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2   **Uncertain Pathways to a Future Safe Climate**
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41   # Abstract

42   Global climate change is often thought of as a steady and approximately predictable physical
43   response to increasing forcings, which then requires commensurate adaptation. But adaptation has
44   practical, cultural and biological limits, and climate change may pose unanticipated global hazards,
45   sudden changes or other surprises, as may societal adaptation and mitigation responses. We
46   outline a strategy for better accommodating these challenges by making climate science more
47   integrative, in order to identify and quantify known and novel physical risks even–or especially–
48   when they are highly uncertain, and to explore risks and opportunities associated with mitigation
49   and adaptation responses by engaging across disciplines. This improves the chances of

50 anticipating potential surprises and identifying and communicating "safe landing" pathways that
51 meet UN Sustainable Development Goals and guide humanity toward a better future.
52
53

Introduction

55 A common metaphor for global warming is that rather than causing disasters directly, it "loads the
56 dice," changing the probability of high-impact weather events such as extreme rains, droughts and
57 storm surges (NAS, 2016). But increasingly events occur that appear unprecedented, even
58 previously considered virtually impossible—we are playing with a new set of dice. Australian
59 bushfires more intense than any since European settlement and Canadian ones setting new
60 burned-area records, severe long-term flooding following extreme monsoon rainfall in Pakistan,
61 and temperatures in western Canada reaching 49℃ have produced shocking headlines. Can
62 climate science anticipate such extraordinary events and their consequences? In some cases it
63 has: for example unprecedented heat waves and heavy rains have been predicted (e.g., Fischer et
64 al. 2021) and are now evident on several continents. However, consequences such as record-
65 breaking fires and floods and their associated fatality and damage tolls have come as surprises. It
66 is unclear how multiple changes can be navigated, or where adaptation will reach limits such as
67 those already attained for coral atoll communities (IPCC 2019).

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

78 One concern is climate "tipping points" or regime shifts where regional or global systems could
79 change rapidly and perhaps irreversibly on human timescales (Solomon et al., 2009) to an
80 unfamiliar state if the global temperature crosses some threshold (Armstrong McKay et al. 2022).
81 These include dieback of the Amazon or other forests (Wang et al., 2023), shutdown of the Atlantic
82 thermohaline circulation, changes in ocean chemistry that affect marine life (e.g., Heinze et al.,
83 2021), ice shelf collapse or ice sheet melt, and many other possibilities. Concern about tipping
84 points among the science community has been increasing since the first Intergovernmental Panel
85 on Climate Change (IPCC) assessment report (Lenton et al. 2019), and some were explicitly
86 addressed in the Summary for Policymakers of the 2021 report (IPCC 2021). These alarming
87 possibilities embody a broader problem: how can society be sure that it is adequately prepared, not
88 just for what is expected, but for "*low-likelihood, high-impac*t" (LoHi) possibilities a warming planet
89 might throw at us? This requires realistically identifying and assessing risk in order to develop a
90 resilient mitigation and adaptation strategy.

91 Adding to the challenge, climate change is not happening in isolation but is part of a broader
92 spectrum of human influences on the environment. In addition to climate change, native forests
93 are affected by deforestation and fires; groundwater by irrigation and other water use; coastal
94 erosion by development; ice retreat by air pollutants that darken the ice surface; disease
95 propagation by human travel; and species extinctions--at a geologically dizzying rate--by habitat
96 destruction (IPBES 2019). Future changes in human well-being, as encapsulated by the United

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

103 Is climate science up to the challenge of preparing decision makers at all levels for this uncertain
104 future? Science has made steady progress but there are important aspects overlooked by the
105 traditional approaches. This paper discusses two overarching and challenging questions that
106 climate science must now strive to answer. First: *what potential high-impact climate hazards,*
107 *surprises or irreversible changes should society be genuinely worried about and how can the*
108 *associated risks be usefully quantified and communicated*? And second: *what do achievable,*
109 *internally consistent and safe pathways to a future climate look like that also meet broader human*
110 *needs, and how can we identify them*? These questions are interrelated, and answering them will
111 require the climate science community to work across disciplines to identify risks arising within the
112 entire earth/human system, and to connect with all aspects of society. To spur progress in
113 answering these questions, in 2021 the World Climate Research Programme (WCRP) launched
114 the "Safe Landing Climates" Lighthouse Activity, one of several new activities designed to facilitate
115 cross-cutting climate research that better informs society about climate risk.
116
An Interdisciplinary Challenge
118
119 These concerns are not new. Economists have long noted for example that the upper tail on the
120 probability distribution of climate sensitivity dominates risk rather than the central value, due to the
121 highly nonlinear increase of damages with warming (Weitzman 2009, 2012, Nordhaus 2011,
122 Ackerman and Stanton 2012). Observers and climate scientists have more recently highlighted
123 "missing risks" of climate change that are poorly understood and hard to quantify; the importance
124 of including them somehow in economic evaluations and decision making processes (Simpson et
125 al. 2021, Calel et al. 2020, Rising et al. 2022); and the need for a risk-based framing for climate
126 change (Sutton 2019). Frameworks such as "planetary boundaries" (Rockström 2009) have been
127 proposed to cope with the multiple problem dimensions and needs (including for multiple
128 communities) encapsulated in UN SDGs, particularly those relating to water and food security and
129 protection of biodiversity, yet still struggle with the inter-relatedness of individual boundaries.
130 "Storylines" of possible futures are a simple hence useful way of dealing with deep uncertainty
131 (Shepherd et al., 2018), and expert elicitation can make progress on problems that are hard to
132 quantify (Dessai et al. 2018). Yet in spite of these tools and awareness, assessment of climate risk
133 has been limited by a focus on incomplete modelling tools and "linear thinking" rather than thinking
134 more broadly about rare events and possibly nonlinear and cascading consequences.
135
136 Tipping points are one example of where science needs to focus. A recent assessment (Armstrong
137 McKay et al. 2022) gives global tipping temperatures for a range of systems, identifying 1.5 °C
138 above preindustrial as a potential trigger for multiple tipping points, but a look behind the best
139 estimates reveals wide ranges and considerable uncertainty, as also illustrated in the "burning
140 embers" diagrams of IPCC (IPCC, 2022). It has been suggested that multiple system transitions
141 could interact leading to "tipping cascades" (Wunderling et al. 2021; Fig. 1) although the idea is not
142 well tested. While risk-analysis frameworks ideally start with hazard probabilities and damages,
143 climate science currently struggles to quantify either of these in a useful way, except for frequently
144 occurring examples like annual-maximum precipitation (e.g., Kim et al. 2020). While this is helpful,
145 the greatest risk typically comes from very rare, unprecedented or compound events (Kotz et al.

146 2022; Zscheischler et al., 2018). The most recent IPCC report, while acknowledging a few high-
147 profile tail risks, still focuses on likely outcomes, and frames them as deviations from today's
148 climate while thresholds might be crossed that lead to very different impacts. Meanwhile impacts
149 can be hard to quantify based on today's observations even for relatively frequent events, as future
150 adaptation responses may affect limits (see IPCC, 2022).
151
152 Most of these science gaps involve coupling between physical climate and subsystems such as
153 vegetation, ocean biochemistry, ice sheets, or human responses that are typically treated
154 individually or coupled only rudimentarily in present modelling tools. A sobering example of the
155 problem is the US "Dust Bowl" of the 1930's, where rapid land cover change contributed to
156 unprecedented temperature extremes; these lay well outside the envelope of retrospective climate-
157 model predictions (Fig. 2) because models lacked land-use feedbacks and realistic land cover
158 forcing. The extreme temperatures likely caused physical teleconnections to the rest of the
159 northern hemisphere climate (Meehl et al. 2022) and led to mass human migration; similar coupling
160 has affected Lake Chad (Franzke et al. 2022) and may lead to human conflicts (IMCCS 2021).
161 Model ensembles struggle to explain other climate variations such as the mid-Holocene "green
162 Sahara" (e.g., Hopcroft and Valdes 2021) and increases during recent decades in Pacific trade
163 winds and surface temperature gradients (Kajtar et al. 2018). It is not clear that all such problems
164 result from coupling, as models also still inadequately represent processes such as mixing, clouds
165 and convection. These affect LoHi's such as extreme climate sensitivity or atmosphere/ocean
166 circulation shifts (Bjordal et al. 2020, Carlson and Caballero 2016), while inadequate model
167 coupling compromises representation of possible tipping of Boreal and tropical forests (see Wang
168 et al., 2023) including bushfire risk, rapid ice sheet change leading to rapid rises in global sea level,
169 regional flood risk, and others. In general, multi-model ensembles therefore cannot be relied upon
170 to fully characterise uncertainty as often assumed, especially for unprecedented situations or
171 changes that involve strong coupling between Earth system components.

172 Human responses are an even more challenging modelling problem. They can exhibit tipping
173 behaviours apparently analogous to those in physical systems (Winkelmann et al. 2022), and can
174 provide positive or negative feedbacks on climate change through adaptation behaviour. Modelling
175 of these interactions remains in its infancy even compared to Earth System Models, but studies are
176 beginning to project global-mean economy-climate interactions (e.g., Moore et al. 2022,
177 Ramanathan et al. 2022).

178 Current endeavours to identify future impacts and to generate possible future societal pathways
179 are largely independent, even though strong coupling is expected among impacts, mitigations, and
180 adaptations for climate change and other UN SDGs. For example, scenarios for IPCC reports
181 begin with quantitative assumptions about future trends in populations, economies and
182 technologies, while these may be influenced by climate change. In IPCC (2021), the Shared
183 Socioeconomic Pathways (SSPs, Riahi 2017) were defined by five narratives about future global
184 directions concerning energy use, population, etc., and were loosely constrained to fit with
185 outcomes corresponding to five global temperature increases by 2100. These temperature
186 increases were in turn set by a backward-looking analysis based on the concept of a carbon
187 budget (IPCC 2021 and earlier) of allowable GHG emissions for a given warming target. The fact
188 that the uncertainties associated with the underlying, detailed assumptions were not well quantified
189 made it impossible to properly assess the risks associated with each scenario, or to assess how
190 self-consistent the various assumptions were. These elements need to be better integrated to
191 capture or at least bound possible feedbacks and uncertainties.

192 Understanding limits to biophysical and societal adaptation is crucial in assessing whether a given
193 climate trajectory is safe or dangerous. Climate damage calculations are usually extrapolated

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

203 Indeed humanity is grappling with how to remain within multiple "planetary boundaries" for multiple
204 communities, limiting climate change while meeting the societal and biodiversity needs
205 encapsulated in the UN SDGs. This becomes harder as more boundaries enter the picture (Lade
206 et al. 2020) and assessment of plausible pathways puts climate alongside the other UN SDGs
207 (Pörtner et al. 2021). As humans are influencing the Earth system in so many ways, adaptations
208 and mitigations interact, requiring a holistic view. If, for example, a climate mitigation strategy such
209 as biofuel development leads to increased pressure on a land or water resource, unintended
210 consequences may affect the ability to mitigate climate change or reach other UN SDGs.
211 Adaptations may, on the other hand, produce co-benefits such as improvements in biodiversity
212 while expanding green space.

213

A Strategy for Integrative Climate Science

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

220

Safe Landing Pathways Exploration

222

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

232 One particular science need is to better understand the human perturbation of the global carbon
233 cycle. There is for example an opportunity to reassess the Transient Climate Response to
234 Emissions (TCRE) by combining multiple lines of evidence similar to a recent effort for the
235 "Charney" sensitivity (Sherwood et al. 2020), consolidating past research on understanding the
236 land and ocean carbon fluxes and pools, and how they respond to observed and future rises in
237 atmospheric CO_2 and changing climate (e.g. Turetsky et al. 2020, Canadell et al. 2021). Direct
238 interventions such as large-scale afforestation or other biologically based carbon dioxide removal
239 options, however, may pose new challenges to safe pathways for food, water, and biodiversity, and
240 expose gaps in current research.

241 Recent ambitious goals of the UNFCCC framework such as the Net Zero objective or the
242 Global Methane Pledge now open the possibility of declines in CH_4 and CO_2 concentrations well
243 before the end of the century. The unique impacts that such forcing reversals would have on the
244 Earth system need to be investigated. In particular better quantification of the key relevant carbon
245 turnover times, both in the ocean and land continuum, will be key to assess the response of the
246 carbon cycle to zero or even negative emissions (McDougall et al 2022). Understanding of
247 potential hysteresis and irreversibility or potential transition from carbon sinks to sources under
248 such conditions is largely uncharted territory. This requires growing a research emphasis on high-
249 mitigation pathways and what the consequences would be on the carbon cycle, climate response,
250 SDGs and associated impacts.

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

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

271 The complexity of the system demands new types of integrative and exploratory models and new
272 types of data (Figs. 3,4). Paleoclimate data can provide valuable constraints on biological
273 responses to climate where direct human impacts are absent (Salvatecchi et al. 2022) but are not
274 completely analogous to our current situation. If we are to understand the societal actions
275 necessary to remain within planetary boundaries from the viewpoint of all UN SDGs, some degree
276 of modelling of the physical-human interface or at least exploration of possible interaction
277 scenarios is needed (Moore et al. 2022, Ramanathan et al. 2022), discussed further below. Going
278 very far down this path takes modelling into a realm where its verification becomes even more
279 challenging, so the goal must be the illumination of possible hazards, cascades, and trade-offs
280 rather than reliable prediction. In addition to capturing more interactions, this type of modelling
281 becomes inherently more relevant to decision makers, who are trying to anticipate all types of
282 important hazards, synergies, or efficiencies in an uncertain and complex environment. A clearer
283 picture is needed of impacts as adaptation limits are approached and how they depend on other
284 factors (e.g., for heat stress, the availability of water and power), to help anticipate failures of
285 coping mechanisms.

286 Various modern industries and academics have turned to analytical "games" to simulate
287 hypothetical yet plausible future scenarios (Bontoux et al. 2020; Bartels 2020). Gaming exercises
288 in complex scenario planning can illuminate the intricacies and feedbacks that lead to unexpected

289 outcomes, and the decision (or tipping) points that led to them—potentially helping to avoid
290 adverse scenarios. Such activities involving sectoral experts would throw light on the issues and
291 times at which a dynamic adaptation of policy pathways (DAPP, Haasnoot, 2013) is needed. The
292 development and implementation of regularly scheduled climate "pathways" gaming workshops
293 could allow for frequent assessments of ever-evolving possible pathways on decadal and century
294 timescales. A successful approach must be inclusive of scientific expertise, stakeholders, industry
295 partners, community groups and policymakers to include input on recent geopolitical, societal,
296 technological, and sustainable advances. The results of these exercises could inform new and
297 nimble scenarios for climate modelling efforts, international and local policies, and communication
298 of climate risks, and could provide an understanding of the range of plausible and timely pathways
299 to safe landing climates.

300

301 ***Signposts of Change for Adaptation***

302

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

316 How can the science community assess risk and calibrate responses in a way that is 1)
317 geographically aware, 2) can be incorporated into a flexible management strategy (such as DAPP;
318 Haasnoot et al. 2013), and 3) recognises the risk of compound and cascading threats? We
319 propose that a key strategy be the development of a suite of geographically-aware sentinel signals
320 ("signposts" Hermans et al. 2017) of changes in threat drivers that would foreshadow the need to
321 alter a regional planning pathway, particularly when exceedance of a relevant tipping point in some
322 global process essentially rules out lower projections. In concept, regional adaptation plans can be
323 made for multiple projections, with a strategy for moving from one plan to the next as a particular
324 projection becomes more likely. By anchoring adaptation plans to such signposts of physical
325 change, we can simultaneously guide adaptations to better manage the greatest risks, while also
326 making adaptation more predictable so that it can be incorporated into projected future global
327 pathways.

328 Sea level rise offers one clear opportunity to apply this approach. The phenomenon is highly
329 heterogeneous globally: increased rates of ice sheet melting contribute unequally to sea level
330 acceleration across the globe (Kopp et al. 2015), and slowing of the AMOC is connected to shifts in
331 the Gulf Stream (Ceasar et al. 2018) that specifically affect sea level in the Mid-Atlantic region of
332 the United States. Therefore the risk of rapid sea level rise in that region, over a multidecadal
333 planning horizon, is strongly influenced by tipping point indicators associated with the Atlantic
334 circulation as well as ice sheets, and will not be picked up in time by only monitoring sea level itself
335 (Wenzel and Schroter 2010, Houston 2021). A regionally targeted "signposts" approach would
336 escalate local responses based on specific changes in remote drivers, for example Atlantic

337   meridional overturning, Antarctic sea ice (Purich and Doddridge 2023), Antarctic surface
338   temperature, and Antarctic ice shelf integrity (Orr et al., 2023). This can mitigate the difficulties that
339   communities often face to coalesce around similar perspectives of the future (Sallenger et al. 2012,
340   Mitrovica et al., 2009, Jackson et al., 2015), and can allow regionally differentiated adaptations to
341   be both better supported by evidence and more predictable.

342   Complications in selecting adaptation scenarios are exacerbated by significant uncertainty in global
343   projections (IWR 2011), which in the case of sea level rise is mainly due to uncertainty about
344   change in the West Antarctic and Greenland ice sheets (Edwards et al. 2021; DeConto et al. 2021;
345   Fig. 4). This points to a need for improved global modelling, while the heterogeneity of impacts and
346   desire to identify quantitative signposts calls for the complementary development of global and
347   regional models that resolve the relevant processes and enable risk assessment (Scambos et al.,
348   2017). These should ideally include compounding stressors such as changes in weather systems
349   and resulting storm surges. On the other hand a signpost-like approach can mitigate against
350   modelling limitations by identifying observable indicators of risk. Concerning a flood-prone region
351   for example, different-than-expected increases in the most extreme rainfall events collectively
352   across other regions may become evident long before a signal clearly emerges in that particular
353   region itself; these would inform the local risk because prediction uncertainty arising from
354   atmospheric model process errors is correlated geographically (Bador et al. 2018). For both of
355   these examples, however, better observations (of tropical rainfall and polar ice processes) would
356   be needed to fully exploit them.

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

365

366   ***Characterising Low-Likelihood, High-Impact (LoHi) Risks***

367

368   The discussion so far indicates that the traditional approach of considering (and presenting in
369   reports like those of the IPCC) only anomalies and likely ranges (see Fig. 2) needs to be
370   supplemented by a risk-oriented framework that focuses on lower likelihood, high impact
371   possibilities, extreme events, and exceedance of absolute adaptation thresholds. For example,
372   exceeding extreme heat thresholds (e.g., Freychet et al., 2022, Henry, 2022) due to any
373   combination of the above factors would lead to dramatically greater impact on humans, the
374   biosphere and/or crops.

375   Given that climate risk is strongly influenced (if not dominated) by LoHi possibilities, how do we
376   anticipate and characterise these scientifically when, by definition, they involve events for which
377   there will be few if any direct past analogues? There are a few options. The first is to draw on
378   relevant cases from prior observations and paleoclimate archives to better understand possible
379   events and their consequences, and then evaluate how these would change in a warmer world.
380   Events could include record-breaking observed extremes and rapid changes (involving the
381   cryosphere and ocean) in paleo records, though not limited to these. The second is to improve
382   modelling tools to be able to better represent LoHI events, including tipping points, irreversible
383   events and event cascades; this is part of an overall modelling strategy discussed in the next
384   subsection. The third is to change the way we use existing models and analyse Earth system data

385   (simulated and observed), to focus more on climate risk and to break it down onto hazard and
386   probability components for estimating what events are possible, their probabilities, impacts,
387   reversibility, and interaction with pathways to a mitigated climate.

388   Observed case studies of the most severe events from instrumental or paleoclimate proxy data can
389   challenge models and show storylines of how the most extreme events unfold. This applies
390   particularly to past cases that have taken society and the scientific community by surprise, such as
391   the record-shattering 2021 Pacific heatwave (McKinnon and Simpson 2022; Thompson et al.,
392   2023) and other recent drought and extreme heat events. These have been followed by severe
393   wildfires across continents in the Western US, Australia, the Mediterranean, Siberia, and most
394   recently Canada. Wildfire seasons and ranges have extended on every fire-prone continent and
395   intense fires appear to be damaging even fire-adapted ecosystems (e.g., Williams et al. 2019)
396   suggesting a rapidly growing risk. Fire and drought can lead to substantial changes in carbon
397   uptake or release (Humphrey et al., 2021), affect air quality over wide regions, and when
398   compounded heat and drought events can lead to failures of multiple breadbaskets (Zscheischler
399   et al. 2018) potentially affecting the global food supply (Korngruber et al. 2018; see also Meehl et
400   al., 2023). Although worsening heat and stronger evaporation exacerbating drought are features of
401   global warming (IPCC 2021), paleo records show the potential for very severe drought in the last
402   millennium (Cook et al., 2007). These records are crucial for testing our understanding and
403   modelling of regional rare climate extremes and tipping points (Braconnot et al. 2019, Hopcroft and
404   Valdes 2021), and show changes that might have contributed to civilisation collapse such as the
405   end of the Indus ~4.2 kyr BP (e.g. Staubwasser et al. 2003). The same arguments apply to risks
406   from rising sea level and severe rainfall, where recent events have led to surprisingly severe
407   consequences such as the Ahrtal floods of 2022 in Germany. We need to learn how the most
408   severe events unfold physically, even if future events will not be identical to them. In practice this
409   can be done using analogue methods or process studies (see Yiou et al., 2014; e.g. Cowan et al.,
410   2020b), and benefits from storyline approaches to specific events (Shepherd et al., 2018).
411   Ensemble boosting methods (Leach et al. 2022, Gessner 2022) and the UNSEEN method
412   (Thompson et al., 2017) can simulate feasible events similar to, but more severe than those which
413   occurred in reality or in a conventional simulation.

414   To generalise, we can use the model types and observations currently available but analyse them
415   in a more risk-facing way, focusing on thresholds, near-term irreversibility and the potential for
416   impacts to cascade. The design of the next modelling exercise (CMIP7 and beyond) is an
417   opportunity to go further to explore the potential for breaching tipping points within the coupled
418   Earth system using more complete models.

419   To get a better handle on LoHi events, we advocate a "what-if" strategy: first identify potentially
420   important event scenarios, then address their associated risks by separating the objectives of
421   estimating their probability vs. estimating their consequences. These two objectives can be met
422   with different modelling setups or observations; for example, consequences can be estimated by
423   imposing a scenario in an ensemble of ESM simulations (e.g., Amazon dieback in LUMIP) to build
424   a more complete picture, including for different scenario variants. Some tipping points, for example,
425   might have only modest impacts and so may not figure strongly in risk. Separate approaches
426   (perhaps combining model and long or paleo datasets) may be able to estimate scenario
427   probability (or plausibility). This strategy can be widely applied; for example in the expert elicitation
428   case of Dessai et al. (2018), impacts were expressed conditional on (unknown) changes in
429   moisture advection into a the study region, the probabilities of which could in turn be estimated
430   given other global-change scenarios. This approach of separating impact from probability could
431   also be useful for some compound events and event cascades, where the conditional probability of

432   one event given another can be estimated, although uncertainties inflate when estimating chains of
433   events.

434   Quantifying HiLo probabilities has been a serious challenge. For example although some individual
435   studies proposed quantitative probabilities for extreme sea level rise this century (DeConto et al.
436   2021, Bamber et al. 2021) this has not yet been attempted by WGI, who from AR4-AR6 tried
437   various other strategies to convey uncertainty (e.g. via caveats) and tail risks as relevant to
438   different stakeholders (Kopp 2023). Quantifying a PDF of climate sensitivity was likewise
439   contentious in assessments, but was eventually done with broad community support (Sherwood et
440   al. 2020). Even if challenging, a rough idea of the informed probability of HiLO events would be
441   extremely useful even if this involves transparently subjective judgments, since even careful and
442   well-intentioned qualitative explanations often end up misinterpreted or their caveats overlooked
443   (Kopp 2023). Interdisciplinary work across all IPCC working groups is needed to address HiLO
444   challenges.

445
446   ***More Complete Earth-System Modelling Approaches***
447

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

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

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

479   These needs for holism and large ensembles for risk assessment are in tension with the current
480   push for large-scale, ultra high-resolution (km-scale) atmosphere/ocean models, for example with
481   "digital twin" initiatives (Bauer et al. 2021). Such models are clearly of scientific value due to their
482   ability to simulate a great range of scale interactions in the atmosphere and ocean, which may
483   address long-standing biases and uncertainties, for example in circulation variability and change
484   (Palmer et al., 2022; Slingo et al., 2022). However, these high resolution models are too unwieldy
485   to be used for broad exploration of pathways or climate transitions (Stainforth and Calel 2021), to
486   include and resolve earth system feedbacks on their relevant timescales, or for more than a small
487   number of them to be developed. They therefore need to be complemented by simpler, faster
488   models that can for example accommodate feedbacks from the cryosphere or biosphere within
489   many possible climate trajectories.

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

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

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

520
521   ***Communication***
522

523   Achieving many of the goals above will be impossible without better communication between
524   disciplines. This may require long-term, interactive in-person collaboration to educate physical and
525   social scientists about one-anothers' conceptual approaches, methods, and terminology. It may be
526   valuable to develop educational resources targeted at this application. We also need to learn how

527 scientific understanding can be best used to inform effective decision making, recognizing that
528 models are but one source of information and guidance. These goals will require ongoing iteration
529 between the physical science community and climate information users, as well as the
530 development of a community of science practitioners who can apply scientific knowledge to thorny
531 complex problems. The communication of climate information to stakeholders, via e.g., climate
532 services, is still underdeveloped (e.g., Hansen et al. 2019).

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

544 Communication needs to distinguish between genuinely unlikely and more probable events. Some
545 challenging high-impact possibilities are not even LoHi's because they are increasingly likely. New
546 signs are emerging that the West Antarctic Ice Sheet (WAIS) is becoming unstable (Gudmundsson
547 et al. 2019), so its eventual collapse (perhaps centuries from now) is not unlikely. Likewise, tree
548 mortality is accelerating in the Amazon rainforest (Hubau et al. 2020) and observed hydrological
549 changes suggest a few areas could be approaching collapse (Fig. 5; Saatchi et al. 2021). Some
550 transitions (e.g., collapse of WAIS) are low-likelihood in the near term, but become probable with
551 more warming. Because, like most LoHi's, these high-impact events have no historical analogue, it
552 is challenging to tally their costs or get people to appreciate and act on the risks, both for
553 interdisciplinary as well as public communication. Record-breaking weather and climate extremes
554 also fit in this category. The lack of experienced analogues is why some citizens don't respond to
555 warnings about extreme events, mirroring the global-scale readiness problem for anything
556 unprecedented (e.g., Baron and Petersen 2015), while others may respond with climate doom-ism
557 which is not helpful either.

558 When communicating extreme climate risk including that of tipping points, it is therefore important
559 to provide a sense of perspective, emphasising how a combination of mitigation and adaptation
560 can help to navigate climate risk, and how positive tipping may accelerate the transition (e.g.,
561 Tabara et al., 2018). The study of pathways that incorporate both hazards and responses,
562 preferably in an interactive and adaptable way, are able to support gaming and communications
563 platforms that convey this sense of agency.

564

565 Conclusion

566

567 We propose a strategy that pivots physical climate science toward addressing pressing needs by
568 answering questions about, first, global climate-related risks (including low-likelihood, high-impact
569 events) and how to communicate them, and second, possible self-consistent pathways (good or
570 bad) that lay before us. This strategy involves a stronger focus on worst-case outcomes and limits
571 to adaptation that must be avoided, but also aims to identify and hence avoid maladaptation
572 scenarios that could unintentionally upset climate or other Sustainable Development Goals. More
573 serious global risks need to be separated from less serious ones by an evidence-based approach.

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

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

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

600

601 **AVAILABILITY STATEMENT**
602 No new software or data were generated for this article.

603

604 **REFERENCES**

605 Ackerman, F and Stanton, EA Climate Risks and Carbon Prices: Revising the Social Cost of Carbon. Economics-The Open
606 Access Open-Assessment E-Journal, Volume6, Article Number201210, (2012), DOI10.5018/economics-ejournal.ja.2012-10

607 Armstrong McKay, D.I., Staal, A., Abrams, J.F., Winkelmann, R., Sakschewski, B., Loriani, S., Fetzer, I., Cornell, S.E.,
608 Rockström, J. and Lenton, T.M., 2022. Exceeding 1.5° C global warming could trigger multiple climate tipping points. Science,
609 377(6611), p.eabn7950.

610 Bador, Margot; Donat, Markus G.; Geoffroy, Olivier; Alexander, Lisa V., Assessing the Robustness of Future Extreme
611 Precipitation Intensification in the CMIP5 Ensemble. Journal of Climate, Vol. 31 Issue 16, pp. 6505–6525, 2018.

612 Bamber, J. L., M. Oppenheimer, R. E. Kopp and R. M Cooke, Ice sheet contributions to future sea-level rise from structured
613 expert judgment, PNAS 116, 116 (23) 11195-11200, https://doi.org/10.1073/pnas.1817205116

614 Baron, N. and Petersen, L.K., 2015. Climate change or variable weather: rethinking Danish homeowners' perceptions of floods
615 and climate. Regional Environmental Change, 15(6), pp.1145-1155.

616 Bartels, E. M., Incorporating Gaming into Research Programs in International Relations: Repetition, Game Series, and Multi-
617 Method Analysis, APSA Annual Conference, September 11, 2020.

618 Bauer, P., Stevens, B. & Hazeleger, W. A digital twin of Earth for the green transition. *Nat. Clim. Chang*. 11, 80–83 (2021).
619 https://doi.org/10.1038/s41558-021-00986-y

620 Bjordal, J., Storelvmo, T., Alterskjær, K. et al. Equilibrium climate sensitivity above 5°C plausible due to state-dependent cloud
621 feedback. Nat. Geosci. 13, 718–721 (2020). https://doi.org/10.1038/s41561-020-00649-1

Bontoux L, Sweeney JA, Rosa AB, Bauer A, Bengtsson D, Bock A-K, Caspar B, Charter M, Christophilopoulos E, Kupper F, Macharis C, Matti C, Matrisciano M, Schuijer J, Szczepanikova A, van Criekinge T & Watson R, A Game for All Seasons: Lessons and Learnings from the JRC's Scenario Exploration System, World Futures Review, 2020, Vol. 12(1) 81–103, DOI: 10.177/1946756719890524

Braconnot, P, J. Cretat,O.; Marti, Y. Balkanski, A. Caubel, A. Cozic, M.A. Foujols, and S. Sanogo, Impact of Multiscale Variability on Last 6,000 Years Indian and West African Monsoon Rain, Geophys. Res. Lett., 2019, 46, 14021-14029, DOI10.1029/2019GL084797.

Caesar, L., Rahmstorf, S., Robinson, A., Feulner, G. and Saba, V., 2018. Observed fingerprint of a weakening Atlantic Ocean overturning circulation. Nature, 556(7700), pp.191-196.

Cai, Y. Y. and TS.. Lontzek, The Social Cost of Carbon with Economic and Climate Risks, J. Political Economy,Volume: 127 Pages: 2684-2734, DOI: 10.1086/701890.

Calel, R., Chapman, S.C., Stainforth, D.A. *et al.* Temperature variability implies greater economic damages from climate change. *Nat Commun* **11**, 5028 (2020). https://doi.org/10.1038/s41467-020-18797-8

Canadell, J.G., P.M.S. Monteiro, M.H. Costa, L. Cotrim da Cunha, P.M. Cox, A.V. Eliseev, S. Henson, M. Ishii, S. Jaccard, C. Koven, A. Lohila, P.K. Patra, S. Piao, J. Rogelj, S. Syampungani, S. Zaehle, and K. Zickfeld, 2021: Global Carbon and other Biogeochemical Cycles and Feedbacks. In Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 673–816, doi:10.1017/9781009157896.007.

Carlson, H. and R. Caballero, Enhanced MJO and transition to superrotation in warm climates. JAMES, 2016, DOI:10.1002/2015MS000615

Centre for Public Impact, Public Engagement for Net-Zero: A Literature review, https://www.centreforpublicimpact.org/assets/documents/cpi-cgf-public-engagement-net-zero-lit-review.pdf

Chen, D., M. Rojas, B.H. Samset, K. Cobb, A. Diongue Niang, P. Edwards, S. Emori, S.H. Faria, E. Hawkins, P. Hope, P. Huybrechts, M. Meinshausen, S.K. Mustafa, G.-K. Plattner, and A.-M. Tréguier, 2021: Framing, Context, and Methods. InClimate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change[Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 147–286, doi:10.1017/9781009157896.003.

Cohen-Solal, E and Le Treut, H., 1999. Unstable behaviour of an upper ocean atmosphere coupled model: role of atmospheric radiative processes and oceanic heat transport. Clim. Dyn., 15, 895-908. DOI10.1007/s003820050320.

Cook, E., R. Seager, M. Cane and D. W. Stahle (2007). North American drought: Reconstructions, causes, and consequences. Earth Sci. Rev., 81, 93-134.

Cowan, T, Hegerl, GC, Schurer, Andrew, Tett, SFB, Vautard, R, Yiou, P, Jezequel, A, Otto, FEL, Harrington, LJ, and Ng, B (2020): Ocean and land forcing of the record-breaking Dust Bowl heatwaves across central United States. Nature Communications 11.

Crutzen, P.J. My life with O_3, NO_x, and other YZO_x compounds (Nobel Lecture). Angew. Chem. Int. Ed. Engl. 35, 1758– 1777 (1996).

DeConto, R.M., Pollard, D., Alley, R.B. et al. The Paris Climate Agreement and future sea-level rise from Antarctica. *Nature* 593, 83–89 (2021). https://doi.org/10.1038/s41586-021-03427-0

Dessai, S. et al 2018 Building narratives to characterise uncertainty in regional climate change through expert elicitation. Environ. Res. Lett. 13 074005, DOI 10.1088/1748-9326/aabcdd

Dewulf, A. and Termeer, C., 2015. Governing the future? The potential of adaptive delta management to contribute to governance capabilities for dealing with the wicked problem of climate change adaptation. Journal of Water and Climate Change, 6(4), pp.759-771.

Dommenget, D. and M. Rezny (2018), A Caveat Note on Tuning in the Development of Coupled Climate Models, JAMES, 10, 78-97, DOI10.1002/2017MS000947.

Edwards, T. L., Nowicki, S., Marzeion, B., Hock, R., Goelzer, H., Seroussi, H., Jourdain, N. C., Slater, D. A., Turner, F. E., Smith, C. J., McKenna, C. M., Simon, E., Abe-Ouchi, A., Gregory, J. M., Larour, E., Lipscomb, W. H., Payne, A. J., Shepherd, A., Agosta, C., Alexander, P., Albrecht, T., Anderson, B., Asay-Davis, X., Aschwanden, A., Barthel, A., Bliss, A., Calov, R., Chambers, C., Champollion, N., Choi, Y., Cullather, R., Cuzzone, J., Dumas, C., Felikson, D., Fettweis, X., Fujita, K., Galton-

675 Fenzi, B. K., Gladstone, R., Golledge, N. R., Greve, R., Hattermann, T., Hoffman, M. J., Humbert, A., Huss, M., Huybrechts, P.,
676 Immerzeel, W., Kleiner, T., Kraaijenbrink, P., Le clec'h, S., Lee, V., Leguy, G. R., Little, C. M., Lowry, D. P., Malles, J. H., Martin,
677 D. F., Maussion, F., Morlighem, M., O'Neill, J. F., Nias, I., Pattyn, F., Pelle, T., Price, S. F., Quiquet, A., Radić, V., Reese, R.,
678 Rounce, D. R., Rückamp, M., Sakai, A., Shafer, C., Schlegel, N. J., Shannon, S., Smith, R. S., Straneo, F., Sun, S., Tarasov, L.,
679 Trusel, L. D., Van Breedam, J., van de Wal, R., van den Broeke, M., Winkelmann, R., Zekollari, H., Zhao, C., Zhang, T., and
680 Zwinger, T.: Projected land ice contributions to 21st century sea level rise, *Nature*, 593(7857), 74–82,
681 https://doi.org/10.1038/s41586-021-03302-y, 2021.

682 Eyring, V., Bony, S., Meehl, G. A., Senior, C. A., Stevens, B., Stouffer, R. J., and Taylor, K. E.: Overview of the Coupled Model
683 Intercomparison Project Phase 6 (CMIP6) experimental design and organization, *Geosci. Model Dev.*, 9, 1937–1958,
684 https://doi.org/10.5194/gmd-9-1937-2016, 2016.

685 Eyring V; Cox PM; Flato GM; Gleckler PJ; Abramowitz G; Caldwell P; Collins WD; Gier BK; Hall AD; Hoffman FM; Hurtt GC;
686 Jahn A; Jones CD; Klein SA; Krasting JP; Kwiatkowski L; Lorenz R; Maloney E; Meehl GA; Pendergrass AG; Pincus R; Ruane
687 AC; Russell JL; Sanderson BM; Santer BD; Sherwood SC; Simpson IR; Stouffer RJ; Williamson MS, 2019, 'Taking climate
688 model evaluation to the next level', Nature Climate Change, vol. 9, pp. 102 - 110, http://dx.doi.org/10.1038/s41558-018-0355-
689 y

690 Exarchou, E., C. Prodhomme, L. Brodeau, V. Guemas, and F. Doblas-Reyes, 2018: Origin of the warm eastern tropical Atlantic
691 SST bias in a climate model. Clim Dyn, 51, 1819–1840, https://doi.org/10.1007/s00382-017-3984-3.

692 Fischer, E. M., S. Sippel and R. Knutti, Increasing probability of record-shattering climate extremes. *Nat. Climate Change*, 11,
693 2021, 689–695, 10.1038/s41558-021-01092-9.

694 Franzke, CLE et al 2022: Perspectives on tipping points in integrated models of the natural and human Earth system:
695 cascading effects and telecoupling. Environ. Res. Lett. 17 015004

696 Freychet, N. et al. Robust increase in population exposure to heat stress with increasing global warming. Environ. Res. Lett.
697 17, 064049 (2022).

698 Gerrard, M. & G. E. Wannier, Threatened Island Nations:Legal Implications of Rising Seas and a Changing Climate, (Co-
699 Editors) (Cambridge University Press, 2013).

700 Gessner, C. (2022) Physical storylines for very rare climate extremes. Ph.D. Thesis, ETH Zurich. https://doi.org/10.3929/ethz-
701 b-000591221

702 Gudmundsson, G. H., Paolo, F. S., Adusumilli, S., & Fricker, H. A. (2019). Instantaneous Antarctic ice- sheet mass loss driven
703 by thinning ice shelves. Geophysical Research Letters, 46, 13903– 13909. https://doi.org/10.1029/2019GL085027

704 Haasnoot, M., Kwakkel, J. H., Walker, W. E., & Maat, J. ter. (2013). Dynamic adaptive policy pathways: A method for crafting
705 robust decisions for a deeply uncertain world. Global Environmental Change, 23(2), 485–498.

706 Hansen J, Furlow J, Goddard L, Nissan H, Vaughan C, Rose A, Fiondella F, Braun M, Steynor A, Jack C, Chinowsky P,
707 Thomson M, Baethgen W, Dinku T, Senato AY, Do MP, Huq S, Ndiaye O. 2019. Scaling Climate Services to Enable Effective
708 Adaptation Action. Rotterdam, the Netherlands & Washington, DC, United States: Global Commission on Adaptation.
709 https://hdl.handle.net/10568/105763.

710 Heinze, C. T. Blenckner, H. Martins, D. Rusiecka, R. Döscher, M. Gehlen, N. Gruber, E. Holland, Ø. Hov, F. Joos, J. B. R.
711 Matthews, R. Rødven, and S. Wilson: The quiet crossing of ocean tipping points, Proceedings of the National Academy of
712 Sciences of the United States of America,118 (9) e2008478118; https://doi.org/10.1073/pnas.2008478118, 2021.

713 Henry, R. C. et al. (2022). Global and regional health and food security under strict conservation scenarios. Nature
714 Sustainability 5.4, pp. 303–310.

715 Hermans, L. M., M. Haasnoot, J. ter Maat and J. Kwakkel (2017). Designing monitoring arrangements for collaborative learning
716 about adaptation pathways. Environmental Science & Policy 69 (2017) 29–38. http://dx.doi.org/10.1016/j.envsci.2016.12.005.

717 Hopcroft, P.O. and P.J.Valdes (2021), Paleoclimate-conditioning reveals a North Africa land-atmosphere tipping point, *Proc.*
718 *Nat. Acad. Sci.* 118, e2108783118, 10.1073/pnas.2108783118.

719 Houston, J.R., 2021. Sea-Level Acceleration: Analysis of the World's High-Quality Tide Gauges. Journal of Coastal Research,
720 37(2), pp.272-279.

721 Hubau, W., Lewis, S.L., Phillips, O.L. et al. Asynchronous carbon sink saturation in African and Amazonian tropical forests.
722 Nature 579, 80–87 (2020). https://doi.org/10.1038/s41586-020-2035-0

723 Humphrey, V., Berg, A., Ciais, P. et al. Soil moisture–atmosphere feedback dominates land carbon uptake variability. Nature
724 592, 65–69 (2021). https://doi.org/10.1038/s41586-021-03325-5

725 IPBES, 2019: Summary for policymakers of the global assessment report on biodiversity and ecosystem services of the
726 Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. S. Díaz, J. Settele, E. S. Brondízio, H. T.

Ngo, M. Guèze, J. Agard, A. Arneth, P. Balvanera, K. A. Brauman, S. H. M. Butchart, K. M. A. Chan, L. A. Garibaldi, K. Ichii, J. Liu, S. M. Subramanian, G. F. Midgley, P. Miloslavich, Z. Molnár, D. Obura, A. Pfaff, S. Polasky, A. Purvis, J. Razzaque, B. Reyers, R. Roy Chowdhury, Y. J. Shin, I. J. Visseren-Hamakers, K. J. Willis, and C. N. Zayas (eds.). IPBES secretariat, Bonn, Germany. 56 pages. https://doi.org/10.5281/zenodo.3553579

IMCCS (International Military Council on Climate and Security) 2021 The world climate and security report 2021 available at: https://imccs.org/the-world-climate-and-security-report-2021.

IPCC, 2019: Summary for Policymakers. In: IPCC Special Report on the Ocean and Cryosphere in a Changing Climate [H.-O. Pörtner, D.C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegría, M. Nicolai, A. Okem, J. Petzold, B. Rama, N.M. Weyer (eds.)].

IPCC, 2021: Summary for Policymakers. In: *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)].

IPCC, 2022: Summary for Policymakers [H.-O. Pörtner, D.C. Roberts, E.S. Poloczanska, K. Mintenbeck, M. Tignor, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem (eds.)]. In: Climate Change 2022: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, B. Rama (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 3-33, doi:10.1017/9781009325844.001.

IWR. International World Report. 2011. Flood Risk Management Approaches: As being practiced in Japan, Netherlands, United Kingdom and United States. IWR Report No: 2011-R-08. 126pp.

Jackson, L. C., R. Kahana, T. Graham, M. A. Ringer, T. Woollings, J. V. Mecking, and R. A. Wood (2015), Global and European climate impacts of a slowdown of the AMOC in a high resolution GCM, Clim Dynam, 45(11-12), 3299-3316, https://doi.org/10.1007/s00382-015-2540-2.

Kajtar, JB, A. Santoso, S. McGregor, MH England, and Z Baillie (2018), Model under-representation of decadal Pacific trade wind trends and its link to tropical Atlantic bias. Clim. Dyn. 560, 1471-1484. DOI10.1007/s00382-017-3699-5.

Kim, YH, SK Min, XB Zhang, J Sillmann, and M Sandstad, Evaluation of the CMIP6 multi-model ensemble for climate extreme indices. Wea. Clim. Extremes 29, Art. 100269 (2020), DOI10.1016/j.wace.2020.100269.

Kopp, R. E., Hay, C. C., Little, C. M., & Mitrovica, J. X. (2015). Geographic variability of sea-level change. Current Climate Change Reports, 1(3), 192-204.

Kopp, R.E., Oppenheimer, M., O'Reilly, J.L. et al. Communicating future sea-level rise uncertainty and ambiguity to assessment users. Nat. Clim. Chang. 13, 648–660 (2023). https://doi.org/10.1038/s41558-023-01691-8

Kornhuber, K. et al. (2020). Amplified Rossby waves enhance risk of concurrent heatwaves in major breadbasket regions. Nature Climate Change 10.1, pp. 48–53.

Kotz, M., Levermann, A. & Wenz, L. The effect of rainfall changes on economic production. Nature 601, 223–227 (2022). https://doi.org/10.1038/s41586-021-04283-8

Lade, S.J., Steffen, W., de Vries, W. et al. Human impacts on planetary boundaries amplified by Earth system interactions. *Nat Sustain* 3, 119–128 (2020). https://doi.org/10.1038/s41893-019-0454-4

Lambert, Catherine E., et al. "Eroding Land and Erasing Place: A Qualitative Study of Place Attachment, Risk Perception, and Coastal Land Loss in Southern Louisiana." Sustainability 13.11 (2021): 6269.

Leach NJ, Watson PAG, Sparrow SN, et al (2022) Generating samples of extreme winters to support climate adaptation. Weather Clim Extrem 36, 100419. doi: 10.1016/j.wace.2022.100419.

Lemos, M. C. and R. Rood, Climate projections and their impact on policy and practice. *WIREs Climate Change* 1:5, 670-682. https://wires.onlinelibrary.wiley.com/doi/10.1002/wcc.71.

Lenton, Timothy M., Johan Rockström , Owen Gaffney , Stefan Rahmstorf , Katherine Richardson , Will Steffen & Hans Joachim Schellnhuber, Climate tipping points — too risky to bet against. *Nature* 575, 592-595 (2019), doi: https://doi.org/10.1038/d41586-019-03595-0

Lontzek, T. S., Y. Y. Cai, K. L, Judd, and T. M. Lenton, Stochastic integrated assessment of climate tipping points indicates the need for strict climate policy. Nat. Clim. Change, 5, 441-444 (2015), DOI: 10.1038/NCLIMATE2570.

MacDougall, A. H., Frölicher, T. L., Jones, C. D., Rogelj, J., Matthews, H. D., Zickfeld, K., Arora, V. K., Barrett, N. J., Brovkin, V., Burger, F. A., Eby, M., Eliseev, A. V., Hajima, T., Holden, P. B., Jeltsch-Thömmes, A., Koven, C., Mengis, N., Menviel, L., Michou, M., Mokhov, I. I., Oka, A., Schwinger, J., Séférian, R., Shaffer, G., Sokolov, A., Tachiiri, K., Tjiputra , J., Wiltshire, A.,

779 and Ziehn, T.: Is there warming in the pipeline? A multi-model analysis of the Zero Emissions Commitment from CO2,
780 Biogeosciences, 17, 2987–3016, https://doi.org/10.5194/bg-17-2987-2020, 2020.

781 McKinnon, K.A. and Simpson, I.R., 2022. How unexpected was the 2021 Pacific Northwest heatwave?. Geophysical Research
782 Letters, 49(18), p.e2022GL100380.

783 McNorton, J., Wilson, C., Gloor, M., Parker, R. J., Boesch, H., Feng, W., Hossaini, R., and Chipperfield, M. P.: Attribution of
784 recent increases in atmospheric methane through 3-D inverse modelling, Atmos. Chem. Phys., 18, 18149–18168,
785 https://doi.org/10.5194/acp-18-18149-2018, 2018.

786 Meehl, G.A., Teng, H., Rosenbloom, N. et al. How the Great Plains Dust Bowl drought spread heat extremes around the
787 Northern Hemisphere. Sci Rep 12, 17380 (2022). https://doi.org/10.1038/s41598-022-22262-5

788 Mitrovica, J. X., N. Gomez, and P. U. Clark (2009), The Sea-Level Fingerprint of West Antarctic Collapse, Science, 323(5915),
789 753-753, https://doi.org/10.1126/science.1166510.

790 Monteverde, C., F. De Sales, and C. Jones, 2022: Evaluation of the CMIP6 Performance in Simulating Precipitation in the
791 Amazon River Basin. Climate, 10, 122, https://doi.org/10.3390/cli10080122.

792 Moore, F. C., K. Lacasse, K.j.Mach, Y. A. Shin, L. J. Gross and B. Beckage (2022), Determinants of emissions pathways in the
793 coupled climate–social system, *Nature*, 603, 103-111, 10.1038/s41586-022-04423-8.

794 Natali, Susan M., John P. Holdren, Brendan M. Rogers, Rachael Treharne, Philip B. Duffy, Rafe Pomerance, and Erin
795 MacDonald, Permafrost carbon feedbacks threaten global climate goals. *PNAS*, May 25, 2021 118 (21) e2100163118;
796 https://doi.org/10.1073/pnas.2100163118.

797 National Academies of Sciences, Engineering, and Medicine. 2016. Attribution of Extreme Weather Events in the Context of
798 Climate Change. Washington, DC: The National Academies Press. https://doi.org/10.17226/21852.

799 Nordhaus, WD The Economics of Tail Events with an Application to Climate Change Review Of Environmental Economics And
800 Policy, Volume5, Issue2, Page240-257 (2011). DOI10.1093/reep/rer004

801 Ocko, I. B. and Hamburg, S. P.: Climate consequences of hydrogen emissions, Atmos. Chem. Phys., 22, 9349–9368,
802 https://doi.org/10.5194/acp-22-9349-2022, 2022.

803 Palmer, T. & Stevens, B. The Scientific Challenge of Understanding and Estimating Climate Change. Proceedings of the
804 National Academy of Sciences 116, 24390–24395. (2022) (Dec.18, 2019).

805 Pörtner, H.O., Scholes, R.J., Agard, J., Archer, E., Arneth, A., Bai, X., Barnes, D., Burrows, M., Chan, L., Cheung, W.L.,
806 Diamond, S., Donatti, C., Duarte, C., Eisenhauer, N., Foden, W., Gasalla, M. A., Handa, C., Hickler, T., Hoegh-Guldberg, O.,
807 Ichii, K., Jacob, U., Insarov, G., Kiessling, W., Leadley, P., Leemans, R., Levin, L., Lim, M., Maharaj, S., Managi, S., Marquet, P.
808 A., McElwee, P., Midgley, G., Oberdorff, T., Obura, D., Osman, E., Pandit, R., Pascual, U., Pires, A. P. F., Popp, A., Reyes-
809 García, V., Sankaran, M., Settele, J., Shin, Y. J., Sintayehu, D. W., Smith, P., Steiner, N., Strassburg, B., Sukumar, R., Trisos,
810 C., Val, A.L., Wu, J., Aldrian, E., Parmesan, C., Pichs-Madruga, R., Roberts, D.C., Rogers, A.D., Díaz, S., Fischer, M.,
811 Hashimoto, S., Lavorel, S., Wu, N., Ngo, H.T. 2021. Scientific outcome of the IPBES-IPCC co-sponsored workshop on
812 biodiversity and climate change; IPBES secretariat, Bonn, Germany, DOI:10.5281/zenodo.4659158.

813 Purich, A., Doddridge, E.W. Record low Antarctic sea ice coverage indicates a new sea ice state. Commun Earth Environ 4,
814 314 (2023). https://doi.org/10.1038/s43247-023-00961-9

815 Quiquet, A., Roche, D. M., Dumas, C., Bouttes, N., and Lhardy, F. (2021) Climate and ice sheet evolutions from the last glacial
816 maximum to the pre-industrial period with an ice-sheet–climate coupled model, Clim. Past, 17, 2179–2199,
817 https://doi.org/10.5194/cp-17-2179-2021.

818 Ramanathan, V., Y. Xu and T. Versace, 2022, Modelling human-natural systems interactions with implications for twenty-first-
819 century warming. *Nat. Sustainability*, 5, 263-271, https://doi.org/10.1038/s41893-021-00826-z.

820 Rasp, S., Pritchard, M. S. & Gentine, P. Deep learning to represent subgrid processes in climate models. Proc National Acad
821 Sci 115, 201810286 (2018).

822 Ratnayake, H. U., M. R. Kearney, P. Govekar, D. Karoly, and J. A. Welbergen (2019), Forecasting wildlife die-offs from extreme
823 heat events, Animal Conservation, 22, 386-395. https://doi.org/10.1111/acv.12476.

824 Riahi et al., 2017, The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions
825 implications: An overview, *Global Env. Change*, 153-168, doi.org/10.1016/j.gloenvcha.2016.05.009.

826 Rising, J., Tedesco, M., Piontek, F. & Stainforth, D. A. The missing risks of climate change. Nature 610, 643–651 (2022).

827 Rockström, J., W. Steffen, K. Noone, Å. Persson, et.al. 2009. Planetary boundaries: exploring the safe operating space for
828 humanity. Ecology and Society 14(2): 32

829 Saatchi, S. et al., (2021) Detecting vulnerability of humid tropical forests to multiple stressors. One Earth, 4, 988-1003,
830 https://doi.org/10.1016/j.oneear.2021.06.002.

831 Sallenger, A., Doran, K, and Howd, P., 2012. Hotspot of accelerated sea-level rise on the Atlantic coast of North America.
832 Nature Climate Change, DOI: 10.1038/NCLIMATE1597.

833 Salvatecchi et al. Smaller fish species in a warm and oxygen-poor Humboldt Current system DOI: 10.1126/science.abj0270

834 Scambos, T., Bell, R.E., Alley, R.B., Anandakrishnan, S., Bromwich, D.H., Brunt, K., Christianson, K., Creyts, T., Das, S.B.,
835 DeConto, R., et al. (2017). How much, how fast?: a review and science plan for research on the instability of Antarctica's
836 Thwaites Glacier in the 21st century. Glob. Planet. Change 153, 16–34.

837 Sharkov, E.V. Catastrophic Volcanic Eruptions: Causes and Mechanisms. J. Volcanolog. Seismol. 14, 373–378 (2020).
838 https://doi.org/10.1134/S0742046320040041.

839 Shepherd, T. G., Boyd, E., Calel, R. A., Chapman, S. C., Dessai, S., Dima-West, I. M., Fowler, H. J., James, R., Maraun, D.,
840 Martius, O., Senior, C. A., Sobel, A. H., Stainforth, D. A., Tett, S. F. B., Trenberth, K. E., van den Hurk, B. J. J. M., Watkins, N.
841 W., Wilby, R. L. and Zenghelis, D. A. (2018) *Storylines: an alternative approach to representing uncertainty in physical aspects*
842 *of climate change.* Climatic Change, 151 (3-4). pp. 555-571. ISSN 0165-0009 doi: https://doi.org/10.1007/s10584-018-2317-9

843 Sherwood, S. C. and M. Huber, An adaptability limit to global warming due to heat stress, *Proceedings of the National*
844 *Academy of Sciences*, Vol. 107, 2010, 9552-9555, doi:10.107/pnas.0913352107.

845 S. C. Sherwood, M. J. Webb, J. D. Annan, K. C. Armour, P. M. Forster, J. C. Hargreaves, G. Hegerl, S. A. Klein, K. D. Marvel, E.
846 J. Rohling, M. Watanabe, T. Andrews, P. Braconnot, C. S. Bretherton, G. L. Foster, Z. Hausfather, A. S. von der Heydt, R.
847 Knutti, T. Mauritsen, J. R. Norris, C. Proistosescu, M. Rugenstein, G. A. Schmidt, K. B. Tokarska, M. D. Zelinka, An
848 Assessment of Earth's Climate Sensitivity Using Multiple Lines of Evidence, 2020. *Rev. Geophys.*,
849 https://doi.org/10.1029/2019RG000678.

850 Simpson, N.P. et al, A framework for complex climate change risk assessment, One Earth, 4, 489-501, 2021.
851 DOI:https://doi.org/10.1016/j.oneear.2021.03.005

852 Slingo, J., Bates, P., et al. Ambitious Partnership Needed for Reliable Climate Prediction.20. Nat. Clim. Chang. 12, 499–503.
853 issn: 1758-6798. (2022) (June 2022).

854 Solomon, S., Stratospheric ozone depletion: A review of concepts and history, *Rev. Geophys.*, 1999, 37, 275-316,
855 10.1029/1999RG900008.

856 Stainforth and Calel Nat Comm 2021 New Priorities for Climate Sci and Climate Economics in the 2020's
857 https://doi.org/10.1038/s41467-020-16624-8

858 M. Staubwasser, F. Sirocko, P. M. Grootes, M. Segl (2003). Climate change at the 4.2 ka BP termination of the Indus valley
859 civilization and Holocene south Asian monsoon variability. Geophys. Res. Lett., 30, 1425.
860 https://doi.org/10.1029/2002GL016822.

861 Sutton, RT (2019): Climate Science Needs to Take Risk Assessment Much More Seriously *Bull. Amer. Meteorolog. Soc.*,   DOI:
862 10.1175/BAMS-D-18-0280.1

863 Tàbara, J.D., Frantzeskaki, N., Hölscher, K., Pedde, S. Lamperti, F. Kok, K., Christensen, J.H., Jäger, J., and P. Berry. 2018.
864 Positive tipping points for a rapidly warming world. Current Opinion in Environmental Sustainability. Special Issue on
865 Sustainability Governance and Transformation, 31: 120-129. https://doi.org/10.1016/j.cosust.2018.01.012

866 Thompson, V., Dunstone, N.J., Scaife, A.A. et al. High risk of unprecedented UK rainfall in the current climate. Nat Commun 8,
867 107 (2017). https://doi.org/10.1038/s41467-017-00275-3Trauernicht, C. (2017). Global risk of deadly heat. Nature climate
868 change, 7(7), 501-506.

869 Turetsky, M.R., Abbott, B.W., Jones, M.C. et al. Carbon release through abrupt permafrost thaw. *Nat. Geosci.* 13, 138–143
870 (2020). https://doi.org/10.1038/s41561-019-0526-0

871 Wang, S. et al. (2023). Mechanisms and Impacts of Earth System Tipping Elements. Reviews of Geophysics 61.1.

872 Weitzmann, M. On Modeling And Interpreting The Economics Of Catastrophic Climate Change. Review Of Economics And
873 Statistics, Volume91, Issue1, Page1-19 (2009). DOI10.1162/rest.91.1.1

874 Weitzman, ML (Weitzman, Martin L.) GHG Targets as Insurance Against Catastrophic Climate Damages. Journal Of Public
875 Economic Theory, Volume14, Issue2, Page221-244 (2012), DOI10.1111/j.1467-9779.2011.01539.x

876 Wenzel, M. and Schroter, J., 2010. Reconstruction of regional mean ¨ sea level anomalies from 595 tide gauges using neural
877 networks. Journal of Geophysical Research, 115(C8), C08013.

878 White, JW, G. Hoogenboom, B. A. Kimball and G.W. Wall. Methodologies for simulating impacts of climate change on crop
879 production. Field Crops Research, 124, 357-368 (2011) 10.1016/j.fcr.2011.07.001

880 Wilby, R. L. and S. Dessai. 2010. Robust adaptation to climate change. Weather, 65(7), 180-185.

881 Williams, A. P. et al. (2019). Observed Impacts of Anthropogenic Climate Change on Wildfire in California. Earth's Future 7.8,
882 pp. 892–910.

883 Winkelmann, R, Donges, JF, Smith, EK, Milkoreit, M, Eder, C, Heitzig, J, Katsanidou, A, Wiedermann, M, Wunderling, N,
884 Lenton T. M.. Social tipping processes towards climate action: A conceptual framework. Ecological Economics, 192. Article
885 Num. 107242 (2022) DOI10.1016/j.ecolecon.2021.107242.

886 Wunderling, N. and J. F. Donges and J. Kurths and R. Winkelmann, Interacting tipping elements increase risk of climate
887 domino effects under global warming, *Earth System Dynamics*, 12, 601-619 (2021) 10.5194/esd-12-601-2021.

888 Yiou, P., Boichu, M., Vautard, R., Vrac, M., Jourdain, S., Garnier, E., Fluteau, F. and Menut, L. (2014) Ensemble meteorological
889 reconstruction using circulation analogues of 1781-1785. Climate of the Past, 10, 797–809.

890 Zevenbergen, C., Khan, S.A., van Alphen, J., Terwisscha van Scheltinga, C. and Veerbeek, W., 2018. Adaptive delta
891 management: a comparison between the Netherlands and Bangladesh Delta program. International Journal of River Basin
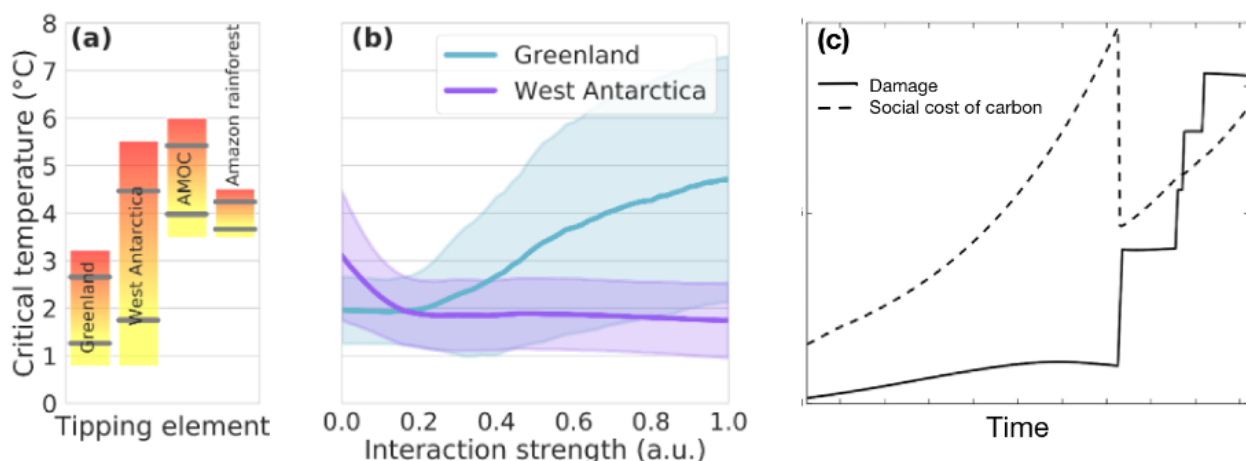892 Management, 16(3), pp.299-305.

893 Zommers, Z., Marbaix, P., Fischlin, A. et al. Burning embers: towards more transparent and robust climate-change risk
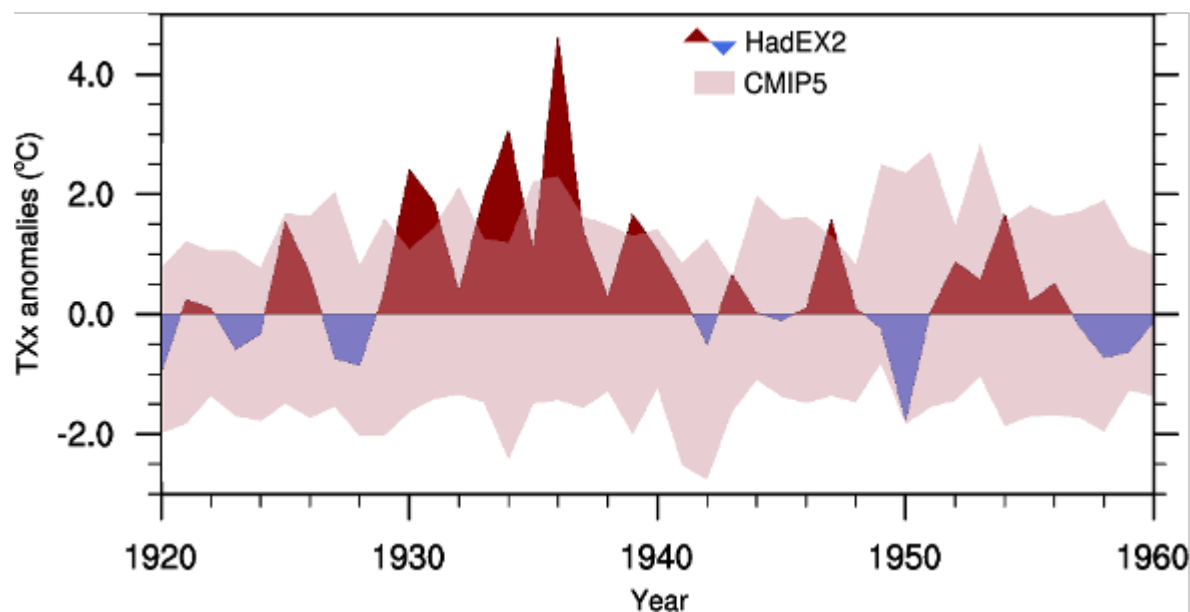894 assessments. *Nat Rev Earth Environ* 1, 516–529 (2020). https://doi.org/10.1038/s43017-020-0088-0

895 Zscheischler, J., et al. (2018). Future climate risk from compound events. Nature Climate Change, 8(6), 469-477.

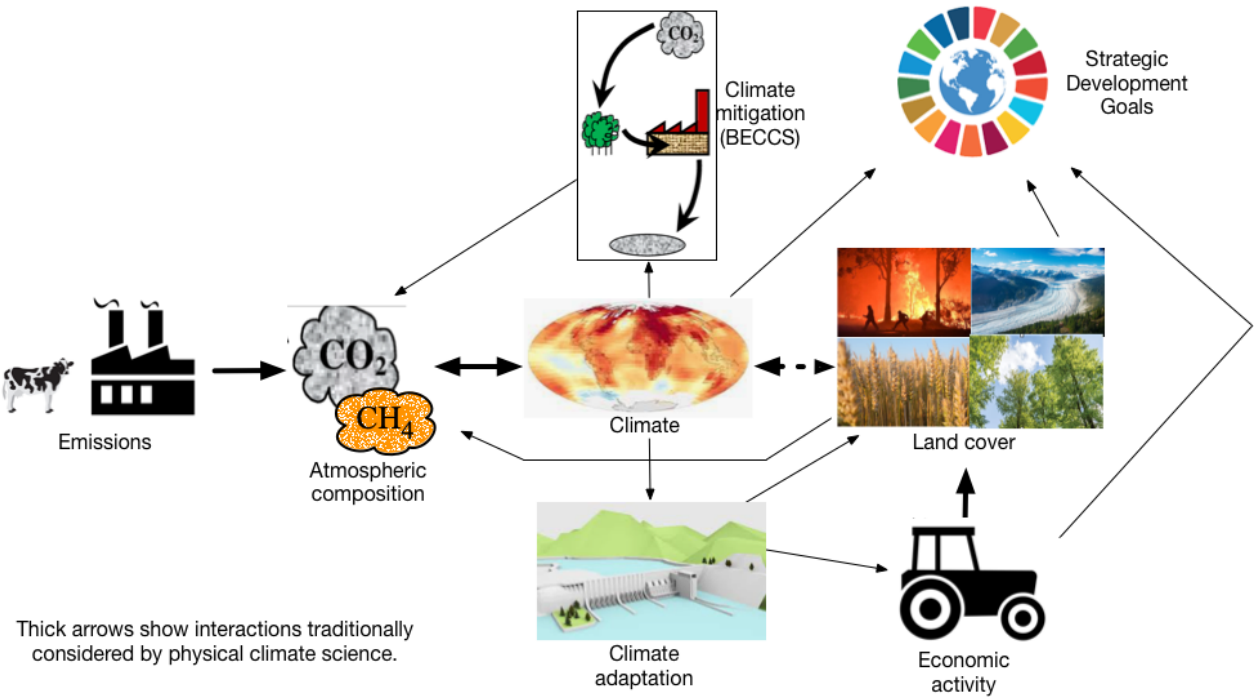**Figure 1. Transition thresholds for important geophysical system transitions remain highly uncertain. (A) Warming thresholds estimated for a few isolated tipping point transitions. (B) If the two systems interact strongly (higher values of interaction strength), a collapse of the WAIS may increase 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).

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Thick arrows show interactions traditionally considered by physical climate science.

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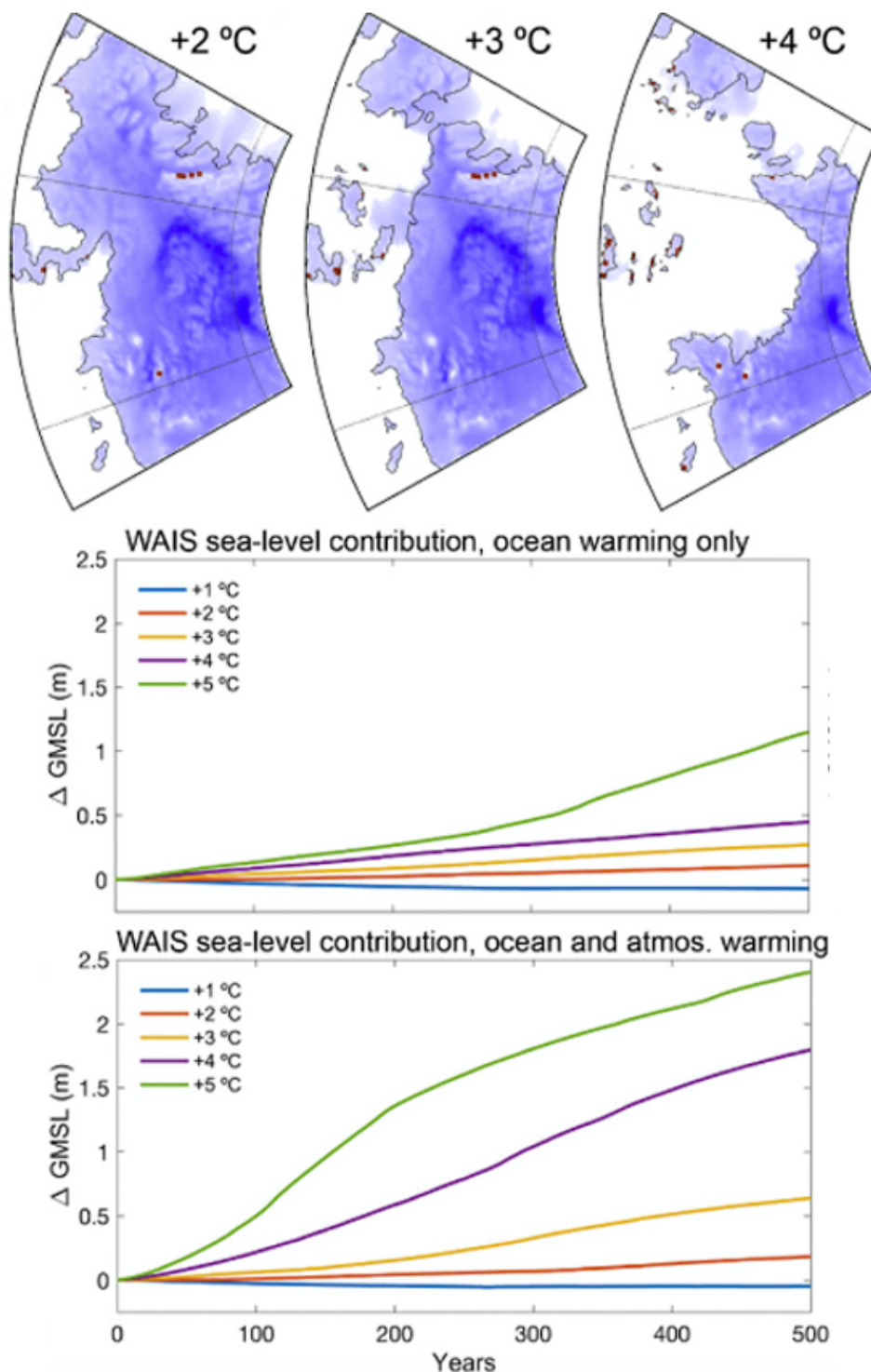922 **novel ways of addressing deep uncertainty.**

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

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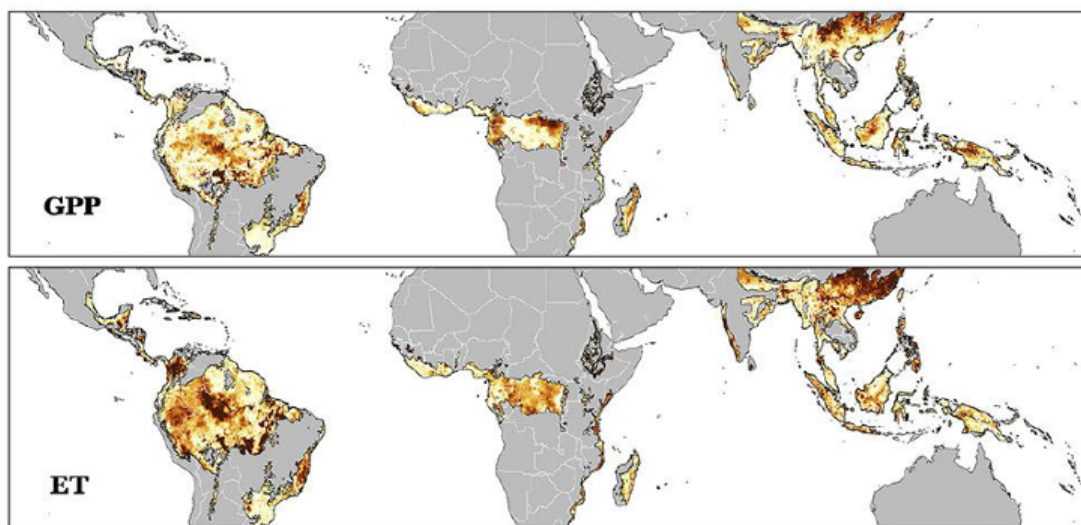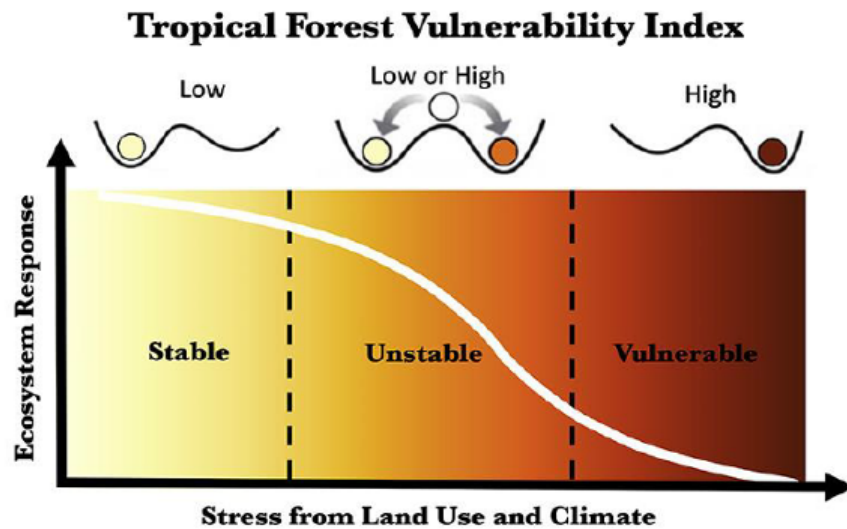*Figure 4. Maps of vulnerability of humid tropical gross primary productivity (GPP) and evapotranspiration (ET). Source: Saatchi et al., 2021.*

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).