Uncertain Pathways to a Future Safe Climate

Authors: Sherwood, S. C. (1), G. Hegerl (2), P. Braconnot (3), P. Friedlingstein (4,5), H. Goelzer (6), N. R. P. Harris (7), E. Holland (8), H. Kim (9, 10, 11), M. Mitchell (12), T. Naish (13), P. Nobre (14), B. L. Otto-Bliesner (15), K. A. Reed (16), J. Renwick (17) and N. P. M. van der Wel (18)

(1) Climate Change Research Centre, UNSW Sydney, Sydney Australia
(2) School of Geosciences, the University of Edinburgh, Edinburgh, UK
(3) Laboratoire des sciences du climat et de l'Environnement (LSCE-IPSL), Orme des Merisiers, 91191 Gif-sur-Yvette cedex
(4) Faculty of Environment, Science and Economy,University of Exeter, Exeter EX4 4QF, UK
(5) Laboratoire de Météorologie Dynamique, Institut Pierre-Simon Laplace, CNRS, École Normale Supérieure, Université PSL, Paris, France
(6) NORCE Norwegian Research Centre, Bjerknes Centre for Climate Research, Bergen, Norway
(7) School of Water, Energy and Environment, Cranfield University, Cranfield, UK
(8) Pacific Center for Environment and Sustainable Development, University of the South Pacific, Laucala Bay, Fiji
(9) Moon Soul Graduate School of Future Strategy, Korea Advanced Institute of Science and Technology, Deajeon, Korea
(10) Dept. of Civil and Environmental Engineering, Korea Advanced Institute of Science and Technology, Deajeon, Korea
(11) Institute of Industrial Science, The University of Tokyo, Tokyo, Japan
(12) Virginia Institute of Marine Science, William & Mary, Gloucester Point, VA, United States
(13) Antarctic Research Centre, Victoria University of Wellington | Te Herenga Waka PO Box 600, Wellington 6140, New Zealand
(14) National Institute for Space Research - INPE, São José dos Campos, Brazil
(15) Climate and Global Dynamics Laboratory, National Center for Atmospheric Research, Boulder, USA
(16) School of Marine and Atmospheric Sciences, Stony Brook University, Stony Brook, USA
(17) School of Geography, Environment and Earth Sciences, Victoria University of Wellington, New Zealand
(18) World Climate Research Programme Secretariat, 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. 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 even–or especially–when they are highly uncertain, and to explore risks and opportunities associated with mitigation and adaptation responses by engaging across disciplines. This improves 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.

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, severe long-term flooding following extreme monsoon rainfall in Pakistan, and temperatures in western Canada reaching 49℃ have produced shocking headlines. 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 come as surprises. It is unclear how multiple changes can be navigated, or where adaptation will reach limits such as those already attained for coral atoll communities (IPCC 2019).

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 completely 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, could 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, changes in ocean chemistry that affect marine life (e.g., Heinze et al., 2021), ice shelf collapse or ice sheet melt, and many other possibilities. Concern about tipping points among the science community has been increasing since the first Intergovernmental Panel on Climate Change (IPCC) assessment report (Lenton et al. 2019), and some were explicitly addressed in the Summary for Policymakers of the 2021 report (IPCC 2021). 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 “*low-likelihood, high-impac*t” (LoHi) possibilities a warming planet might throw at us? This requires realistically identifying and assessing risk in order to develop a resilient mitigation and adaptation strategy.

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--at a geologically dizzying rate--by habitat destruction (IPBES 2019). Future changes in human well-being, as encapsulated by the United

Nations Sustainable Development Goals (SDGs), will depend not only on climate but on many other stressors and on how (or whether) human and natural systems can adapt to the new climate. These changes will have widely varying impacts across diverse communities around the globe, and efforts to mitigate one problem will redound on other problems. Issues of equity and multi-dimensional approaches to vulnerability were highlighted in the decades of loss and damage negotiations leading to COP27 in 2022 (Gerrard and Wannier 2013).

Is climate science up to the challenge of preparing decision makers at all levels for this uncertain future? Science has made steady progress but there are important aspects overlooked by the traditional approaches. 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. To spur progress in answering these questions, in 2021 the World Climate Research Programme (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.

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 (Weitzman 2009, 2012, Nordhaus 2011, Ackerman and Stanton 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 (Simpson et al. 2021, Calel et al. 2020, Rising et al. 2022); and the need for a risk-based framing for climate change (Sutton 2019). Frameworks such as “planetary boundaries” (Rockström 2009) have been proposed to cope with the multiple problem dimensions and needs (including for multiple communities) encapsulated in UN SDGs, particularly those relating to water and food security and protection of biodiversity, 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 focus on incomplete modelling tools and “linear thinking” rather than thinking more broadly about rare events and possibly nonlinear and cascading consequences.

Tipping points are one example of where science needs to focus. A recent assessment (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” (Wunderling et al. 2021; Fig. 1) although the idea is not well tested. While risk-analysis frameworks ideally start with hazard probabilities and damages, climate science currently struggles to quantify either of these in a useful way, except for frequently occurring examples like annual-maximum precipitation (e.g., Kim et al. 2020). While this is helpful, the greatest risk typically comes from very rare, unprecedented or compound events (Kotz et al.

2022; Zscheischler et al., 2018). 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. Meanwhile impacts can be hard to quantify based on today's observations even for relatively frequent events, as future adaptation responses may affect limits (see IPCC, 2022).

Most of these 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 modelling 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 (Fig. 2) because models lacked land-use feedbacks and realistic land cover forcing. The extreme temperatures likely caused physical teleconnections to the rest of the northern hemisphere climate (Meehl et al. 2022) and led to mass human migration; similar coupling has affected Lake Chad (Franzke et al. 2022) and may lead to human conflicts (IMCCS 2021). Model ensembles struggle to explain other climate variations such as the mid-Holocene "green Sahara" (e.g., Hopcroft and Valdes 2021) and increases during recent decades in Pacific trade winds and surface temperature gradients (Kajtar et al. 2018). It is not clear that all such problems result from coupling, as models also still inadequately represent processes such as mixing, clouds and convection. These affect LoHi's such as extreme climate sensitivity or atmosphere/ocean circulation shifts (Bjordal et al. 2020, Carlson and Caballero 2016), while inadequate model coupling compromises representation of possible tipping of Boreal and tropical forests (see Wang et al., 2023) including bushfire risk, rapid ice sheet change leading to rapid rises in global sea level, regional flood risk, and others. In general, multi-model ensembles therefore cannot be relied upon to fully characterise uncertainty as often assumed, especially for unprecedented situations or changes that involve strong coupling between Earth system components.

Human responses are an even more challenging modelling problem. They can exhibit tipping behaviours apparently analogous to those in physical systems (Winkelmann et al. 2022), and can provide positive or negative feedbacks on climate change through adaptation behaviour. Modelling 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).

Current endeavours to identify future impacts and to generate possible future 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 quantitative assumptions about future trends in populations, economies and technologies, while these may be influenced by climate change. In IPCC (2021), the Shared Socioeconomic Pathways (SSPs, Riahi 2017) were defined by five narratives about future global directions concerning energy use, population, etc., and were loosely constrained to fit with outcomes corresponding to five global temperature increases by 2100. These temperature increases were in turn set by a backward-looking analysis based on the concept of a carbon budget (IPCC 2021 and earlier) 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 associated with each scenario, or to assess how self-consistent the various assumptions were. These elements need to be better integrated to capture or at least bound possible feedbacks and uncertainties.

Understanding limits to biophysical and societal adaptation is crucial in assessing whether a given climate trajectory is safe or dangerous. Climate damage calculations are usually extrapolated empirically from the impact of natural climate variations. In some domains, such as agriculture, the apparent negative impacts of rising temperatures would be muted by adaptations on longer time scales, for example growing different crops (White et al. 2011). But in other domains, for example human heat stress, adaptations implicit in the empirical data would eventually reach biophysical limits and fail with sufficient warming (Sherwood and Huber 2010) leading to a dramatic escalation of impacts. Plants (Bokszczanin and Fragkostefanakis 2013), wildlife (Ratnayake et aol., 2019) and marine species can all reach temperature or carbon-dioxide tolerance limits (Heinze et al. 2021). This requires more attention to accurately calibrated variables rather than just anomalies from the current or preindustrial state, and going beyond "likely" changes to consider plausible alternatives.

Indeed humanity is grappling with how to remain within multiple "planetary boundaries" for multiple communities, limiting climate change while meeting the societal and biodiversity needs encapsulated in the UN SDGs. This becomes harder as more boundaries enter the picture (Lade et al. 2020) and assessment of plausible pathways puts climate alongside the other UN SDGs (Pörtner et al. 2021). As humans are influencing the Earth system in so many ways, adaptations and mitigations interact, requiring a holistic view. 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. Adaptations may, on the other hand, produce co-benefits such as improvements in biodiversity while expanding green space.

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.

Safe Landing Pathways Exploration

Identifying safe trajectories requires a highly interdisciplinary and whole-of-system approach to explore the effect of interacting mitigations 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 CO_2 and changing climate (e.g. Turetsky et al. 2020, Canadell et al. 2021). 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 CH_4 and CO_2 concentrations well before the end of the century. 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 (McDougall et al 2022). Understanding of potential hysteresis and irreversibility or potential transition from carbon sinks to sources under such conditions is largely uncharted territory. This requires growing a research emphasis on high-mitigation pathways and what the consequences would be on the carbon cycle, climate response, 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 (Fig. 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 and Hamburg 2022), on the oxidising 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 (Figs. 3,4). Paleoclimate data can provide valuable constraints on biological responses to climate where direct human impacts are absent (Salvatecchi et al. 2022) but are not completely analogous to our current situation. If we are to understand the societal actions necessary to remain within planetary boundaries from the viewpoint of all UN SDGs, some degree of modelling of the physical-human interface or at least exploration of possible interaction scenarios is needed (Moore et al. 2022, Ramanathan et al. 2022), discussed further below. Going very far down this path takes modelling into a realm where its verification becomes even more challenging, so 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 modelling 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 analytical “games” to simulate hypothetical yet plausible future scenarios (Bontoux et al. 2020; Bartels 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, 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 modelling 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.

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. This is prevalent among 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). This favours in situ adaptation (or possibly, failure to adapt) rather than relocation. Such issues are also debated in developed countries, for example in Australia where 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 realised, 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 1) geographically aware, 2) can be incorporated into a flexible management strategy (such as DAPP; Haasnoot et al. 2013), and 3) recognises 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 this 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 slowing of the AMOC is connected to shifts in the Gulf Stream (Ceasar 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 picked up in time by only monitoring sea level itself (Wenzel and Schroter 2010, Houston 2021). 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 and 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 (Sallenger et al. 2012, Mitrovica et al., 2009, Jackson et al., 2015), and can allow regionally differentiated adaptations to be both better supported by evidence and more predictable.

Complications in selecting adaptation scenarios are exacerbated by significant uncertainty in global projections (IWR 2011), which in the case of sea level rise is mainly due to uncertainty about change in the West Antarctic and Greenland ice sheets (Edwards et al. 2021; DeConto et al. 2021; Fig. 4). This points to a need for improved global modelling, 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 modelling limitations by identifying observable indicators of risk. Concerning a flood-prone region for example, 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 of these examples, however, better observations (of tropical rainfall and polar ice processes) would be needed to fully exploit them.

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 recognised as critical to balancing investment with long-term resilience under uncertainty (e.g., Wilby & Dessai 2010, Dewulf, & Termeer 2015, 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.

Characterising Low-Likelihood, High-Impact (LoHi) 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 Fig. 2) needs to be supplemented by a risk-oriented framework that focuses on lower likelihood, high impact possibilities, extreme events, and exceedance of absolute adaptation thresholds. For example, exceeding extreme heat thresholds (e.g., Freychet et al., 2022, Henry, 2022) due to any combination of the above factors would lead to dramatically greater impact on humans, the biosphere and/or crops.

Given that climate risk is strongly influenced (if not dominated) by LoHi possibilities, how do we anticipate and characterise these scientifically when, by definition, they involve events for which there will be few if any direct past analogues? 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, though not limited to these. The second is to improve modelling tools to be able to better represent LoHI events, including tipping points, irreversible events and event cascades; this is part of an overall modelling strategy discussed in the next subsection. The third is to change the way we use existing models and analyse 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, reversibility, 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 and Simpson 2022; Thompson et al., 2023) and other recent drought and extreme heat events. These have been followed by severe wildfires across continents in the Western US, Australia, the Mediterranean, Siberia, and most recently 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 (Korngruber et al. 2018; see also Meehl et al., 2023). 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 modelling of regional rare climate extremes and tipping points (Braconnot et al. 2019, Hopcroft and Valdes 2021), and show changes that might have contributed to civilisation collapse such as the end of the Indus ~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. In practice this can be done using analogue methods or process studies (see Yiou et al., 2014; e.g. Cowan et al., 2020b), and benefits from storyline approaches to specific events (Shepherd et al., 2018). Ensemble boosting methods (Leach et al. 2022, Gessner 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 generalise, we can use the model types and observations currently available but analyse 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 modelling 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.

To get a better handle on LoHi 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 vs. estimating their consequences. These two objectives can be met with different modelling 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 have only modest impacts and so may not figure strongly in risk. Separate approaches (perhaps combining model and long or paleo datasets) 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 HiLo probabilities has been a serious challenge. For example although some individual studies proposed quantitative probabilities for extreme sea level rise this century (DeConto et al. 2021, Bamber 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 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 HiLO 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 2023). Interdisciplinary work across all IPCC working groups is needed to address HiLO challenges.

More Complete Earth-System Modelling Approaches

While imperfect model skill is a well-known issue affecting all of climate science, the challenges discussed here also call for new modelling approaches to tackle three additional needs. First, current modelling 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 (see Fig. 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 modellers 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. Chen et al., 2021, Calel et al. 2020).

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.

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 behaviours 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 behaviour 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 (Palmer et al., 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 and 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.

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 behaviour, 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.

One challenge in coupling models, already experienced with atmosphere-ocean coupled models, is that this often amplifies biases (e.g. Cohen-Solal and 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 and 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 recognise 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 and Rood 2010). It is also important to recognise 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 modelling system. This synergises 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.

Communication

Achieving many of the goals above will be impossible without better communication between 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 e.g., 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 LoHi's because they are increasingly likely. New signs are emerging that the 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 (Fig. 5; Saatchi et al. 2021). Some transitions (e.g., collapse of WAIS) are low-likelihood in the near term, but become probable with more warming. Because, like most LoHi's, these high-impact events have no historical analogue, 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 analogues is why some citizens don't respond to warnings about extreme events, mirroring the global-scale readiness problem for anything unprecedented (e.g., Baron and 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, emphasising 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, are able to support gaming and communications platforms that convey this sense of agency.

Conclusion

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.

Pathway exploration, risk framing and deep uncertainty are natural to decision makers and can serve both science and communication purposes, and help social science and physical sciences communities communicate.

This requires climate science to become more integrative. 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. It 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. 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.

Delivering on this strategy will require working across the IPCC Working Groups and disciplinary entities such as the WCRP Core Projects. It will require examining how physical climate changes interact with mitigation strategies and adaptations such as geoengineering, land-use changes, migration, and others, and do so fully interactively instead of using a pipeline approach from physical change to impact and mitigation. The authors invite the scientific and broader communities to help.

AVAILABILITY STATEMENT

No new software or data were generated for this article.

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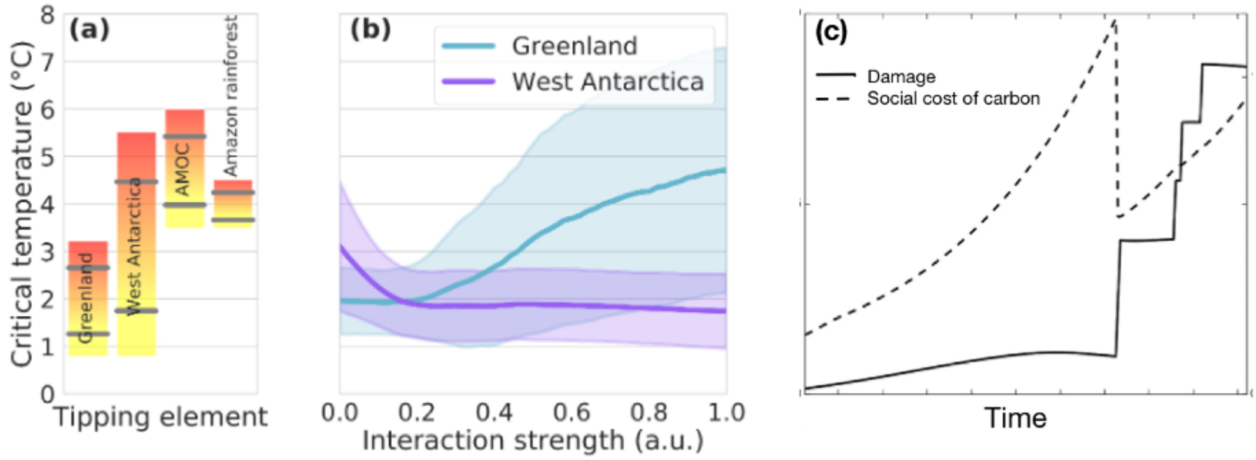

Figure 1. Transition thresholds for important geophysical system transitions remain highly uncertain. (A) Warming thresholds estimated for a few isolated tipping point transitions. (B) If the two systems interact strongly (higher values of interaction strength), a collapse of the WAIS may increase the threshold for Greenland while a collapse of Greenland could reduce that for the WAIS. (C) The threat of uncertain tipping point occurrence and damage (solid line) increases benefits of early mitigation (dashed line). Panels (a,b) from Wunderling et al. (2021), (c) from Cai and Lontzek (2019).

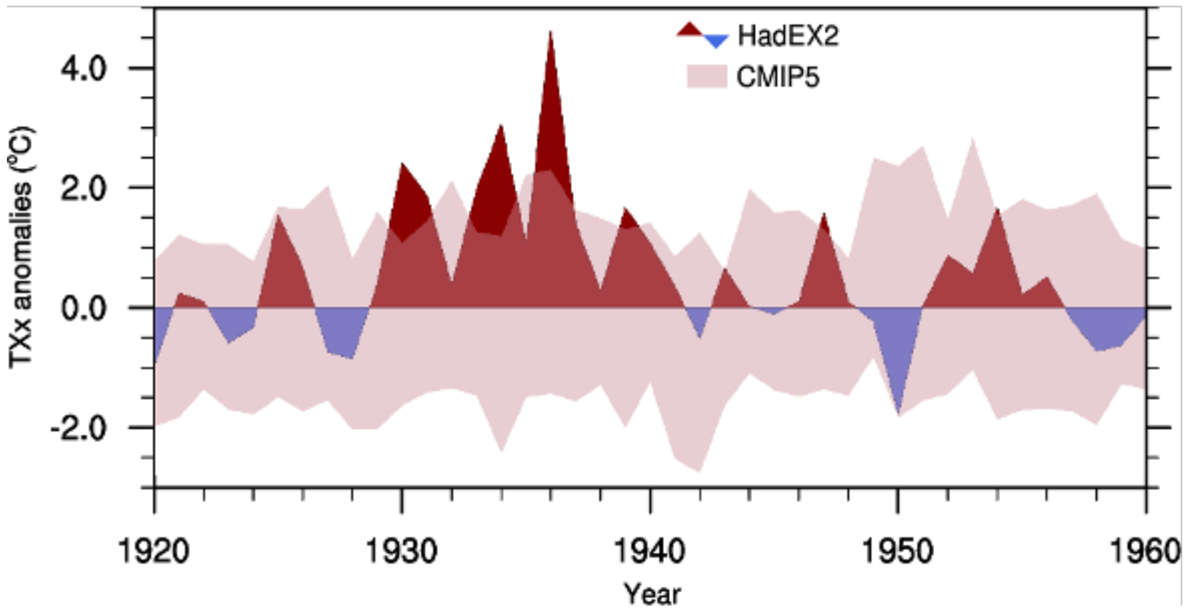

Figure 2. Dust bowl extreme temperature anomalies exceeded worst model hindcasts. 90% range of CMIP5 model historical simulations shown by light shading, observed values shown by dark red/blue shading. The extreme high values are likely due to land surface changes not represented in the models. Adapted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

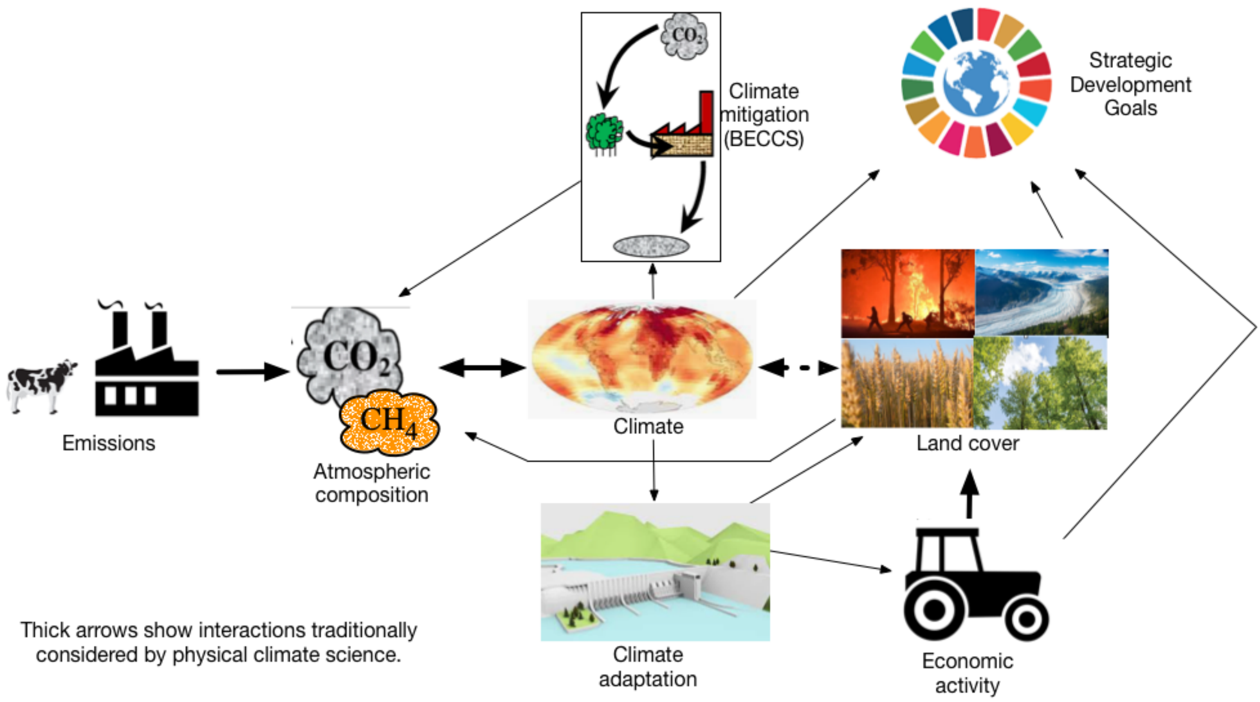

Figure 3: System interconnections for the example problem of land-cover change. Thick arrows show interactions that are considered by physical climate scientists so far, yet may not be fully coupled (e.g. land cover response to climate); thin arrows show additional interactions that may be crucial in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

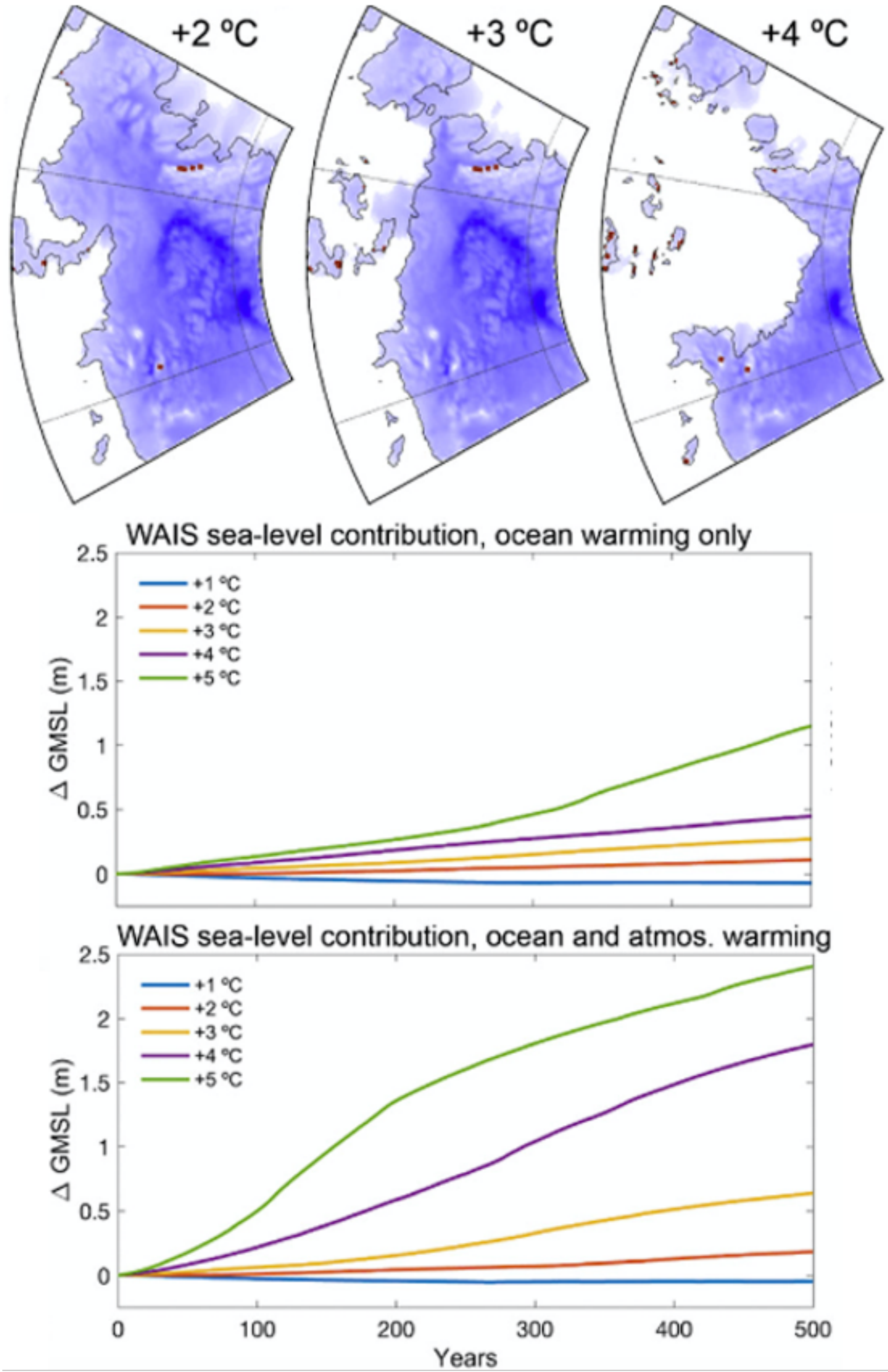

Figure 4. Projected loss of West Antarctic Ice Sheet is sensitive to coupled processes. Substantial loss of the WAIS and consequent sea level contribution of well over a metre within two centuries is projected by one model if global warming exceeds 3C when atmosphere-ocean coupled warming is accounted for (top row and bottom panel; blue colour at top denotes ice thickness). This is not predicted if only ocean warming of the ice shelf is accounted for (middle panel). Adapted from Scambos et al. (2017). Quantifying this threshold and ice loss rates is crucial for coastal communities.

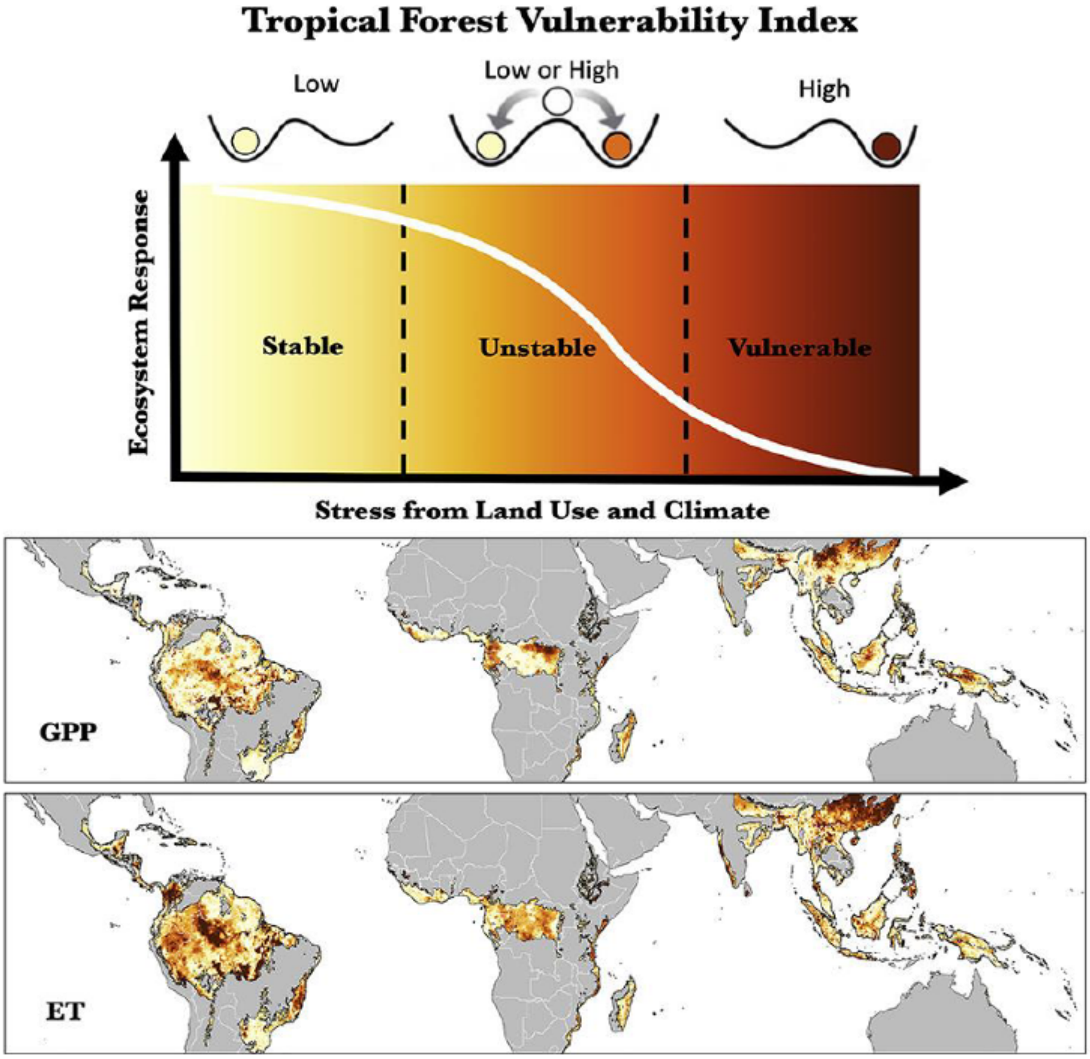

Figure 4. Maps of vulnerability of humid tropical gross primary productivity (GPP) and evapotranspiration (ET). Source: Saatchi et al., 2021.

Figure 5. Many tropical land biomes are already under existential threat from climate change and land use. (top) stress regimes as determined by variance analysis of observables from 1980-2020. Increases in persistent co-variability of stressors such as land-use or climate changes and responses such as primary productivity (middle panel) and evapotranspiration (bottom panel) suggest instability and an approaching transition to a new biome (shown by brown areas). From Saatchi et al. (2021).