A climate science toolkit for high impact-low likelihood climate risks

Article

Published Version

Wood, R. A. ORCID: https://orcid.org/0000-0002-3960-9513, Crucifix, M. ORCID: https://orcid.org/0000-0002-3437-4911, Lenton, T. M., Mach, K. J. ORCID: https://orcid.org/0000-0002-5591-8148, Moore, C., New, M., Sharpe, S., Stocker, T. F. and Sutton, R. T. ORCID: https://orcid.org/0000-0001-8345-8583 (2023) A climate science toolkit for high impact-low likelihood climate risks. Earth's Future, 11 (4). e2022EF003369. ISSN 2328-4277 doi: https://doi.org/10.1029/2022ef003369 Available at https://centaur.reading.ac.uk/111752/

To link to this article DOI: http://dx.doi.org/10.1029/2022ef003369

Publisher: American Geophysical Union (AGU)

AGU ADVANCING EARTH AND SPACE SCIENCE

Earth's Future

COMMENTARY
10.1029/2022EF003369

A Climate Science Toolkit for High Impact-Low Likelihood Climate Risks

Richard A. Wood[1], Michel Crucifix[2], Timothy M. Lenton[3], Katharine J. Mach[4,5], Crystal Moore[6], Mark New[7], Simon Sharpe[8], Thomas F. Stocker[9], and Rowan T. Sutton[10]

[1]Met Office Hadley Centre, Exeter, UK, [2]UCLouvain, Earth and Life Institute, Louvain-la-Neuve, Belgium, [3]Global Systems Institute, University of Exeter, Exeter, UK, [4]Department of Environmental Science and Policy, Rosenstiel School of Marine, Atmospheric and Earth Science, University of Miami, Miami, FL, USA, [5]Leonard and Jayne Abess Center for Ecosystem Science and Policy, University of Miami, Coral Gables, FL, USA, [6]Environment Agency, Bristol, UK, [7]African Climate and Development Initiative, University of Cape Town, Cape Town, South Africa, [8]Institute for Innovation and Public Purpose, University College London, London, UK, [9]Climate and Environmental Physics and Oeschger Centre for Climate Change Research, University of Bern, Bern, Switzerland, [10]National Centre for Atmospheric Science, University of Reading, Reading, UK

Key Points:

- Climate outcomes or events that have a high impact are a key component of climate risk, even if their likelihood is low
- Traditional climate projections are of limited use to inform management of high impact-low likelihood risks
- Physical climate science needs an increased focus on storylines, early warning and monitoring to inform management of high impact risks

Correspondence to:

R. A. Wood,
richard.wood@metoffice.gov.uk

Citation:

Wood, R. A., Crucifix, M., Lenton, T. M., Mach, K. J., Moore, C., New, M., et al. (2023). A climate science toolkit for high impact-low likelihood climate risks. *Earth's Future*, *11*, e2022EF003369. https://doi.org/10.1029/2022EF003369

Received 6 DEC 2022
Accepted 10 MAR 2023

Author Contributions:

Conceptualization: Richard A. Wood, Michel Crucifix, Timothy M. Lenton, Katharine J. Mach, Crystal Moore, Mark New, Simon Sharpe, Thomas F. Stocker, Rowan T. Sutton
Writing – original draft: Richard A. Wood, Michel Crucifix, Timothy M. Lenton, Katharine J. Mach, Crystal Moore, Mark New, Simon Sharpe, Thomas F. Stocker, Rowan T. Sutton
Writing – review & editing: Richard A. Wood, Michel Crucifix, Timothy M. Lenton, Katharine J. Mach, Crystal Moore, Mark New, Simon Sharpe, Thomas F. Stocker, Rowan T. Sutton

Abstract An important component of the risks from climate change arises from outcomes that are very unlikely, but whose impacts if they were to occur would be extremely severe. Examples include levels of surface warming, or changes in the water cycle, that are at the extreme of plausible ranges, or crossing of a climate system "tipping point" such as ice sheet or ocean circulation instability. If such changes were to occur their impacts on infrastructure or ecosystems may exceed existing plans for adaptation. The traditional approach of ensemble climate change projections is not well suited to managing these High Impact-Low Likelihood (HILL) risks, where the objective is to "prepare for the worst" rather than to "plan for what's likely." In this paper we draw together a number of ideas from recent literature, to classify four types of HILL climate outcome and to propose the development of a practical "toolkit" of physical climate information that can be used in future to inform HILL risk management. The toolkit consists of several elements that would need to be developed for each plausible HILL climate outcome, then deployed individually to develop targeted HILL risk management approaches for individual sectors. We argue that development of the HILL toolkit should be an important focus for physical climate research over the coming decade, and that the time is right for a focused assessment of HILL risks by the Intergovernmental Panel on Climate Change in its 7th Assessment Cycle.

Plain Language Summary To prepare for the risks that arise from climate change (and avoid them where possible), it is important to understand how climate is likely to change in future, and what the impacts are likely to be. Over many years, climate science has developed sophisticated climate projections to estimate these likely impacts, and these are widely used to plan how people and societies will need to adapt to climate change. However it is also important to understand possibilities that are unlikely, but would have even more severe impacts if they did occur—for example, global warming levels at the high end of plausible estimates, or crossing a "tipping point" for major changes in ice sheets or ocean currents. A different type of information is needed to plan for these risks. In this paper we propose a new set of climate information "tools" to respond to these high-impact risks. The tools include plausible scenarios of extreme outcomes, and early warning systems to detect if they are on the horizon. Combining these new tools with existing climate projections will allow society to understand more fully the risks of climate change, and to *plan for the likely* effects while *preparing for the worst*.

1. High Impact-Low Likelihood Climate Risks

Over the past 40 years, climate science has established with ever greater certainty that climate is changing as a result of human activity. Recently the Intergovernmental Panel on Climate Change (IPCC) concluded that the effect of human activity on climate is "unequivocal", and that climate change is already worsening extreme weather events across the globe (IPCC, 2021).

The emphasis of physical climate science to date (summarized in successive IPCC Assessments) has been on quantifying the human influence on climate and its impacts over the coming decades (IPCC, 2021, 2022). The focus has been on projection of what is most likely to occur. But now the reality of climate change is beyond

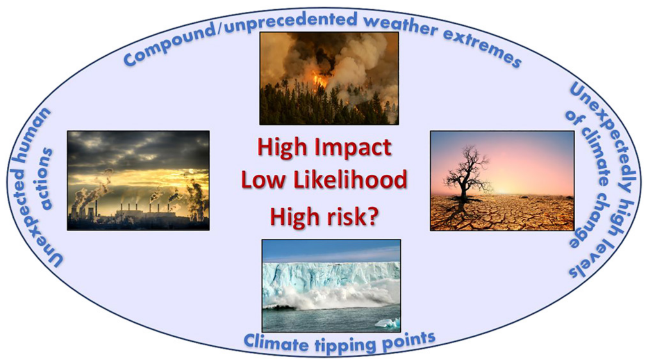

Figure 1. Schematic illustrating the four types of high impact climate hazard discussed in this paper. Clockwise from top: compound or unprecedented weather extremes (image shows a forest fire in California, USA in July 2021, during the heat wave that produced unprecedented temperature extremes in the region); levels of climate change (e.g., warming, water cycle changes) that are above the assessed likely ranges; crossing tipping points/thresholds in the physical climate system such as rapid ice sheet collapse; and unexpected human actions such as a rapid increase in emissions from a particular sector. (Images: Shutterstock).

doubt, and societies are increasingly focusing on what actions are needed to address the risks, as well as opportunities, that climate change presents. This implies a new set of questions for climate science.

As the Covid pandemic has reminded us, the greatest risks often come from hazards that are not the most likely. In risk assessment and planning in many fields, attention is paid not only to likely outcomes but also to what would have the highest impact (what is the worst that could happen), even if its likelihood is low or uncertain. Societies need to know what the worst outcomes of climate change could be, to inform action to limit climate change to avoid such outcomes, and to build resilience if they are not avoided (Sutton, 2019).

We have identified several categories of high impact-low likelihood (HILL) climate hazard (Figure 1):

- Weather events that go beyond the established study of likely changes in extreme weather types. This includes record-shattering extremes (Fischer et al., 2021), compound events due to coincidence of several factors (Zhang et al., 2022; Zscheischler et al., 2018) and rapid shifts between opposite extremes (e.g., drought/flood)
- Levels or rates of global climate change (and hence regional changes) that are above the likely ranges assessed by IPCC (e.g., because the climate sensitivity of the real world, or the response of the hydrological cycle to a given warming, turns out to be at the upper end of plausible ranges (IPCC, 2021))
- Crossing large scale tipping points in the climate system, for example, instability of ice sheets, major shifts in atmosphere/ocean circulation systems, or loss of major ecosystems (Armstrong McKay et al., 2022).
- Climatic consequences of unexpected human actions, possibly by specific sectors of society (e.g., major increases in greenhouse gas emissions, or attempted geoengineering, by individual groupings)

Working Group I of the IPCC recently noted the importance of such HILL outcomes in a risk-based approach to climate change assessment (IPCC, 2021), but while the Policymakers' Summary of Working Group II takes such outcomes into account in its "Reasons for Concern," they receive little explicit discussion (IPCC, 2022). This reflects the relatively low level of research focus on HILL outcomes in physical climate and impacts science, and is a disconnect between climate science and society's needs to inform responses to climate risk. The World Climate Research Program's Lighthouse Activity on "Safe Landing Climates" has identified "High-Risk Climate Events" as one of its five science themes, and the need to improve knowledge of HILL outcomes is also recognized in the Lighthouse Activities "Explaining and Predicting Earth System Change" and "My Climate Risk" (https://www.wcrp-climate.org/lha-overview).

In this paper we propose a new research agenda for the coming decade, to respond to this need by developing a suite of climate information needed to inform societal decisions on responses to HILL risks.

2. From Projection to Risk Management

In many fields, risk is assessed through a likelihood-impact matrix (Figure 2). The high impact-high likelihood outcomes clearly require most attention. But differing approaches are needed for the low-to-mid impact-high likelihood, and high impact-low likelihood (HILL) outcomes.

Reducing emissions to reduce the overall rate of climate change produces widespread benefits by moving nearly all hazards toward the lower left of the diagram. But plausible pathways to net zero emissions still result in a residual commitment to climate change. For these unavoidable hazards, adaptation and resilience-building across sectors is a key response. The traditional climate science approach, focusing on projections, is well designed to inform adaptation to the high likelihood side of the risk matrix ("plan for what's likely"). But building resilience to the HILL side of the matrix could require extremely high levels of investment, which may never be used and which may have undesirable side effects (e.g., building a high sea defense which reduces a community's attractiveness for tourism). While some "no regrets" actions may be available, investment in resilience to HILL risks

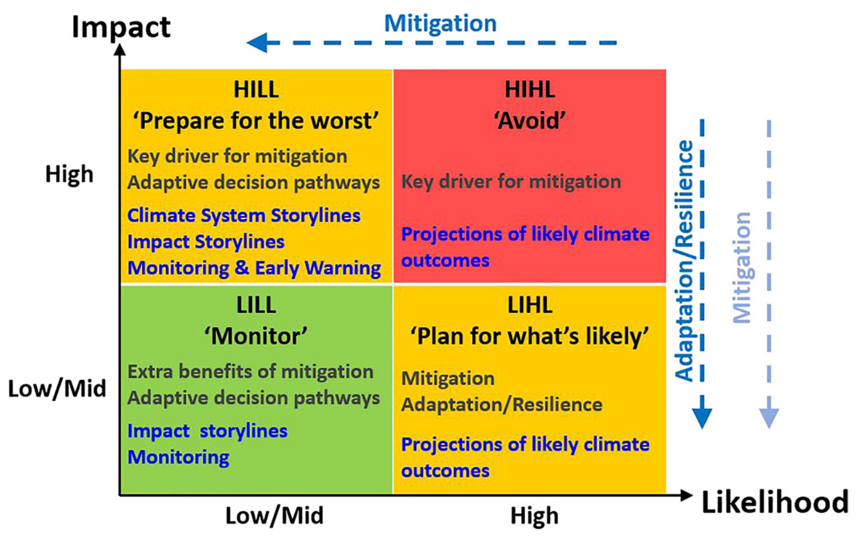

Figure 2. A simple impact-likelihood matrix for climate risk. For each quadrant, the implications for the broad response areas of mitigation (reducing the drivers of climate change such as greenhouse gas emissions) and adaptation and resilience building (adapting societal systems to the climate changes that remain after mitigation) are shown in gray. The types of climate science information needed to support those responses are shown in blue. Mitigation and adaptation/resilience responses tend to move outcomes in the directions shown by the dashed arrows. For many of the HILL outcomes discussed in this paper, mitigation action moves that outcome to a lower likelihood. But for high climate sensitivity, mitigation action reduces the impact.

("preparing for the worst") may be best deferred until the need becomes clear. This approach needs a different type of climate information.

In some cases (e.g., compound extremes), approaches using large climate model ensembles may be useful to assess the likelihood of the hazard at different warming levels (Fischer et al., 2021; Thompson et al., 2017; Zhang et al., 2022; Zscheischler et al., 2018). In other cases (e.g., some climate tipping points) uncertainty may be so deep that robust quantitative estimates of likelihood are impossible. Nevertheless, decision making can still take account of such risks (Desai & Hulme, 2011). Methods that support decision making under deep uncertainty, including robustness analyses or adaptive policy pathways that retain flexibility to respond as new information emerges, are becoming more widely used in the adaptation and policy communities (Marchau et al., 2019). However, despite some examples of successful application in coastal planning (e.g., Ranger et al., 2013), physical climate science has so far paid relatively little attention to the climate information that is needed for such approaches. A new research agenda is needed for physical climate science that enables societies to develop a risk-based approach to decision making, that includes the HILL quadrant of the risk matrix.

3. Informing Management of High Impact-Low Likelihood Climate Risks

Informing societal management of HILL risks needs more than just packaging of existing physical climate research. It will require deep interaction among physical climate scientists, impacts scientists, experts in planning, policy and practice, and society at large, to ensure that climate science informs broader questions such as: what are the key climate-sensitive vulnerabilities that must be managed? (e.g., people's thresholds for habitability under heat stress and water scarcity); what plausible climate hazards (including HILL) could expose those vulnerabilities?; what adaptation/mitigation responses are available?; what is the acceptable cost?; and how might today's choices constrain the options of future generations? (Sharpe, 2019). Without such interactions we risk developing knowledge that is attractive in its specialist field but fails to provide information that enables decisions.

However, a purely vulnerability-focused approach cannot drive the necessary climate science insights. The climate outcomes we are considering here would have impacts across multiple sectors (e.g., health, ecosystems, agriculture, built infrastructure, energy systems, finance). Furthermore, specific sectors may be vulnerable to some low-likelihood climate outcomes but not others. For example, a coastal planner in western Europe would be concerned about tipping points in both the West Antarctic Ice Sheet (WAIS) and the Atlantic Meridional

Overturning Circulation (AMOC), as both these events would result in accelerated regional sea level rise (Bouttes et al., 2014). However an inland farmer in western Europe might be relatively unaffected by WAIS tipping, but still highly vulnerable to AMOC tipping due its cooling and drying impacts (Ritchie et al., 2020). Hence it is not possible to produce a single "HILL climate scenario" to inform all sectors. Instead, we introduce the idea of a "HILL Climate Toolkit": a package of climate information to be developed for each plausible HILL climate outcome, and used as input to the process of developing tailored risk management approaches for individual sectors.

4. A HILL Climate Risk Toolkit

The elements of the "HILL Climate Toolkit" would need to be developed separately for each HILL climate outcome. For each identified HILL outcome H (e.g., a specific tipping point):

- Storylines of dangerous climate system properties, pathways and events. What are the properties or pathways of the climate system that could lead to outcome H? This may involve properties of the climate system itself (e.g., a particular cloud-climate feedback turns out to be strong (Sherwood et al., 2020), or a specific combination of weather events occurs (Sillman et al., 2021)); or it may be a response to specific human actions (e.g., fast vs. slow paths to net zero, geoengineering). These storylines inform mitigation action by better defining "safe operating pathways" of the climate system, and they enable the development of Impact Storylines and Early Warning Indicators.
- Storylines of impacts and impact thresholds. An increased focus on HILL outcomes is needed in impacts modeling, which has historically concentrated on the most likely range of climate drivers. To build resilience it is necessary to understand, for each outcome H, its potential impacts across multiple sectors, in isolation and in combination with possible changes in other climate elements. Such information is essential to underpin regional and sector-specific risk management.
- Early warning indicators. Where likelihood cannot be estimated, are there indicators to detect whether H is becoming more likely over time (e.g., Boers, 2021)? Or could improving knowledge of a specific climate process lead to better understanding of the likelihood of H? Would such warnings give time to avoid H through mitigation action, or would it be committed/"baked-in," leaving adaptation or forced transformation as the only options (Jackson & Wood, 2018; Ritchie et al., 2021)? How much warning time would there be to adapt? (Jackson & Wood, 2017)?
- Monitoring and attribution. How do we build and maintain operational systems of observation and modeling to flag these early warning indicators and to interpret unfolding changes? Can early warning indicators based on dynamical systems ideas (e.g., Boers, 2021) or on simplified process-based models (e.g., Alkhayuon et al., 2019) offer useful detection and warning times in the context of real-world climate noise?

These elements will provide a baseline of climate information for each hazard H, that can be built into tailored climate services for decision makers to develop sector- and locally specific approaches to managing HILL climate risks. Climate scientists will need to work closely with these sectors to co-design and refine the toolkit to meet application needs. The needs of decision makers and scientists in low-income countries, where vulnerabilities and long-term impacts may be greatest, will be particularly important. Some key challenges will include:

- Thresholds. Identify physical, biological and socioeconomic thresholds or limits to adaptation (IPCC, 2022), and assess whether these thresholds may be crossed in the storylines above. A specific example would be crossing temperature and humidity thresholds that are beyond the limits of human tolerance (Andrews et al., 2018)
- Responses. What feasible responses could reduce dangerous impacts under these climate pathways (adaptation, resilience building, mitigation), while minimizing risks of damaging side-effects? When would transformative, rather than incremental measures be needed?

5. Conclusions

Climate scientists need to broaden their thinking from quantifying the most likely climate changes, to considering as well what plausible changes could cause the greatest impact. We propose a "HILL Climate Toolkit", a core set of climate information based around storylines, early warning and monitoring, that can be used by decision makers to develop actions to manage HILL climate risks in their specific sectors.

Some elements of the Toolkit will require long term research programmes, and some may prove to be unattainable for particular climate outcomes. Nonetheless the approach is progressive in that each element, as it is added to the toolbox, enhances the overall ability to build resilience to HILL hazards. However the Toolkit on its own will not be enough, as the pathway to use the tools to inform sector-specific decision making will need to be developed through close interaction between climate scientists and decision makers.

Physical climate and impacts science are only just starting to consider these tools. The IPCC recently developed "low likelihood, high impact" climate storylines for high levels of warming and global sea level rise (IPCC, 2021), and a few studies have evaluated impacts at high levels of warming (e.g., Arnell et al., 2019). Similar assessments are needed for other global- and regional-scale climate hazards, and multiple impact sectors. Some international and national research programmes are now recognizing the need for improved information on HILL outcomes (e.g., https://cinea.ec.europa.eu/programmes/horizon-europe/climate-action-horizon-europe_en, https://www.ukclimateresilience.org/themes/climate-resilience/, Stocker et al., 2022), leading to the prospect of real scientific progress over the coming years.

Progress must be underpinned by improved understanding and modeling. As we see increasing numbers of extreme climate events, we need to use these to challenge climate models. Basing assessments entirely on ensembles of "best-estimate" models may systematically underplay high-impact "tails" (Valdes, 2011), while some key processes and feedbacks (e.g., ice sheets) may be missing from many Earth System Models. This suggests that a model hierarchy approach, going beyond the traditional design of climate model intercomparison projects (https://www.wcrp-climate.org/wgcm-cmip), may be needed to explore the full range of possibilities.

Balanced communication on the science of HILL climate hazards will be a particular challenge. Science needs to inform society about the full range of risks and responses, without either inducing feelings of helplessness or fearing accusations of "scaremongering." Such communication needs to be supported by a balanced and comprehensive assessment of current knowledge and research practices, such as can be provided by the IPCC.

As the focus of climate change policy moves from defining the problem to implementing solutions, the need for reliable scientific information on HILL outcomes is becoming ever greater. With prospects of real scientific progress over the coming years in the areas we have outlined, we believe the time is right for IPCC to place a particular focus on High Impact-Low Likelihood Events, and the associated risks, consequences and responses, in its 7th assessment cycle.

Data Availability Statement

There was no actual data collected or used for writing this commentary.

Acknowledgments

RAW was supported by the Met Office Hadley Centre Climate Programme funded by BEIS. MC is funded as Research Director by the Belgian National Fund for Scientific Research. TML was supported by the Bezos Earth Fund and DARPA. MN was supported by the AXA Research Fund, through the AXA Research Chair in African Climate Risk. TFS acknowledges support by SNF 200492. RAW, MC, and TFS were supported by the European Union's Horizon 2020 research and innovation programme under Grant agreement no. 820970 (TiPES project). This paper is TiPES contribution number 197. The authors thank the organisers of the Met Office Conference "Science for a Resilient Future" in 2021, which initiated this study.

References

Alkhayuon, H., Ashwin, P., Jackson, L. C., Quinn, C., & Wood, R. A. (2019). Basin bifurcations, oscillatory instability and rate-induced thresholds for AMOC in a global oceanic box model. *Proceedings of the Royal Society A*, *475*(2225), 20190051. https://doi.org/10.1098/rspa.2019.0051

Andrews, O., Le Quéré, C., Kjellstrom, T., Lemke, B., & Haines, A. (2018). Implications for workability and survivability in populations exposed to extreme heat under climate change: A modelling study. *The Lancet Planetary Health*, *2*(12), e540–e547. https://doi.org/10.1016/S2542-5196(18)30240-7

Armstrong McKay, D. I., Staal, A., Abrams, J. F., Winkelmann, R., Sakschewski, B., Loriani, S., et al. (2022). Exceeding 1.5°C global warming could trigger multiple climate tipping points. *Science*, *377*(6611), eabn7950. https://doi.org/10.1126/science.abn7950

Arnell, N. W., Lowe, J. A., Challinor, A. J., & Osborn, T. J. (2019). Global and regional impacts of climate change at different levels of global temperature increase. *Climatic Change*, *155*(3), 377–391. https://doi.org/10.1007/s10584-019-02464-z

Boers, N. (2021). Observation-based early-warning signals for a collapse of the Atlantic Meridional Overturning Circulation. *Nature Climate Change*, *11*(8), 680–688. https://doi.org/10.1038/s41558-021-01097-4

Bouttes, N., Gregory, J. M., Kuhlbrodt, T., & Smith, R. S. (2014). The drivers of projected North Atlantic sea level change. *Climate Dynamics*, *43*(5–6), 1531–1544. https://doi.org/10.1007/s00382-013-1973-8

Desai, S., & Hulme, M. (2011). Does climate adaptation policy need probabilities? *Climate Policy*, *4*, 107–128. https://www.tandfonline.com/doi/abs/10.1080/14693062.2004.9685515

Fischer, E. M., Sippel, S., & Knutti, R. (2021). Increasing probability of record-shattering climate extremes. *Nature Climate Change*, *11*(8), 689–695. https://doi.org/10.1038/s41558-021-01092-9. https://www.nature.com/articles/s41558-021-01092-9

IPCC. (2021). Summary for policymakers. In V. Masson-Delmotte, P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, et al. (Eds.), *Climate change 2021: The physical science basis. Contribution of working group I to the sixth assessment report of the intergovernmental panel on climate change* (pp. 3–32). Cambridge University Press. https://doi.org/10.1017/9781009157896.001

IPCC. (2022). Summary for policymakers. In H.-O. Pörtner, D. C. Roberts, E. S. Poloczanska, K. Mintenbeck, M. Tignor, A. Alegría, et al. (Eds.), *Climate change 2022: Impacts, adaptation and vulnerability. Contribution of working group II to the sixth assessment report of the intergovernmental panel on climate change* (pp. 3–33). Cambridge University Press. https://doi.org/10.1017/9781009325844.001

10.1029/2022EF003369

Jackson, L. C., & Wood, R. A. (2017). Timescales of AMOC decline in response to fresh water forcing. *Climate Dynamics*, *51*(4), 1333–1350. https://doi.org/10.1007/s00382-017-3957-6

Jackson, L. C., & Wood, R. A. (2018). Hysteresis and resilience of the AMOC in an eddy-permitting GCM. *Geophysical Research Letters*, *45*(16), 8547–8556. https://doi.org/10.1029/2018GL078104

Marchau, V. A. W. J., Walker, W. E., Bloemen, P. J. T. M., & Popper, S. W. (Eds.). (2019). *Decision making under deep uncertainty: From theory to practice*. Springer. Retrieved from https://link.springer.com/book/10.1007%2F978-3-030-05252-2

Ranger, N., Reeder, T., & Lowe, J. (2013). Addressing 'deep' uncertainty over long-term climate in major infrastructure projects: Four innovations of the Thames Estuary 2100 project. *EURO Journal on Decision Processes*, *1*(3–4), 233–262. https://doi.org/10.1007/s40070-013-0014-5

Ritchie, P. D. L., Clarke, J. J., Cox, P. M., & Huntingford, C. (2021). Overshooting tipping point thresholds in a changing climate. *Nature*, *592*(7855), 517–523. https://doi.org/10.1038/s41586-021-03263-2

Ritchie, P. D. L., Smith, G. S., Davis, K. J., Halleck-Vega, C. F. S., Harper, A. B., Boulton, C. A., et al. (2020). Shifts in national land use and food production in Great Britain after a climate tipping point. *Nature Food*, *1*, 76–83. https://doi.org/10.1038/s43016-019-0011-3

Sharpe, S. (2019). Telling the boiling frog what he needs to know: Why climate change risks should be plotted as probability over time. *Geoscience Communication*, *2*(1), 95–100. https://doi.org/10.5194/gc-2-95-2019

Sherwood, S. C., Webb, M. J., Annan, J. D., Armour, K. C., Forster, P. M., Hargreaves, J. C., et al. (2020). An assessment of Earth's climate sensitivity using multiple lines of evidence. *Reviews of Geophysics*, *58*(4), e2019RG000678. https://doi.org/10.1029/2019RG000678

Sillmann, J., Shepherd, T. G., van den Hurk, B., Hazeleger, W., Martius, O., Slingo, J., & Zscheischler, J. (2021). Event-based storylines to address climate risk. *Earth's Future*, *9*(2), e2020EF001783. https://doi.org/10.1029/2020EF001783

Stocker, T. F., Hegerl, G. C., Hurrell, J. W., Lenton, T. M., Seneviratne, S. I., & Winkelmann, R. (2022). Tipping points in the climate system. In *United in science 2022* (pp. 21–23). World Meteorological Organization. Retrieved from https://public.wmo.int/en/resources/united_in_science

Sutton, R. (2019). Climate science needs to take risk assessment much more seriously. *Bulletin of the American Meteorological Society*, *100*(9), 1637–1642. https://doi.org/10.1175/bams-d-18-0280.1

Thompson, V., Dunstone, N. J., Scaife, A. A., Smith, D. M., Slingo, J. M., Brown, S., & Belcher, S. E., (2017). High risk of unprecedented UK rainfall in the current climate. *Nature communications*. Retrieved from https://www.nature.com/articles/s41467-017-00275-3

Valdes, P. (2011). Built for stability? *Nature Geoscience*, *4*(7), 414–416. https://doi.org/10.1038/ngeo1200

Zhang, Q., Dunxian, S., Zhang, L., Wang, G., & Hao, Z. (2022). High sensitivity of compound drought and heatwave events to global warming in the future. *Earth's Future*, *10*(11), e2022EF002833. https://doi.org/10.1029/2022EF002833

Zscheischler, J., Westra, S., van den Hurk, B. J. J. M., Seneviratne, S. I., Ward, P. J., Pitman, A., et al. (2018). Future climate risk from compound events. *Nature Climate Change*, *8*(6), 469–477. https://doi.org/10.1038/s41558-018-0156-3