



## Risk from responses to a changing climate

Talbot M. Andrews<sup>a</sup>, Nicholas P. Simpson<sup>b,\*</sup>, Katharine J. Mach<sup>c</sup>,  
Christopher H. Trisos<sup>a,d</sup>

<sup>a</sup> Department of Political Science, University of Connecticut, Storrs, CT, USA

<sup>b</sup> African Climate and Development Initiative, University of Cape Town, Cape Town, South Africa

<sup>c</sup> Department of Environmental Science and Policy, Rosenstiel School of Marine, Atmospheric, and Earth Science, and Leonard and Jayne Abess Center for Ecosystem Science and Policy, University of Miami, Miami, FL, USA

<sup>d</sup> Centre for Statistics in Ecology, Environment and Conservation, University of Cape Town, Cape Town, South Africa

### ARTICLE INFO

#### Keywords:

Climate change  
Response risk  
Managed retreat  
Solar geoengineering  
Cascading risk  
Compound risk  
Climate risk management

### ABSTRACT

Effectively responding to intensifying climate change hazards requires identifying risks arising from each response, as well as risks arising from the dynamic interactions between responses. Using examples of managed retreat and solar geoengineering, we illustrate the importance of understanding response as a determinant of climate change risk. We highlight a continuum of severity of response risks, both at the site of deployment and across temporally and geographically distant contexts. While responses might moderate a specific hazard, due to the complexity of climate change risk they may be ineffective at reducing net climate-related risk for any given actor or system. We also show how some responses to climate change affect vulnerability, exposure, and other responses to climate change independent of the targeted hazard and can lead to maladaptation. We conclude by emphasizing the importance of integrating climate change responses together with other determinants of risk to better inform climate risk management and guide research on the feasibility of individual response options.

### 1. Introduction

There is urgent need for informed responses to climate change, including rapid greenhouse gas mitigation, more effective and equitable adaptation, as well as broader response options. Expanded implementation requires a better understanding of climate change response itself as an important determinant of climate change risk (Simpson et al., 2023, 2021). Response risks can include responses to climate change failing to achieve their intended outcomes, as well as responses creating additional adverse outcomes as they exacerbate hazards, vulnerability, and exposure to climate change risk. As we consider combinations and the feasibility of available response strategies, we must do so in the challenging context of both the climate risks we are attempting to avert and the possible risks arising from individual responses. Here, we use examples of managed retreat and geoengineering to highlight the dynamic nature of response risks, and how they interact with other existing vulnerabilities to climate change and the hazards they aim to prevent.

\* Corresponding author at: 6th Floor, Geological Sciences Building, Upper Campus, University of Cape Town, Rondebosch, Cape Town, South Africa.

E-mail addresses: [talbot.andrews@uconn.edu](mailto:talbot.andrews@uconn.edu) (T.M. Andrews), [nick.simpson@uct.ac.za](mailto:nick.simpson@uct.ac.za) (N.P. Simpson), [kmach@rsmas.miami.edu](mailto:kmach@rsmas.miami.edu) (K.J. Mach).

<https://doi.org/10.1016/j.crm.2023.100487>

Received 1 June 2022; Received in revised form 8 January 2023; Accepted 12 February 2023

Available online 13 February 2023

2212-0963/© 2023 The Author(s). Published by Elsevier B.V. This is an open access article under the CC BY-NC-ND license (<http://creativecommons.org/licenses/by-nc-nd/4.0/>).

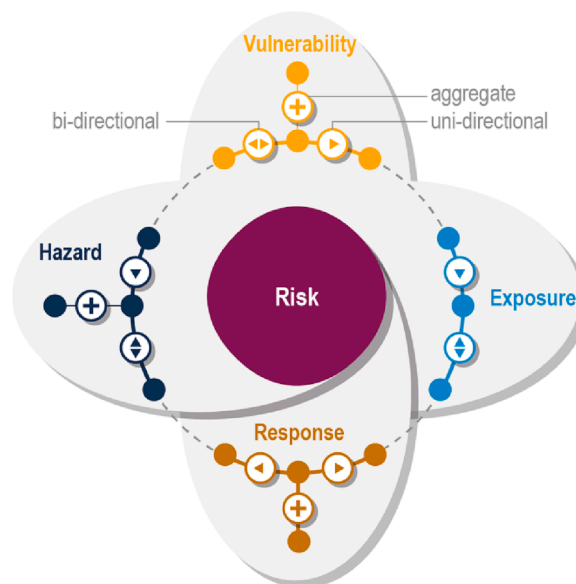
## 2. Risk from response

Recognizing the importance of risk from climate responses, the Intergovernmental Panel on Climate Change (IPCC) recently updated its risk framework to include response risks and assesses with ‘high confidence’ that “some responses to climate change result in new impacts and risks” (IPCC, 2022) (see, Fig. 1). Such risks can arise from adaptation and mitigation, as well as negative emissions technologies such as carbon dioxide removal. While all human decision making has the potential to affect hazards, vulnerabilities, and exposure in the context of climate change, as we choose between response options it is especially critical to consider the risks that can arise from these potential responses.

With calls for climate action now including more extreme responses there is heightened concern about the consequences of such responses (Biermann et al., 2022; IPCC, 2022). For example, there are concerns that extreme responses might lead to policy inertia as decision makers consider the ways in which committed responses might affect each other in a complex and changing world (Reed et al., 2022; Simpson et al., 2021). As we delay deploying responses to consider these risks, we accept ongoing risk escalation as global warming levels increase. At the same time, ‘quick-fix’ or uninformed responses can lead to maladaptation through feedbacks on increased exposure and vulnerability to climate hazards, particularly for socio-economically vulnerable groups (Reed et al., 2022). Yet, when responses are integrated within climate risk assessment and management there is greater potential to advance the urgency of response and safeguards for the most vulnerable (Simpson et al., 2023). Both mitigation and adaptation responses can have co-benefits with each other as well as with broader developmental goals. This can increase the efficiency and cost-effectiveness of climate actions (IPCC, 2022).

The problem of response risks is amplified when the affordability of climate change response options is highly unequal. For example, the majority of the global population will not be able to afford air conditioning units to cope with future warming levels for most of the twenty-first century (Rode et al., 2021). This can occur even when, at the time of deployment, a selected response was considered a feasible and effective hazard reduction strategy (Clark-Ginsberg et al., 2021; Eriksen et al., 2021; Magnan et al., 2016).

Critically, climate change response costs, co-benefits or trade-offs between response options affect more than just the target beneficiaries. For example, they have potential consequences for decision makers, affecting their reputation and, under democratic institutions, their probability of re-election (Carter et al., 2021; Healy and Malhotra, 2013, 2009). As another example, response costs can affect constituents who may be spatially or temporally disconnected from those responses are aimed to protect (Simpson et al., 2021; Thiery et al., 2021). Key to this consideration is the ‘risk-response feedback’ (Jebari et al., 2021): a model of the feedback between risks and their responses that attempts to account for the full spectrum of risk associated a proposed activity. In doing so, ‘risk-response feedback’ also outlines the trade-offs between multiple potential outcomes because of different combinations of available greenhouse gas mitigation, adaptation, or other strategies targeting a climate-resilient future.



**Fig. 1. Integrating response as a dimension of climate change risk.** Figure shows that risk is affected by the interactions between multiple determinants, including multiple responses (bottom petal). Grey petals indicate interactions among each determinant of a risk, namely hazard, vulnerability, exposure, and response to climate change. Interactions of multiple drivers within each determinant of risk include multiple responses to climate change which affect other responses as well as other drivers of risk in aggregating, compounding and cascading ways (for example, how adopting irrigation agriculture to better manage rainfall variability can improve livelihoods and nutrition, but can also negatively affect groundwater). As climate change risk assessment spans all three Working Groups of the IPCC, the specific roles of risk determinants for risk related to hazards, exposures, vulnerabilities and responses (including both adaptation and mitigation) have become an increasingly important feature of climate risk assessment and management (IPCC, 2022; Simpson et al., 2021).

Here we discuss two examples of response: the localized response of managed retreat and the global response of solar radiation management. Both aim to manage one dimension of climate change risk, one avoiding the hazards associated with flooding and sea level rise, and the other attempting to stabilize or reduce global average temperature, but in doing so they also introduce additional risks (Fig. 2). These examples illustrate the degrees of severity of response risks, as well as variation in the extent of these risks as they interact and compound with other determinants of risk, namely hazard, vulnerability, exposure, and response.

### 3. Risk from managed retreat

Managed retreat is currently considered primarily in the context of coastal and inland flooding. It refers to the removal of people, assets, and infrastructure from areas of increasing risk of immediate flooding. It can involve buyouts of flood-prone properties or the relocation of entire communities (Ajibade, 2019; Hino et al., 2017). Managed retreat has clear potential to reduce risk, especially if residents relocate to safer areas. However, it is challenging for many reasons, including its potential impacts on disrupting peoples' place attachment, social cohesion, economic opportunities, and heritage (McNamara et al., 2016). Managed retreat also has the potential to disrupt communities that receive those who have been relocated (e.g., Forsyth and Peiser, 2021). It additionally has the potential to exacerbate ongoing injustices for marginalized or oppressed communities. These "other reasons" are, in essence, risks from the response.

Inherent in retreat is the simultaneous presence of benefits and harms—it effectively reduces some risks, but introduces response risks that have the potential to exacerbate adverse outcomes (Mach and Siders, 2021). For some categories of incremental adaptation, it is easier to focus on the benefits, but most adaptation responses have both benefits and harms. A giant seawall, for instance, can fundamentally change one's relationship with the coastline, whether the amenity of a view, the ecosystem services provided by a coastline, or the ease of access to coastal transport or livelihoods. However, these response risks are sometimes overlooked or not managed proactively. In the case of managed retreat, there has been an important focus on trade-offs, harms, and losses in order to maximize benefits, minimize harms, and also support compassionate engagement with losses that are inevitable in a changing climate (Tschakert et al., 2017). The management contexts range from circumstances where residents want out of an increasingly perilous

| Risk from Response                                 | Example: Coastal Managed Retreat                                                                                                                                                           | Example: Solar Aerosol Injection                                                                                                                                                                                                   |
|----------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>Response objective and target hazard</b>        | To move people and infrastructure away from hazards such as coastal flooding, sea level rise, storm surge, erosion, and cyclones, and to restore the land to open space                    | To stabilise or decreases global mean temperature by reflecting sunlight                                                                                                                                                           |
| <b>Geographic risks associated with deployment</b> | Localised effects on leaving and receiving sites (e.g., coastlines) and communities                                                                                                        | Global consequences with potential disruption to e.g., biosphere integrity and hydrological systems                                                                                                                                |
| <b>Temporal risks associated with deployment</b>   | Permanent, intergenerational change through relocation, as well as disruption of the local ecosystem and people's relationship to the coastline                                            | Potential long-term disruption of biophysical systems, even after the response is no longer being deployed.                                                                                                                        |
| <b>Interaction with hazards</b>                    | Can reduce flooding hazard by rebuilding natural floodplains and introducing a buffer between people and the coastline                                                                     | Exacerbates existing natural hazards, e.g., disrupting summer monsoon seasons and exacerbating hole in ozone layer                                                                                                                 |
| <b>Interaction with vulnerabilities</b>            | Ongoing injustice for marginalized communities, e.g., where underserved communities may be unable to move on their own, or those who do move face discrimination at the site of relocation | Increase in vulnerability to food insecurity, which is felt most by communities vulnerable to climate change e.g., rainfed small holder agriculture.                                                                               |
| <b>Interaction with exposures</b>                  | Reduction in exposure for those who can move, those most socially vulnerable may remain with increasing exposure                                                                           | Potential reduction in exposure to higher warming levels for the duration of deployment                                                                                                                                            |
| <b>Interaction with responses</b>                  | Increased cost of coping and adapting in place for those unable to move                                                                                                                    | Potential demobilization of support for strong, rapid and sustained reduction in anthropogenic emissions                                                                                                                           |
| <b>Interaction with other risks</b>                | Risks from social integration at new site, solistagia, loss of sense of place and heritage, property prices changes, or affordability of insurance                                         | Food security, water scarcity, global trade networks, exceedance of thermal velocity and tolerances of species, mass extinction, increase frequency of heatwaves, exposure to extreme heat, decline in outdoor labour productivity |

Fig. 2. Examples of how risks can emerge from climate change response. Geographic and temporal limits to two examples of climate change response are identified for coastal managed retreat and solar aerosol injection together with potential interactions of each response with associated hazards, vulnerabilities, exposures, and additional resulting response strategies affecting risk.

location yet finance and institutional support are not available, through to circumstances where residents may not consider relocation even though costs and damages from remaining in place are increasing. In this second case, residents may reject financial and institutional support for managed retreat in favor of remaining in place, especially if such support is insufficient to offset the loss of home and community (Ajibade et al., 2022).

Despite its challenges, both managed and unmanaged retreat are likely to occur to a greater degree under increasing climate change (Hauer et al., 2019), for hazards where the footprint is unavoidably explicit (such as sea level rise), and also for hazards where the geographic extent and temporal occurrence of the hazards are more wide-ranging, episodic, or diffuse (such as wildfire or drought). Increased incidence of unmanaged retreat in response to hazards is especially concerning, and preventable in part by more effective managed retreat. When relocating in response to a hazard, people often move to less optimal areas than those engaging in managed retreat (Do Yun and Waldorf, 2016). For example, in the wake of Hurricane Katrina, many who left New Orleans moved to other counties within the state with even higher hurricane incidence (Eyer et al., 2018).

Reflecting its growing necessity, the amount of research on managed retreat has steadily increased over time (O'Donnell, 2022). The challenges of the response risks point to the critical importance of implementation drawing from best practices, ranging from visioning and planning stages, through to community-led implementation pursued through inclusive processes, transparent conflict resolution, and a direct engagement with the risks of the response itself. The complexity of risks from the response of managed retreat highlight the need to especially consider local geographic and socio-political contexts for successful implementation (Dedekorkut-Howes et al., 2020; Siders et al., 2021).

#### 4. Risk from geoengineering

Considering current and projected limits to responses to climate change and to-date ineffective measures to reduce greenhouse gas emission, increasing attention turned to geoengineering. Geoengineering is a broad category which includes negative emissions technologies such as bioenergy with carbon capture and storage or direct air carbon capture and storage (Fuss et al., 2018). Geoengineering additionally includes solar aerosol injection (or “solar geoengineering”). This form of geoengineering is the process of increasing reflective particles in the stratosphere, which decreases global mean temperature by reflecting sunlight (IPCC, 2021). While solar geoengineering does not address the underlying cause of climate change, by delaying or reducing global mean temperature rise, solar geoengineering could buy time to implement other critical mitigation and adaptation strategies (IPCC, 2021).

These responses also introduce risks that could compound with the portfolio of available response policy options (Aldy et al., 2021). However, compared to managed retreat, the response risks in this case extend far beyond where the strategies are deployed. Implementation may exacerbate or misestimate geographically and temporally distant risks as well as affect response capabilities of those disconnected from decision making centers. As a consequence, while solar geoengineering buys time by slowing global mean temperature rise, some argue the costs are too high (e.g., Robock et al., 2008). For example, geoengineering is projected to undermine progress towards malaria eradication for nearly-one billion people at risk of malaria by 2070 (Carlson et al., 2022). Geoengineering strategies targeting a reduction of warming are therefore not guaranteed to unilaterally improve developmental outcomes such as health. The introduction of reflective particles in the atmosphere may affect global precipitation patterns, causing drying over east Africa and India that disrupts summer monsoon seasons (Visioni et al., 2018). Such disruption would exacerbate food insecurity, decreasing both agricultural production and water availability in the region (Mishra et al., 2020), as well as affect available sunlight needed for solar energy systems (Hu et al., 2022). This insecurity would be felt most by already marginalized groups. Solar geoengineering is a response to potential climate change risks, but it compounds with other physical hazards, which then compound with vulnerabilities to such changes in physical systems.

These compounding risks are not constrained to the locations in which solar geoengineering is deployed, raising questions about how to best govern geoengineering research, development, deployment, and maintenance (Reynolds, 2019). Indeed, concerns about an absence of an international institution with the authority, or adequate representation of the countries most vulnerable to solar geoengineering response risks, has led some to introduce a non-use agreement (Biermann et al., 2022). But, as we face greater risks of climate hazards, we will likely see growing public support for solar geoengineering (Andrews et al., 2018), and effective governance will have to take into account the global nature of the potential risks from this response.

There are additional concerns that solar geoengineering could interact with other climate change response strategies. Because this strategy delays the onset of climate disaster without addressing their underlying causes, many worry it will undermine a sense of urgency that drives support for other necessary mitigation and adaptation policies (Markusson et al., 2018). This perverse decreased support for other mitigation strategies, often referred to as “moral hazard”, has been theorized even in response to research about geoengineering strategies (Bellamy et al., 2016; Hale, 2012; Markusson et al., 2018). This might excuse decision makers from taking urgent climate action, and translate into increased carbon emissions (McLaren and Markusson, 2020). We emphasize that evidence thus far finds learning about aerosol injection does *not* reduce individual mitigation efforts (Andrews et al., 2022; Merk et al., 2016). Instead, this example serves to highlight the importance of considering mitigation strategies more broadly in the existing political and policy context (see also (Jebari et al., 2021)).

A single hazard or, in the case of solar geoengineering, a single climate response, when studied in isolation underestimates potential risks. The case of solar geoengineering illustrates the potential far-reaching risks as responses interact with other physical and social systems. Some evidence suggests there is support for such strategies as the risks of climate hazards rise (Andrews et al., 2018). But response to climate risk cannot be considered in isolation. It needs to be integrated as a determinant of climate change risk for assessment and informed action. The extent of such response risks depends both on the response being deployed and the context of its deployment.

## 5. Informed responses to climate change

A deeper understanding of dynamic response risks improves our ability to select and govern climate change responses. Our current approach examines these risks in isolation, exemplified by the three working groups of the IPCC where mitigation (Working Group III) has been assessed separately to hazards (Working Group I) and risk, vulnerability, and adaptation (Working Group II). Informed responses to climate change will require consideration of the interactions between all determinants of climate change risk, including hazards, exposures, vulnerabilities, and responses (Simpson et al., 2021). Decision making tools under development, such as the Biden administration's Executive Order on Tackling the Climate Crisis at Home and Abroad (Biden, 2021), aim to integrate compound exposure and vulnerability components with climate information to better understand the distributional impacts of climate change and our responses to it. Critical to achieving this are efforts to integrate and understand better the interacting risks that result from climate change responses (Simpson et al., 2021).

Managed retreat and solar geoengineering show how risks can emerge from climate change responses. We are not the first to highlight the potential co-benefits and tradeoffs that arise from many mitigation and adaptation strategies. A large literature on risk management has identified negative consequences of various approaches. For example, past work emphasizes the interrelationship between mitigation and economic development (Cohen et al., 2019) and inland coastal water quality (Sinha et al., 2019). As another example, burning biomass for energy production reduces net carbon emissions as we transition away from fossil fuels, but involves tradeoffs with maintaining ecosystem services (Donnison et al., 2020). Others have pointed to a need to better determine whether urban adaptation strategies exacerbate or ameliorates existing inequities (Anguelovski et al., 2016).

These response risks vary in their geographic and temporal limits and potential interactions with other hazards, vulnerabilities, exposures, and support for other response strategies. This should not be taken to mean we should avoid strategies that, on their face, seem potentially risky. And indeed, response risks arise from more localized adaptation strategies like managed retreat as well as strategies not discussed here. For example, migration can reduce risk to a specific hazard but migration policies can increase the vulnerability of migrants (Cundill et al., 2021). As another example, global carbon pricing policies can have local unintended consequences. Such pricing shifts the distribution of energy and agricultural production, and will likely overtax river basins such as the Zambezi Watercourse (Abdullah et al., 2022).

A response risk framework is more expansive than a focus on maladaptation (situations in which purposeful adaptation increases risk, e.g., Juhola et al., 2016). First, it subsumes a multitude of strategies that purposefully address climate risks, including not only adaptation but also strategies such as mitigation and negative emissions technologies. Second, this framework identifies that responses can mobilize or demobilize other existing priorities across different stakeholders. This is highlighted, for example, in concerns that the solar radiation poses the response risk of demobilizing other mitigation strategies. This latter component historically has been outside of the scope of maladaptation. This more holistic understanding of response risks improves policy decisions in other domains as well. Risks from response are evident, for example, in the decision to close schools to prevent the spread of COVID-19. While doing so saved lives, it negatively affected learning outcomes – especially for low-income students (Psacharopoulos et al., 2021).

Progress in understanding multi-variate interactions of climate change responses will improve our ability to estimate climate change risk and better inform risk management. This is true across the response options discussed here and may identify more climate resilience development pathways, expose gaps in climate risk management approaches, and demonstrate opportunities for more inclusive and positive outcomes. We need to develop ways that responses can be tracked and understood that go beyond *ex post* studies and provide more substantial real-time feedback for decision makers. New opportunities need to be created to provide policy relevant and supportive evaluation of adaptation actions as they are occurring. We also need to create safe spaces to fail, recognizing that failure is often harder to understand because no one wants to talk about it – yet it may be essential to understanding where response risks are posing barriers and even limits to adaptation.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

No data was used for the research described in the article.

## Acknowledgements

NPS received financial support from the UK Government's Foreign, Commonwealth & Development Office and the International Development Research Centre, Ottawa, Canada (grant number 109419–001). CHT is supported by the FLAIR Fellowship Programme: a partnership between the African Academy of Sciences and the Royal Society funded by the UK Government's Global Challenges Research Fund. This collaboration was initiated with support from SESYNC's Pursuit Program: New Scenarios and Models for Climate Engineering.



## References

- Abdullah, K., Giuliani, M., Lamontagne, J.R., Hejazi, M.I., Reed, P.M., Castelletti, A., 2022. Unintended consequences of climate change mitigation for African river basins. *Nat. Climate Change* 2022 12:2 12, 187–192. doi: 10.1038/s41558-021-01262-9.
- Ajibade, I., 2019. Planned retreat in Global South megacities: disentangling policy, practice, and environmental justice. *Clim. Change* 157, 299–317. <https://doi.org/10.1007/S10584-019-02535-1/FIGURES/1>.
- Ajibade, I., Sullivan, M., Lower, C., Yarina, L., Reilly, A., 2022. Are managed retreat programs successful and just? A global mapping of success typologies, justice dimensions, and trade-offs. *Global Environ. Change* 76, 102576. <https://doi.org/10.1016/j.gloenvcha.2022.102576>.
- Aldy, J.E., Felgenhauer, T., Pizer, W.A., Tavoni, M., Belaia, M., Borsuk, M.E., Ghosh, A., Heutel, G., Heyen, D., Horton, J., Keith, D., Merk, C., Moreno-Cruz, J., Reynolds, J.L., Ricke, K., Rickels, W., Shayegh, S., Smith, W., Tilmes, S., Wagner, G., Wiener, J.B., 2021. Social science research to inform solar geoengineering. *Science* 374, 815–818. <https://doi.org/10.1126/science.abj6517>.
- Andrews, T.M., Delton, A.W., Kline, R., 2018. High-risk high-reward investments to mitigate climate change. *Nat. Clim. Chang.* 8, 890–894. <https://doi.org/10.1038/s41558-018-0266-y>.
- Andrews, T.M., Delton, A.W., Kline, R., 2022. Anticipating moral hazard undermines climate mitigation in an experimental geoengineering game. *Ecol. Econ.* 196, 107421. <https://doi.org/10.1016/J.ECOLECON.2022.107421>.
- Anguelovski, I., Shi, L., Chu, E., Gallagher, D., Goh, K., Lamb, Z., Reeve, K., Teicher, H., 2016. Equity impacts of urban land use planning for climate adaptation: critical perspectives from the global north and south. *J. Plan. Educ. Res.* 36. <https://doi.org/10.1177/0739456X16645166>.
- Bellamy, R., Chilvers, J., Vaughan, N.E., 2016. Deliberative Mapping of options for tackling climate change: citizens and specialists ‘open up’ appraisal of geoengineering. *Public Underst. Sci.* 25, 269–286. <https://doi.org/10.1177/0963662514548628>.
- Biden, J., 2021. E.O. 14008: Tackling the Climate Crisis at Home and Abroad.
- Biermann, F., Oomen, J., Gupta, A., Ali, S.H., Conca, K., Hajer, M.A., Kashwan, P., Kotzé, L.J., Leach, M., Messner, D., Okereke, C., Persson, Å., Potočník, J., Schlosberg, D., Scobie, M., VanDeveer, S.D., 2022. Solar geoengineering: the case for an international non-use agreement. *Wiley Interdisciplinary Rev.: Climate Change* e754. <https://doi.org/10.1002/WCC.754>.
- Carlson, C.J., Colwell, R., Hossain, M.S., Rahman, M.M., Robock, A., Ryan, S.J., Alam, M.S., Trisos, C.H., 2022. Solar geoengineering could redistribute malaria risk in developing countries. *Nat. Commun.* 13 (1), 1–9. doi: 10.1038/s41467-022-29613-w.
- Carter, T.R., Benzie, M., Campiglio, E., Carlsen, H., Fronzek, S., Hildén, M., Reyner, C.P.O., West, C., 2021. A conceptual framework for cross-border impacts of climate change. *Glob. Environ. Chang.* 69, 102307. <https://doi.org/10.1016/J.GLOENVCHA.2021.102307>.
- Clark-Ginsberg, A., Easton-Calabria, L.C., Patel, S.S., Balagna, J., Payne, L.A., 2021. When disaster management agencies create disaster risk: a case study of the US's Federal Emergency Management Agency. *Disaster Prevention Manage.: Int. J.* 30, 447–461. <https://doi.org/10.1108/DPM-03-2021-0067/FULL/XML>.
- Cohen, B., Blanco, H., Dubash, N.K., Dukkupati, S., Khosla, R., Scricciu, S., Stewart, T., Torres-Gunfaus, M., 2019. Multi-criteria decision analysis in policy-making for climate mitigation and development. *Clim. Dev.* 11, 212–222. <https://doi.org/10.1080/17565529.2018.1445612>.
- Cundill, G., Singh, C., Adger, W.N., Safra de Campos, R., Vincent, K., Tebboth, M., Maharjan, A., 2021. Toward a climate mobilities research agenda: intersectionality, immobility, and policy responses. *Glob. Environ. Chang.* 69, 102315. <https://doi.org/10.1016/J.GLOENVCHA.2021.102315>.
- Dedekorkut-Howes, A., Torabi, E., Howes, M., 2020. When the tide gets high: a review of adaptive responses to sea level rise and coastal flooding. *63*, 2102–2143. doi: 10.1080/09640568.2019.1708709.
- Do Yun, S., Waldorf, B.S., 2016. The day after the disaster: forced migration and income loss after hurricanes KATRINA and Rita. *J. Reg. Sci.* 56, 420–441. <https://doi.org/10.1111/jors.12250>.
- Donnison, C., Holland, R.A., Hastings, A., Armstrong, L.-M., Eigenbrod, F., Taylor, G., 2020. Bioenergy with Carbon Capture and Storage (BECCS): finding the win–wins for energy, negative emissions and ecosystem services—size matters. *GCB Bioenergy* 12, 586–604.
- Eriksen, S., Schipper, E.L.F., Scoville-Simonds, M., Vincent, K., Adam, H.N., Brooks, N., Harding, B., Khatri, D., Lenaerts, L., Liverman, D., Mills-Novoa, M., Mosberg, M., Movik, S., Muok, B., Nightingale, A., Ojha, H., Sygna, L., Taylor, M., Vogel, C., West, J.J., 2021. Adaptation interventions and their effect on vulnerability in developing countries: help, hindrance or irrelevance? *World Dev.* 141, 105383. <https://doi.org/10.1016/J.WORLDDEV.2020.105383>.
- Eyer, J., Dinterman, R., Miller, N., Rose, A., 2018. The effect of disasters on migration destinations: evidence from Hurricane Katrina. *EconDisCliCha* 2, 91–106. <https://doi.org/10.1007/s41885-017-0020-3>.
- Forsyth, A., Peiser, R., 2021. Lessons from planned resettlement and new town experiences for avoiding climate sprawl. *Landsc. Urban Plan.* 205, 103957. <https://doi.org/10.1016/j.landurbplan.2020.103957>.
- Fuss, S., Lamb, W.F., Callaghan, M.W., Hilaire, J., Creutzig, F., Amann, T., Beringer, T., Garcia, W. de O., Hartmann, J., Khanna, T., Luderer, G., Nemet, G.F., Rogelj, J., Smith, P., Vicente, J.L.V., Wilcox, J., Dominguez, M. del M.Z., Minx, J.C., 2018. Negative emissions—Part 2: Costs, potentials and side effects. *Environ. Res. Lett.* 13, 063002. doi: 10.1088/1748-9326/AAAF9F.
- Hale, B., 2012. The world that would have been: moral hazard arguments against geoengineering. In: Preston, C. (Ed.), *Reflecting Sunlight: The Ethics of Solar Radiation Management*. Rowman and Littlefield.
- Hauer, M.E., Fussell, E., Mueller, V., Burkett, M., Call, M., Abel, K., McLeman, R., Wrathall, D., 2019. Sea-level rise and human migration. *Nat. Rev. Earth Environ.* 1 (1), 28–39. doi: 10.1038/s43017-019-0002-9.
- Healy, A., Malhotra, N., 2009. Myopic voters and natural disaster policy. *Am. Polit. Sci. Rev.* 103, 387–406. <https://doi.org/10.1017/S0003055409990104>.
- Healy, A., Malhotra, N., 2013. Retrospective voting reconsidered. *Annu. Rev. Polit. Sci.* 16, 285–306. <https://doi.org/10.1146/annurev-polisci-032211.219290>.
- Hino, M., Field, C.B., Mach, K.J., 2017. Managed retreat as a response to natural hazard risk. *Nat. Climate Change* 2017 7(5), 364–370. doi: 10.1038/nclimate3252.
- Hu, M., Zhao, B., Suhendri, A., X., Cao, J., Wang, Q., Riffat, S., Su, Y., Pei, G., 2022. Applications of radiative sky cooling in solar energy systems: progress, challenges, and prospects. *Renewable Sustainable Energy Rev.* 160, 112304. doi: 10.1016/J.RSER.2022.112304.
- IPCC, 2021. *Climate Change 2021: The Physical Science Basis*. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press.
- IPCC, 2022. *Climate Change 2022: Impacts, Adaptation, and Vulnerability*. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press.
- Jebbari, J., Táíwó, O.O., Andrews, T.M., Aquila, V., Beckage, B., Belaia, M., Clifford, M., Fuhrman, J., Keller, D.P., Mach, K.J., Morrow, D.R., Raimi, K.T., Visioni, D., Nicholson, S., Trisos, C.H., 2021. From moral hazard to risk-response feedback. *Clim. Risk Manag.* 33, 100324. <https://doi.org/10.1016/j.crm.2021.100324>.
- Juhola, S., Glaas, E., Linnér, B.-O., Neset, T.-S., 2016. Redefining maladaptation. *Environ. Sci. Policy* 55, 135–140. <https://doi.org/10.1016/j.envsci.2015.09.014>.
- Mach, K.J., Siders, A.R., 2021. Reframing strategic, managed retreat for transformative climate adaptation. *Science* 372, 1294–1299. [https://doi.org/10.1126/SCIENCE.ABH1894/ASSET/D4F9D9C0-3459-4FCB-B4AB-DD4600BDBE92/ASSETS/GRAPHIC/372.1294\\_F2.JPEG](https://doi.org/10.1126/SCIENCE.ABH1894/ASSET/D4F9D9C0-3459-4FCB-B4AB-DD4600BDBE92/ASSETS/GRAPHIC/372.1294_F2.JPEG).
- Magnan, A.K., Schipper, E.L.F., Burkett, M., Bharwani, S., Burton, I., Eriksen, S., Gemenne, F., Schaaf, J., Ziervogel, G., 2016. Addressing the risk of maladaptation to climate change. *Wiley Interdiscip. Rev. Clim. Chang.* 7, 646–665. <https://doi.org/10.1002/WCC.409>.
- Markusson, N., McLaren, D., Tyfield, D., 2018. Towards a cultural political economy of mitigation deterrence by negative emissions technologies (NETs). *Global Sustainability* 1. <https://doi.org/10.1017/SUS.2018.10>.
- McLaren, D., Markusson, N., 2020. The co-evolution of technological promises, modelling, policies and climate change targets. *Nat. Climate Change* 2020 10(5), 392–397. doi: 10.1038/s41558-020-0740-1.
- McNamara, K.E., Bronen, R., Fernando, N., Klepp, S., 2016. The complex decision-making of climate-induced relocation: adaptation and loss and damage. *18*, 111–117. doi: 10.1080/14693062.2016.1248886.
- Merk, C., Pönitzsch, G., Rehdanz, K., 2016. Knowledge about aerosol injection does not reduce individual mitigation efforts. *Environ. Res. Lett.* 11, 054009. <https://doi.org/10.1088/1748-9326/11/5/054009>.
- Mishra, V., Thirumalai, K., Singh, D., Aadhar, S., 2020. Future exacerbation of hot and dry summer monsoon extremes in India. *npj Climate Atmos. Sci.* 2020 3(1), 1–9. doi: 10.1038/s41612-020-0113-5.

- O'Donnell, T., 2022. Managed retreat and planned retreat: a systematic literature review. *Philos. Trans. R. Soc. B* 377. <https://doi.org/10.1098/RSTB.2021.0129>.
- Psacharopoulos, G., Collis, V., Patrinos, H.A., Vegas, E., 2021. The COVID-19 cost of school closures in earnings and income across the world. *Comp. Educ. Rev.* 65, 271–287. <https://doi.org/10.1086/713540>.
- Reed, P.M., Hadjimichael, A., Moss, R.H., Brelsford, C., Burleyson, C.D., Cohen, S., Dyreson, A., Gold, D.F., Gupta, R.S., Keller, K., Konar, M., Monier, E., Morris, J., Srikrishnan, V., Voisin, N., Yoon, J., 2022. Multisector dynamics: advancing the science of complex adaptive human-earth systems. *Earth's Future* 10, e2021EF002621. doi: 10.1029/2021EF002621.
- Reynolds, J.L., 2019. *The Governance of Solar Geoengineering: Managing Climate Change in the Anthropocene*. Cambridge University Press.
- Robock, A., Jerch, K., Bunzl, M., 2008. 20 reasons why geoengineering may be a bad idea. *Bull. At. Sci.* 64, 14–59. <https://doi.org/10.1080/00963402.2008.11461140>.
- Rode, A., Carleton, T., Delgado, M., Greenstone, M., Houser, T., Hsiang, S., Hultgren, A., Jina, A., Kopp, R.E., McCusker, K.E., Nath, I., Rising, J., Yuan, J., 2021. Estimating a social cost of carbon for global energy consumption. *Nature* 2021 598(7880), 308–314. doi: 10.1038/s41586-021-03883-8.
- Siders, A.R., Ajibade, I., Casagrande, D., 2021. Transformative potential of managed retreat as climate adaptation. *Curr. Opin. Environ. Sustain.* 50, 272–280. <https://doi.org/10.1016/J.COSUST.2021.06.007>.
- Simpson, N., Williams, P.A., Mach, K.J., Berrang-Ford, L., Biesbroek, R., Haasnoot, M., Segnon, A., Campbell, D., Musah, I., Joe, E.T., Marshall Nunbogu, A., Sabour, S., Meyer, A.L.S., Andrews, T.M., Singh, C., Siders, A.R., Lawrence, J., van Aalst, M., Trisos, C., 2023. Adaptation to compound climate risks: a systematic global stocktake. *iScience*. doi: 10.2139/ssrn.4205750.
- Simpson, N.P., Mach, K.J., Constable, A., Hess, J., Hogarth, R., Howden, M., Lawrence, J., Lempert, R.J., Muccione, V., Mackey, B., New, M.G., O'Neill, B., Otto, F., Pörtner, H.O., Reisinger, A., Roberts, D., Schmidt, D.N., Seneviratne, S., Strongin, S., van Aalst, M., Totin, E., Trisos, C.H., 2021. A framework for complex climate change risk assessment. *One Earth* 4, 489–501. <https://doi.org/10.1016/J.ONEEAR.2021.03.005>.
- Sinha, E., Michalak, A.M., Calvin, K.V., Lawrence, P.J., 2019. Societal decisions about climate mitigation will have dramatic impacts on eutrophication in the 21st century. *Nat. Commun.* 10, 939. <https://doi.org/10.1038/s41467-019-08884-w>.
- Thiery, W., Lange, S., Rogelj, J., Schleussner, C.F., Gudmundsson, L., Seneviratne, S.I., Andrijevic, M., Frieler, K., Emanuel, K., Geiger, T., Bresch, D.N., Zhao, F., Willner, S.N., Büchner, M., Volkholz, J., Bauer, N., Chang, J., Ciais, P., Dury, M., François, L., Grillakis, M., Gosling, S.N., Hanasaki, N., Hickler, T., Huber, V., Ito, A., Jägermeyr, J., Khabarov, N., Koutroulis, A., Liu, W., Lutz, W., Mengel, M., Müller, C., Ostberg, S., Reyer, C.P.O., Stacke, T., Wada, Y., 2021. Intergenerational inequities in exposure to climate extremes. *Science* 374, 158–160. [https://doi.org/10.1126/SCIENCE.ABI7339/SUPPL\\_FILE/SCIENCE.ABI7339\\_SM.PDF](https://doi.org/10.1126/SCIENCE.ABI7339/SUPPL_FILE/SCIENCE.ABI7339_SM.PDF).
- Tschakert, P., Barnett, J., Ellis, N., Lawrence, C., Tuana, N., New, M., Elrick-Barr, C., Pandit, R., Pannell, D., 2017. *Climate change and loss, as if people mattered: values, places, and experiences*. Wiley Interdiscip. Rev. Clim. Chang. 8, e476.
- Visioni, D., Pitari, G., Di Genova, G., Tilmes, S., Cionni, I., 2018. Upper tropospheric ice sensitivity to sulfate geoengineering. *Atmos. Chem. Phys.* 18, 14867–14887. <https://doi.org/10.5194/ACP-18-14867-2018>.