1992 in 93% of (a) American, 84% of (b) African and 88% of (c) Asian tropical rainforests, which are increasingly failing to fully recover to pre-drought conditions after severe drought episodes particularly in the Amazon, highlighting increasing vulnerability. Reprinted from Tao et al. (2022).

West Antarctic Ice Sheet (WAIS) is becoming unstable (Gudmundsson et al., 2019), so its eventual collapse (perhaps centuries from now) is not unlikely. Likewise, tree mortality is accelerating in the Amazon rainforest (Hubau et al., 2020) and observed hydrological changes suggest a few areas could be approaching collapse as forest canopy increasingly struggles to recover from droughts (Figure 5; Saatchi et al., 2021) that have, along with deforestation, contributed to record-low river flows. Some transitions (e.g., collapse of WAIS) are low-likelihood in the near term, but become probable with more warming. Because, like most HILLS, these high-impact events have no historical analog, it is challenging to tally their costs or get people to appreciate and act on the risks, both for interdisciplinary as well as public communication. Record-breaking weather and climate extremes also fit in this category. The lack of experienced analogs is why some citizens don't respond to warnings about extreme events, mirroring the global-scale readiness problem for anything unprecedented (e.g., Baron & Petersen, 2015), while others may respond with climate doom-ism which is not helpful either.

When communicating extreme climate risk including that of tipping points, it is therefore important to provide a sense of perspective, emphasizing how a combination of mitigation and adaptation can help to navigate climate risk, and how positive tipping may accelerate the transition (e.g., Tabara et al., 2018). The study of pathways that

incorporate both hazards and responses, preferably in an interactive and adaptable way (e.g., Terhaar et al., 2022), are able to support gaming and communications platforms that convey this sense of agency.

4. Conclusion

To spur progress in answering these questions, in 2021 the World Climate Research Program (WCRP) launched the “Safe Landing Climates” Lighthouse Activity, one of several new activities designed to facilitate cross-cutting climate research that better informs society about climate risk. We argue that mitigation and adaptation decisions being made today may not reflect the full risk posed by climate change and possible maladaptations to environmental changes. We propose a strategy that pivots physical climate science toward addressing pressing needs by answering questions about, first, global climate-related risks (including low-likelihood, high-impact events) and how to communicate them, and second, possible self-consistent pathways (good or bad) that lay before us. This strategy involves a stronger focus on worst-case outcomes and limits to adaptation that must be avoided, but also aims to identify and hence avoid maladaptation scenarios that could unintentionally upset climate or other Sustainable Development Goals. More serious global risks need to be separated from less serious ones by an evidence-based approach that tracks impacts including cascading consequences. Pathway exploration, risk framing and deep uncertainty are natural to decision makers and can serve both science and communication purposes and help social and physical science communities communicate.

This requires climate science to become more integrative and to explore transdisciplinary approaches. First by considering a richer and more flexible family of future pathways using exploratory techniques like gaming and expert elicitation, and making use of adaptation frameworks such as signposts that mark socially significant thresholds of change and help us continually update assessments of where affected communities stand and what can still be achieved. Climate science can also address a diverse class of high-risk events or event combinations or cascades, potentially using conditioning variables or storylines to break the problem into manageable pieces that can be attacked with different tools. Existing tools can be used to address some interactions between climate, ice, vegetation and permafrost for example, and to focus on thresholds such as heat tolerance with better management of model biases. There is however a need for more integrative models that explore the physical, biological and social systems, and their interactions, more holistically, even though this is challenging. New technologies like machine learning could help to link existing components across scales and spheres. But we must also make better use of observations, particularly of extreme outcomes and rare events including paleoclimate data, and standard model types for example, via model experiment setups or analysis techniques designed to illuminate less-likely but important events. In the face of deep uncertainty we must strive to distinguish what is already known (and should be more clearly communicated), what can be known, and what is probably unknowable on a relevant time scale.

These requirements have implications for upcoming assessments such as those of the IPCC. Assessments need to adopt a more risk-facing perspective, focusing on thresholds, surprises and the potential for impacts to cascade. They must do more to avoid the assumption that CMIP simulations span all possible futures. A thorough and balanced assessment of HILL risks is needed that examines their decision-relevance and how to communicate them appropriately; we advocate strategies that separately address event likelihood versus consequences, that use models innovatively to explore and test hypotheses beyond the traditional CMIP approach, and that use transdisciplinary or cross-working-group activities to explore future pathways. A focus on these “big picture” issues may also bring clarity and perspective to future assessments of climate futures and risk, including mitigation decisions.

Delivering on this strategy will require working across the IPCC Working Groups, as many risks straddle themes addressed in different working groups. The task also transcends disciplinary entities such as the WCRP Core Projects and will require examining how physical climate changes interact with mitigation strategies and adaptations such as geoengineering, land-use changes, migration, and others. This requires a fully interactive rather than pipeline approach. The authors invite the scientific and broader communities to embrace and enable such transdisciplinary collaborations.

Data Availability Statement

Data were not used, nor created for this research.

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