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ARTICLE

# Multi-Risk Governance of Solar Radiation Modification

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## Abstract

Solar radiation modification (SRM) presents important challenges to risk regulation and governance, arising from the array of multiple risks that SRM may influence. SRM would not simply reverse climate change, but could pose further ancillary impacts, depending on the method of SRM, such as stratospheric aerosol injection (SAI), marine cloud brightening (MCB), or a space-based planetary sunshade system (PSS). We identify multiple risks that SRM may influence, both biophysical and sociopolitical, to be compared to the multiple risks that may be affected by greenhouse gas (GHG) mitigation and climate adaptation. This multi-risk framework helps analysts and decision makers identify, evaluate, and compare multiple risks holistically; helps identify affected groups to overcome problems of disregard and omitted voice; helps compare policy options and map the array of risks to corresponding (or missing) governance mechanisms; and seeks risk-superior policies that would reduce multiple risks in concert. We then examine governance frameworks: uncoordinated, coordinated and comprehensive. We suggest two key mechanisms that can help build up from uncoordinated toward more coordinated or even comprehensive approaches, and that can gain support from SRM advocates, observers and critics alike: a series of international assessments of SRM, and a transparent international monitoring system for SRM.

**Keywords:** climate policy; risk analysis; risk governance; risk-risk tradeoff; solar radiation modification

## I. Introduction: multi-risk analysis and governance

We live in a world of multiple risks.[1] Consider current efforts to address risks from, for example, accidents, air pollution, AI, chemicals, climate change, disease, disasters, financial crashes, food, terrorism, tsunamis, water, wastes and more. Policies to reduce any one risk may implicate other risks; for example, food safety regulations may involve complex tradeoffs among the risks of foodborne illnesses, chemical exposures, animal

[1] See P Bernstein, *Against the Gods: The Remarkable Story of Risk* (New York, John Wiley, 1996); JB Wiener, "Learning to Manage the Multi-Risk World" (2020) 40 Risk Analysis 2137. Risk can be understood as the combination of the likelihood (or probability) and severity (or magnitude of impact) of an adverse outcome, including attributes such as timing, uncertainty, and distribution. Recent surveys of multiple risks include World Economic Forum, Global Risks Report 2025 (January 2025), available at https://www.weforum.org/publications/global-risks-report-2025/; United Nations, Global Risks Report (forthcoming 2025).

suffering, food waste, packaging materials, environmental pollution, food insecurity, and economic burdens. Societies seek, but struggle, to govern multiple simultaneous and interconnected risks.[2] Some of these risks may be existential, threatening the existence of humanity or all life on Earth.[3]

A recurring problem is the tendency to focus only on one "target risk" or intended outcome at a time, thereby neglecting other risks – narrowly targeting one out of multiple simultaneous stressors, and also neglecting the side effects on other risks from policies to govern the target risk.[4] In a multi-risk world, policies to reduce a target risk may also affect other risks, both old and new, potentially posing risk–risk tradeoffs.[5] Multi-risk governance aims to address multiple risks, and both intended and unintended consequences of policy options (including both co-benefits and countervailing risks). Hence multi-risk governance involves analytic methods and institutional capacities to: (i) identify and catalogue the multi-risk effects of each candidate policy option; (ii) evaluate and weigh such multi-risk effects and tradeoffs, in order to select policies that best reduce overall risk; and (iii) develop even better "risk-superior" options that overcome trade-offs by reducing multiple risks in concert.[6]

Importantly, the identification of multi-risk effects (such as countervailing risks) does not necessarily warrant declining to manage the target risk. A countervailing risk increase may be small relative to (and thus justified by) the target risk reduction (plus co-benefits). Even if the countervailing risks are relatively large (in some cases possibly even larger than the target risk reduction), they may warrant selecting or designing a different policy option that still reduces the target risk and also better reduces overall risk.[7]

Governance policy responses to climate change must navigate this multi-risk world. In Part II of this paper, we identify the multi-risk profiles of key climate policy response strategies, including mitigation (reducing greenhouse gas [GHG] emissions and enhancing GHG sinks to

[2] See Wiener, "Multi-Risk World" (2020), *supra*; U Beck, *The Risk Society: Towards a New Modernity* (London, Sage, 1986 [tr. 1992]); O Renn, *Risk Governance: Coping with Uncertainty in a Complex World* (London, Earthscan, 2008); K Yeung and S Ranchordás, "The Rise of Risk" ch. 2, pp 41–78, in K Yeung and S Ranchordas, *An Introduction to Law and Regulation* (Cambridge, Cambridge University Press, 2nd edition, 2024).

[3] See JB Wiener, "The Tragedy of the Uncommons" (2016) 7 Global Policy 67; T Ord, *The Precipice: Existential Risks and the Future of Humanity* (New York, Hachette, 2020).

[4] See JD Graham and JB Wiener, eds., *Risk vs. Risk* (Cambridge MA, Harvard University Press, 1995); J Liu et al., "Systems Integration for Global Sustainability" (2015) 347 Science 963. https://doi.org/10.1126/science.1258832; R Baldwin, "Regulatory Excellence and Lucidity," ch. 8, pp 115–130, in C Coglianese, ed., *Achieving Regulatory Excellence* (Washington, DC, Brookings Press, 2017); PT Anastas and JB Zimmerman, "Environmental Protection Through Systems Design, Decision-Making, and Thinking," pp 97–104, in DC Esty, ed., *A Better Planet* (New Haven CT, Yale University Press, 2019).

[5] Graham and Wiener, *Risk vs. Risk* (1995), *supra* n 4.

[6] See Wiener, "Multi-Risk World" (2020), *supra* n 1; Graham and Wiener, *Risk vs. Risk, supra* n 4; T Felgenhauer, G Bala, ME Borsuk, I Camilloni, JB Wiener and J Xu, "Practical Paths to Risk–Risk Analysis of Solar Radiation Modification" (2025) 5 (1) Oxford Open Climate Change kgaf012. https://doi.org/10.1093/oxfclm/kgaf012, available at https://academic.oup.com/oocc/article/5/1/kgaf012/8089845.

[7] Further, the challenge of the multi-risk reality should not delay or paralyze policy with endless analysis; rather, the extent of analysis of each risk in the multi-risk array should be *proportionate* to the importance of that risk in the selection among policy options. Some ancillary risks will be too small to warrant further analysis. See Graham and Wiener, *Risk vs. Risk* (1995), *supra* n 4, ch 1; JB Wiener, "Modernizing Regulatory Review: Assessing All Important Impacts" (2023) 48 (3) ABA Administrative & Regulatory Law News 11–14 (Spring), reprinted in *Yale J. on Regulation Online*, available at https://www.yalejreg.com/nc/modernizing-regulatory-review-assessing-all-important-impacts-by-jonathan-b-wiener/; JD Graham and JB Wiener, "Co-Benefits, Countervailing Risks, and Cost-Benefit Analysis" ch. 34, pp 1167–1188, in D Paustenbach, ed., *Human and Ecological Risk Assessment: Theory and Practice* (New York, John Wiley & Sons, 3rd edition, 2024).

prevent climate change),[8] adaptation (improving resilience to climate impacts), and a third strategy, reflection (cooling the Earth via solar radiation modification (SRM)).[9] In all three types of response strategies, each specific policy option may also affect other risks, including unintended effects on climate and on non-climate risks. No climate policy is immune to multi-risk interactions, though some policies are better than others at dealing with the multi-risk challenge. In Part III, we examine governance frameworks corresponding to these multiple risks, notably governance frameworks that are uncoordinated, coordinated, and comprehensive. We compare the pros and cons of these three types of governance frameworks in a multi-risk world. We then suggest new governance mechanisms for SRM that can build from uncoordinated toward more coordinated and even comprehensive governance approaches, and can find support from SRM researchers, advocates, and critics. These governance mechanisms include a series of iterative and transparent international assessments, and a transparent international monitoring system for SRM.

## II. Multi-risk analysis of climate change policies: mitigation, adaptation and reflection

Climate change is a multi-risk problem. It exhibits multiple simultaneous stressors: multiple greenhouse gases (GHGs) from multiple sectors and sources in multiple countries, contributing to rising global atmospheric concentrations and increasing radiative forcing, with multiple impacts around the world, including on temperature and heat stress, precipitation, flooding, wildfires, glacial melting, sea level rise, vector-borne diseases, agricultural shifts, biodiversity loss and ocean acidification. It interacts with other problems such as stratospheric ozone depletion, air pollution, land use, biodiversity loss, food security and energy access.[10]

The primary policy response to climate risks has been *mitigation*: reducing emissions of GHGs such as CO2, CH4, N2O and HFCs, and/or enhancing sinks of these gases such as through carbon dioxide removal (CDR) and sequestration. But slow progress on mitigation, and worsening climate impacts, have increased attention to *adaptation* – improving resilience to climate impacts – and, over time, to a third approach, *reflection*: strategies to cool the Earth slightly, such as solar radiation modification (SRM).[11]

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[8] The term "mitigation" as used here includes both reducing emissions at sources, and enhancing sinks such as through carbon dioxide removal (CDR) or methane removal from the atmosphere. "Mitigation" is defined by the Intergovernmental Panel on Climate Change (IPCC) to encompass "actions or activities that limit emissions of greenhouse gases (GHGs) from entering the atmosphere and/or reduce their levels in the atmosphere. Mitigation includes reducing the GHGs emitted from energy production and use (e.g., that reduces use of fossil fuels), and land use, and methods to mitigate warming, for example, by carbon sinks which remove emissions from the atmosphere through land-use or other (including artificial) mechanisms." IPCC 6th Assessment Report (2023), WGIII, FAQS, available at https://www.ipcc.ch/report/ar6/wg3/downloads/faqs/IPCC_AR6_WGIII_FAQ_Chapter_01.pdf. Although some analyses lump SRM and CDR together as "geoengineering," they operate quite differently in remedying climate change, and they face different geopolitical incentives, warranting "splitting" their treatment, see S Jinnah, D Morrow and S Nicholson, "Splitting Climate Engineering Governance: How Problem Structure Shapes Institutional Design" (2021) 12 (Supp 1) Global Policy 8–19. https://doi.org/10.1111/1758-5899.12900.

[9] See JB Wiener and T Felgenhauer, "The Evolving International Climate Change Regime: Mitigation, Adaptation, Reflection" (2024) 11 Texas A&M Law Review 451, available at https://scholarship.law.tamu.edu/lawreview/vol11/iss2/6/; EA Parson and DW Keith, "Solar Geoengineering: History, Methods, Governance, Prospects" (2024) 49 Annual Review of Environment and Resources 337. https://doi.org/10.1146/annurev-environ-112321-081911; JE Aldy and R Zeckhauser, Three Prongs for Prudent Climate Policy (2019) 87 Southern Economics Journal 3. https://doi.org/10.1002/soej.12433. Earlier discussions of SRM options include DW Keith and H Dowlatabadi, "A Serious Look at Geoengineering" (1992) 73 EOS 289–96; S Schneider, "Geoengineering: Could – or Should – We Do It?" (1996) 33 Climatic Change 291–302. https://doi.org/10.1007/bf00142577.

[10] See generally IPCC, *6th Assessment Report* (2023), available at https://www.ipcc.ch/assessment-report/ar6/.

[11] See Wiener and Felgenhauer (2024), *supra* n 9; Parson & Keith, ARER (2024), *supra* n 9; Aldy & Zeckhauser (2019), *supra* n 9.

These three strategies of climate policy – mitigation, adaptation and reflection – might be viewed as alternative substitutes, but they are also potential complements, because they operate in different scales of space and time, on different elements of climate risk (e.g., reducing probability vs. reducing impacts), and some argue that they might all be needed if climate risk becomes extremely acute and no one strategy is sufficient.[12] Methods of SRM have been understood by scientists since at least the 1960s, but are now receiving increasing attention, as mitigation has been slow and impacts have worsened. "After a long slow start, solar radiation modification (SRM) is seeing a rapid increase in research, attention, involvement of private and public organisations, and controversy."[13] Several high-level reports on SRM have been issued in recent years.[14] SRM methods include stratospheric aerosol injections (SAI) of particles such as sulfates (emulating the observed global cooling effect of major volcanoes); marine cloud brightening (MCB) for regional cooling; and a space-based planetary sunshade system (PSS) positioned on a stable orbit between the Earth and the Sun.

A good working hypothesis is that every climate policy option may have multi-risk effects. Some options may be better overall than others, but no policy is immune to the multi-risk reality.[15] The specific multi-risk effects depend on the specific policy option, so each policy has a different multi-risk profile or portfolio.

We identify the multi-risk effects of each climate policy strategy – mitigation, adaptation, and reflection – in Table 1. These multi-risk effects include favorable and unfavorable effects on the target risk of climate change, and favorable (co-benefits) and unfavorable (countervailing risks) effects on non-climate risks, as indicated in the four quadrants of Table 1. This process of "risk identification" depicted in Table 1 is intended to help the analyst and policy maker confront the portfolio of multiple risks, beyond just the target risk, associated with each policy option. The lists in Table 1 are not exhaustive; there may be others. The policy options in Table 1 are only described at a very coarse level of generality; risks will vary for more specific policy designs. And the exercise of assembling Table 1 does not yet seek to quantify each risk. Rather it illustrates the key step in multi-risk analysis of: (i) identifying and cataloging the multi-risk effects of each policy option, rather than focusing on the target risk and neglecting or disregarding other effects. This is a key predicate to then (ii) evaluating and weighing the multiple risks, to select or design

[12] See Aldy and Zeckhauer (2019), *supra* n 9. Reflection via SRM could be compared not only to actual current mitigation policies, but also to future and more ambitious mitigation policies, which (if adopted – not an easy task) could be more effective and thus could reduce the need for SRM. Still, if peak climate risk is severe, then SRM and more ambitious mitigation could still be complements, with the optimal response including both. See TML Wigley, "A Combined Mitigation/Geoengineering Approach to Climate Stabilization" (2006) 314 Science 452–4. Meanwhile, though, ambitious mitigation policies could also incur serious risk-risk tradeoffs (as could SRM), as indicated in Table 1 *infra*.

[13] Parson and Keith (2024), *supra* n 9, p 359. Similarly, SRM critic Duncan McLaren observes: "Recently, as the impacts of climate change have become more evident and harmful globally, and the scope for mitigation to reduce climate risk ebbs with depleting carbon budgets, there has been growing interest in 'solar geoengineering.' These are ways to reduce Earth's temperatures by reflecting a small proportion of incoming sunlight." D McLaren, "Governing Emerging Solar Geoengineering: A Role for Risk-Risk Evaluation?" (2023) 24 Georgetown Journal of International Affairs 234. https://doi.org/10.1353/gia.2023.a913651 (footnote omitted).

[14] E.g., US National Academies (NASEM), *Reflecting Sunlight* (2021) available at https://nap.nationalacademies.org/catalog/25762/reflecting-sunlight-recommendations-for-solar-geoengineering-research-and-research-governance; UN Environment Programme (UNEP), *One Atmosphere* (2023), available at https://www.unep.org/resources/report/Solar-Radiation-Modification-research-deployment; Climate Overshoot Commission, *Reducing the Risks of Climate Overshoot* (2023), chapter 8, available at https://www.overshootcommission.org/report; European Commission, Scientific Advice Mechanism, Group of Chief Scientific Advisers, Scientific Opinion No. 17, *Solar Radiation Modification* (December 2024), available at https://scientificadvice.eu/advice/solar-radiation-modification/; European Commission, Scientific Advice Mechanism, *SAPEA Evidence Review Report on SRM* (2024), available at https://scientificadvice.eu/scientific-outputs/solar-radiation-modification-evidence-review-report/.

[15] See Wiener, "Learning to Manage the Multi-Risk World" (2020), *supra* n 1.

**Table 1.** Identifying multiple risks affected by climate response options[16]

| | **Risk Identification** (examples for further analysis; each depends on the specific policy; probabilities and severities may range from low to high for different policies, risks, scenarios, and data) | |
|---|---|---|
| Type of Risk | Favorable | Unfavorable |
| Target risk (climate change) | Benefits – reducing climate risk:<br>• *Mitigation*: reducing GHG emissions (e.g., $CO_2$, $CH_4$) thus reducing both probability and harms of climate change<br>• *Adaptation*: reducing harms of climate change<br>• *Reflection* (SRM): reducing risks of climate change, including heat waves, hurricanes, floods, droughts, wildfires, polar and glacial ice loss, sea level rise, vector-borne disease, exceeding tipping points, etc. | Harms – increasing climate risk:<br>• *Mitigation*: reducing $CO_2$ emissions (e.g. from coal) but increasing other GHGs (e.g., $CH_4$ from natural gas; $N_2O$ from growing biofuels); using biofuels to reduce $CO_2$ from energy but converting carbon-sequestering forests to agricultural land to grow biofuels; afforestation in high latitudes sequestering carbon but also changing albedo<br>• *Adaptation*: air conditioning cooling occupants, but increasing energy use and refrigerant chemicals that are GHGs<br>• *Reflection (SRM)*: adverse global climate change, e.g., excessive cooling, if SRM turns out to be more potent or long-lasting than expected; adverse or disparate regional climate impacts, e.g., on precipitation, monsoons, agriculture |
| Ancillary risks (non-climate) | Co-benefits – reducing other risks:<br>• *Mitigation*: reducing other pollution from fossil fuels (air, water, land); protecting carbon sinks and biodiversity via CDR (e.g., conserving forests, oceans); reducing ocean acidification due to $CO_2$<br>• *Adaptation*: improving resilience against extreme weather, disease, etc.<br>• *Reflection (SRM)*: SAI reducing tropospheric ozone; light diffusion enhancing vegetation productivity in some locations | Countervailing risks – increasing other risks:<br>• *Mitigation*: low ambition due to free rider incentives; risks of new energy sources (e.g. nuclear; EV batteries; land use and biodiversity impacts of solar and wind energy); seismic events (e.g., from unconventional gas, or CDR); using land for biofuels that displaces biodiversity and/or food production<br>• *Adaptation*: "maladaptation," e.g., sea walls impairing marine ecosystems; air conditioning cooling occupants, but increasing energy use and refrigerant chemicals that are ODS, and encouraging migration to arid water-stressed regions<br>• *Reflection (SRM)*: SAI – ozone depletion and increased UV; acid deposition; SRM generally – light diffusion/dimming; effects on mitigation effort (moral hazard/mitigation deterrence, or stimulation?); hasty/unwise use due to free-driver/first-mover incentives; international conflict; termination shock |

[16] Adapted from analyses in T Felgenhauer et al, "Solar Radiation Modification (SRM): A Risk-Risk Analysis," C2G (2022), *infra* n 20; T Felgenhauer et al, "Practical Paths to Risk-Risk Analysis of SRM," (2025), *supra* n 6.

the best policy to reduce overall risk, and (iii) seeking even better "risk-superior" policies. Assembling Table 1 also assists in identifying those groups affected by each risk, helping to overcome potential "disregard" or "omitted voice" of affected groups, and fostering more inclusive participation in governance by all affected groups.[17]

For example, mitigation measures to reduce GHG emissions may reduce climate risk, but may pose a variety of multi-risk effects (depending on the specific policy), such as the co-benefits of reducing conventional air pollution, and the countervailing risks of shifting from one GHG (e.g., CO2) to another (e.g., CH4 or N2O), shifting from one energy source (e.g., coal, oil or gas) to another (e.g., nuclear, hydro, wind or solar), and shifting land uses such as biofuel cultivation and/or forest conservation.[18]

Meanwhile, adaptation measures may also affect multiple risks, such as "maladaptation" that harms other ecological or social systems. For example, sea walls to shield against storm surge may also interfere with marine ecosystems, and air conditioning to cool dwellings may also use energy that increases emissions of GHGs.[19]

As indicated in Table 1, the third strategy, SRM, also poses multi-risk effects. It is not just reversing climate risk; SRM introduces a new climate modification at the same time that GHGs are forcing climate change. Each technique of SRM may reduce climate risk but also pose multiple other risks. Numerous observers have therefore called for risk–risk analysis of SRM.[20] For example, as indicated in Table 1, SRM may reduce peak temperature impacts and thereby reduce mortality from heat,[21] and it may benefit warmer countries

[17] See JB Wiener, "Disregard and Due Regard" (2021) 29 NYU Environmental Law Journal 437, available at http://www.nyuelj.org/wp-content/uploads/2021/10/Wiener-Final.pdf; Graham and Wiener, Risk vs. Risk, *supra* n 4, ch. 11 (on "omitted voice" and neglect of countervailing risks); Shuchi Talati, "Including Every Voice in Solar Geoengineering" (2023), Resources Radio, Episode 242, available at https://www.resources.org/resources-radio/including-every-voice-in-solar-geoengineering-with-shuchi-talati/. Thus, multi-risk or risk-risk analysis is not at odds with inclusive participation; rather, multi-risk analysis is crucial to identifying which groups would be affected and hence which voices need to be included and not disregarded. Calls for more participatory inclusion in decision making about SRM, see e.g., Duncan McLaren [this symposium issue], need some way to identify which groups should participate, and the multi-risk framework is essential to identifying which groups are affected by each policy option.

[18] See Graham and Wiener, *Risk vs. Risk* (1995), *supra* n 4, ch.10; DT Shindell, Y Lee and G Faluvegi, "Climate and Health Impacts of US Emissions Reductions Consistent with 2°C" (2016) 6 Nature Climate Change 503–507; BK Sovacool, "The Low-Carbon Risk Society: Dilemmas of Risk-Risk Tradeoffs in Energy Innovations, Transitions, and Climate Policy" (2024) 45 Risk Analysis 78–107, available at https://onlinelibrary.wiley.com/doi/10.1111/risa.14667; G Bala et al, "Combined Climate and Carbon-Cycle Effects of Large-Scale Deforestation" (2007) 104 PNAS 6550.

[19] See D Reckien et al, "Navigating the Continuum Between Adaptation and Maladaptation" (2023) 13 Nature Climate Change 907. https://doi.org/10.1038/s41558-023-01774-6.

[20] See T Felgenhauer, G Bala, M Borsuk, M Brune, I Camilloni, J Wiener and J Xu, "Solar Radiation Modification (SRM): A Risk-Risk Analysis" (2022) Carnegie Climate Governance Initiative (C2G), available at https://www.c2g2.net/managing-the-risk-of-temperature-overshoot/, or https://bit.ly/SRM-Risk-Risk; T Felgenhauer et al, "Practical Paths to Risk-Risk Analysis of SRM" (2025), *supra* n 6; Climate Overshoot Commission (2023), *supra* n 14, ch 8; EA Parson, "Geoengineering: Symmetric Precaution" (2021) 374 Science 795; EA Parson and D Keith ARER (2024), *supra* n 9; EA Parson, HJ Buck, S Jinnah, J Moreno-Cruz and S Nicholson, "Toward an Evidence-Informed, Responsible, and Inclusive Debate on Solar Geoengineering" (2024) 15 WIREs Climate Change e903, section 2.1. https://doi.org/10.1002/wcc.903; BK Sovacool, CM Baum and S Low, "Risk-Risk Governance in a Low-Carbon Future: Exploring Institutional, Technological, and Behavioral Tradeoffs in Climate Geoengineering Pathways" (2023) 43 Risk Analysis 838–59, available at https://onlinelibrary.wiley.com/doi/full/10.1111/risa.13932. For a quantitative estimate of one such risk-risk tradeoff, see A Harding, G Vecchi, W Yang and D Keith, "Impact of Solar Geoengineering on Temperature-Attributable Mortality" (2024) 121 PNAS No. 0 e2401801121 (Oct. 2). https://doi.org/10.1073/pnas.2401801121.

[21] See A Harding et al (2024), *supra* n 20 (finding that SAI modeled to cool global average surface temperature by 1°C from 2.5°C above preindustrial average in 2080 would reduce temperature-attributable mortality by 400,000 per year out of 9 billion human population = 4 deaths per 100,000, while mortality associated with SAI-induced

more than colder countries.[22] If SRM were deployed and took effect quickly (faster than mitigation), perhaps it could help avoid key tipping points, such as for wildfires, glacial melting and other climate risks.

But as Table 1 also highlights, SRM (specifically SAI) could also pose countervailing risks, including adverse climate changes (globally and regionally), acid deposition, slowed recovery of stratospheric ozone, and light dimming and diffusion with possible effects on photosynthesis. In addition to these biophysical risks, SRM could also pose sociopolitical risks, such as unilateral or non-cooperative use and attendant international conflict[23] (if countries disagree on the optimal global temperature – or if they just disagree on who is in control), adverse influences on mitigation effort (dubbed mitigation deterrence or moral hazard, if actors relax their mitigation efforts in reliance on SRM – though the research findings are mixed, with many studies finding no effect or even the opposite effect of stimulating added mitigation[24]), and "termination shock" if SRM were started and then stopped while GHG concentrations remained high and the Earth's climate re-warmed rapidly.[25] The multi-risk framework helps to identify, evaluate, weigh and compare such

ozone depletion (UV-B exposure) and acid deposition would yield 26,000 deaths = 0.3 per 100,000, for a 13-fold net benefit, while acknowledging that other impacts of SAI are not quantified in this analysis).

[22] See AR Harding, K Ricke, D Heyen, DG MacMartin and J Moreno-Cruz, "Climate Econometric Models Indicate Solar Geoengineering Would Reduce Inter-Country Income Inequality" (2020) 11 Nature Communications 227. https://doi.org/10.1038/s41467-019-13957-x. One implication of this research is that some countries, such as India, may perceive significant benefits from SRM, if they face severe damages from climate change (e.g., extreme heat waves with high mortality). See also S Barrett, "Solar Geoengineering's Brave New World: Thoughts on the Governance of an Unprecedented Technology" (2014) 8 Review of Environmental Economics and Policy 249–69, available at https://www.journals.uchicago.edu/doi/10.1093/reep/reu011 (discussing India's motivations and capabilities to move ahead unilaterally with SRM).

[23] On scenarios of unilateral or non-cooperative use of SRM, see S Barrett, "The Incredible Economics of Geoengineering" (2008) 39 Environmental and Resource Economics 45–54, available at https://link.springer.com/article/10.1007/s10640-007-9174-8; DG Victor, "On the Regulation of Geoengineering" (2008) 24 Oxford Review of Economic Policy 322–36; F Rabitz, "Going Rogue? Scenarios for Unilateral Geoengineering" (2016) 84 Futures 98–107; EA Parson and JL Reynolds, "Solar Geoengineering: Scenarios of Future Governance Challenges" (2021) 133 Futures 102806.

A recent paper by Horton, Smith and Keith argues that only ten countries – the United States, China, Russia, United Kingdom, France, Germany, Japan, Canada, India and Brazil – have the technical capabilities to deploy a global and sustained SAI project rapidly in the near term (fast enough to reduce global average surface temperature by 1°C by 2050), and that only two – the United States and China – currently have the geopolitical power to do so while overriding opposition from other countries. See JB Horton, W Smith, and DW Keith, "Who Could Deploy Stratospheric Aerosol Injection? The United States, China, and Large-Scale, Rapid Planetary Cooling" (2025) – *Global Policy* – (early view online 23 April 2025). https://doi.org/10.1111/1758-5899.70015. Thus, they argue that United States(US)–China relations will be crucial for SRM, including scenarios of joint US-China support for SRM, joint US–China opposition to SRM by others, or US–China conflict over SRM (perhaps exacerbating other US–China conflicts). As they acknowledge, however, more countries than the US and China could in time become fully capable of unilaterally deploying SAI (or other types of SRM) if these parameters change – such as if other countries (e.g., India) grow in relative power, if SRM methods become less costly, if more gradual or regional deployment is considered, if opposition by other countries decreases (or could be more easily overcome), or if plurilateral coalitions of countries (perhaps along with large private actors) act jointly.

[24] *See* AC Lin, "Does Geoengineering Present a Moral Hazard?" (2013) 40 Ecology Law Quarterly 673; T Cherry et al, "Climate Cooperation in the Shadow of Solar Geoengineering: An Experimental Investigation of the Moral Hazard Conjecture" (2023) 32 Environmental Politics 362. https://doi.org/10.1080/09644016.2022.2066285; J Moreno-Cruz, DM McEvoy, M McGinty and TL Cherry, "The Economics and Governance of Solar Geoengineering" (2025) 19 Review Environmental Economics and Policy 1 (Winter), available at https://www.journals.uchicago.edu/doi/full/10.1086/733652.

[25] On "termination shock," see A Parker and PJ Irvine, "The Risk of Termination Shock from Solar Geoengineering" (2018) 6 Earth's Future 456. https://doi.org/10.1002/2017EF000735.

multiple risks holistically, to reduce overall risk, and seeks new risk-superior policies that reduce multiple risks in concert.[26]

If the SRM technology were instead a space-based planetary sunshade system (PSS), a kind of parasol placed in a fairly stable orbit around Sun-Earth LaGrange point L1 (about 1% of the distance from the Earth to the Sun, or just under a million miles from Earth),[27] the climate risk reduction benefits (by reflecting or deflecting a small percentage of energy from the Sun) could in principle be similar to those from SAI (injecting reflective particles into the Earth's stratosphere). But the PSS would avoid the countervailing risks of putting particles (e.g. sulfates) into the stratosphere, such as acid deposition and ozone depletion.[28] The countervailing risk of unilateral/non-cooperative deployment could be lower (than for SAI) if the PSS remains much more expensive to deploy than SAI; but PSS technology is being advanced, the cost of space launches has been declining, and the number of spacefaring countries (and corporations) is growing, so the likelihood of some actor developing a PSS may be rising.[29] The prestige (national or entrepreneurial) from

[26] See T Felgenhauer et al, "SRM: A Risk-Risk Analysis" (2022), *supra* n 20; JB Wiener and T Felgenhauer, "The Evolving International Climate Change Regime" (2024), *supra* n 9, Part III, pp 478–82; T Felgenhauer et al, "Practical Paths to Risk-Risk Analysis of SRM" (2025), *supra* n.6; Sovacool et al (2023), *supra* n 20; M Honegger, "Addressing Risks and Trade-Offs in Governance" in M-V Florin et al, eds., *International Governance Issues on Climate Engineering* (Lausanne, EPFL, International Risk Governance Center (IRGC) 2020). The express attention given by these studies (and the present paper) to both biophysical and sociopolitical risks of SRM – including its risks of unilateral/non-cooperative deployment, moral hazard/mitigation deterrence, and termination shock – demonstrate that it is incorrect to say that risk-risk analysis of SRM exhibits a "shortcoming" in "its focus on rational, ideal scenarios of solar geoengineering deployment, counterposed with more politically realistic, non-ideal efforts at emissions mitigation," D McLaren (2023), *supra* n 13, pp 241–2 & n 25. On the contrary, these risk–risk analyses of SRM focus explicitly and intently on politically realistic, non-ideal efforts at reflection (SRM) as well as mitigation and adaptation.

[27] See Planetary Sunshade Foundation, *State of Space-Based Solar Radiation Modification* (2023), available at https://www.planetarysunshade.org/publications; CL Matonti et al, "Roadmap Toward a Planetary Sunshade for Space-Based Solar Geoengineering" (19 April 2025), draft at https://ssrn.com/abstract=5223310 or https://doi.org/10.2139/ssrn.5223310. Early analyses of space-based planetary sunshade systems go back at least to JT Early, "The Space Based Solar Shield to Offset Greenhouse Effect" (1989) 42 Journal of the British Interplanetary Society 567–569; W Seifritz, "Mirrors to Halt Global Warming?" (1989) 340 (6235) Nature 603. https://doi.org/10.1038/340603a0; Keith and Dowlatabadi (1992), *supra* n 9. For model estimates of sunshades' effects by reducing solar irradiation, see G Bala and K Caldeira, "Geoengineering Earth's Radiation Balance to Mitigate $CO_2$-Induced Climate Change" (2000) 27 Geophysical Research Letters 2141–4; DJ Lunt, A Ridgwell, PJ Valdes and A Seale, "Sunshade World: A Fully Coupled GCM Evaluation of the Climatic Impacts of Geoengineering" (2008) 35 Geophysical Research Letters L12710. For a conjecture that space-based planetary sunshades could be used not only to cool the Earth but also to warm up Mars, see KB Jang and TH Woo, "Analysis of Solar Radiation Shielding in Space for Climate Mitigations of the Earth" (2025) 13 Energy Science & Engineering 1653, 1659. https://doi.org/10.1002/ese3.2083.

[28] See L David, "These Scientists Want to Put a Massive 'Sunshade' in Orbit to Help Fight Climate Change" (Dec. 19, 2023) *Space.com*, available at https://www.space.com/sunshade-earth-orbitclimate-change [https://perma.cc/78U4-5N9P]; Planetary Sunshade Foundation (2023), *supra* n 27. Still, space-based planetary sunshades could pose countervailing risks due to changes in regional temperatures, stratospheric cooling, reduced light for photosynthesis, and other effects, see G Bala, "Space Sunshades and Climate Change" in B. Freedman (ed), *Global Environmental Change, in the Handbook of Global Environmental Pollution*, vol. 1, (Springer 2014) pp 803–15. https://doi.org/10.1007/978-94-007-5784-4_25.

[29] See C Buckley, "Could a Giant Parasol in Outer Space Help Solve the Climate Crisis? Interest in Sun Shields, Once a Fringe Idea, Has Grown. Now, a Team of Scientists Says It Could Launch a Prototype Within a Few Years," *NY Times*, Feb. 3, 2024, p A1, available at https://www.nytimes.com/2024/02/02/climate/sun-shade-climate-geoengineering.html. For example, researchers are investigating ways to reduce costs and test solar sail techniques, see C Fugelsang and MG de Herreros Miciano, "Realistic Sunshade System at L1 for Global Temperature Control" (2021) 186 Acta Astronautica 269–79; ways to reduce the mass of materials and assemble them in space out of lunar or asteroid dust, see I Szapudi, "Solar Radiation Management with a Tethered Sun Shield" (2023) 120 PNAS (32) e2307434120. https://doi.org/10.1073/pnas.2307434120; and ways to optimise the orbital location and station-keeping of the PSS, see JP Sánchez and CR McInnes, "Optimal Sunshade Configurations for Space-Based

launching the PSS and "winning the (next) space race" could add momentum to unilateral deployment of PSS, compared to SAI. The PSS might thus accentuate the sociopolitical risks of international conflict, if there is a race to capture the scarce orbital location at L1, or if countries disagree on optimal global temperature, or if they disagree on who controls the global thermostat. The risk of termination shock might be different for PSS than for SAI, if deploying an expensive and prestigious PSS would elicit greater political dependency – perhaps a lower probability of termination for PSS than for SAI (though the PSS technology might have glitches), but potentially a greater harm from termination for PSS than for SAI (and more costly and time-consuming to replace or resume PSS than to resume SAI). These multiple risks warrant research.

MCB presents a different multi-risk profile, and uncertainty regarding its mechanisms and impacts is high.[30] MCB could involve ships spraying sea salt aerosols into the lower atmosphere, resulting in regional or even global cooling, depending on the geographical scale of deployment. In comparison to SAI, the short lifetime of the MCB particles could in principle allow for a more targeted deployment aimed at cooling a particular region, country, or ecosystem.[31] If MCB were deployed at this scale it might pose lower risks (than would SAI) for mitigation deterrence or termination shock. Yet such localised MCB could have unintended side effects on neighboring countries (with changing precipitation patterns) and also globally via teleconnections. MCB deployed at a scale aiming to cool the globe could bring large negative side effects, depending on the specifics of the deployment strategy.[32] It thus seems worth investigating both regional and global MCB deployment scenarios. Moreover, analysis is needed of scenarios of multiple simultaneous MCBs, if multiple actors each deployed their own version of MCB, posing the risks of interactions among these multiple MCB interventions, both environmentally and geopolitically.

## III. Multi-risk governance of SRM

### 1. Current governance frameworks

Governance of multi-risk problems entails several functional tasks, including: risk assessments of multiple stressors, including their joint effects; standard-setting and policy design, informed by prospective (ex ante) impact assessments, including of multi-risk effects; implementation and enforcement; monitoring of ongoing outcomes, both intended and unintended; retrospective impact assessments (ex post evaluations), including of multi-risk effects; and adaptive learning and updating. Addressing multiple risks, including unintended consequences, under uncertainty, puts a premium on adaptive learning.[33]

Geoengineering near the Sun-Earth L1 Point" (2015) 10 (8) PLoS ONE e0136648. https://doi.org/10.1371/journal.pone.0136648.

[30] CW Stjern, et al, "Response to Marine Cloud Brightening in a Multi-Model Ensemble" (2018) 18 Atmospheric Chemistry and Physics 621. https://doi.org/10.5194/acp-18-621-2018.

[31] J. Quaas, et al, "Solar Radiation Modification: SAPEA Evidence Review Report" (2024) SAPEA (Science Advice for Policy by European Academies), Scientific Advisory Mechanism to the European Commission 2024. https://doi.org/10.5281/zenodo.14283096, available at https://scientificadvice.eu/scientific-outputs/solar-radiation-modification-evidence-review-report/#chapter-8-suggestions-for-policy-options-and-conclusion. The Australian Reef Restoration and Adaptation Programme (RRAP) (https://gbrrestoration.org/) is exploring this possibility. See also DP Harrison, "An Overview of Environmental Engineering Methods for Reducing Coral Bleaching Stress" in E Wolanski and MJ Kingsford (eds), *Oceanographic Processes of Coral Reefs: Physical and Biological Links in the Great Barrier Reef* (2nd ed, CRC Press, Taylor and Francis Group 2024). https://doi.org/10.1201/9781003320425.

[32] C-C Chen, JH Richter, WR Lee, M Tye, DG MacMartin and B Kravitz, "Climate Impact of Marine Cloud Brightening Solar Climate Intervention Under a Susceptibility-Based Strategy Simulated by CESM2" (2025) 130 Journal of Geophysical Research: Atmospheres e2024JD041245. https://doi.org/10.1029/2024JD041245.

[33] See Wiener, "Learning to Manage the Multi-Risk World" (2020), *supra* n 1; JB Wiener and A Alemanno, "The Future of International Regulatory Cooperation" (2015) 78 Law & Contemporary Problems 103; LS Bennear and JB

Impact assessments (prospective and retrospective), monitoring, and adaptive updating all need a broad scope in order to assess and address both intended and unintended outcomes.

Actual governance frameworks do not always – or often – undertake all of these tasks. In principle, these tasks could be undertaken by a single institution or by multiple institutions. In a multi-risk world, yet one in which analysts, decision makers and institutions often focus narrowly on a target risk, it is often the case that governance is a patchwork in which key tasks are omitted, important risks are neglected, and affected groups are disregarded – and, where the key tasks are undertaken, each risk is often regulated by a separate treaty, law or regulation, implemented by a separate ministry or agency, within each of many separate national governments. This pattern yields a complex array of multiple institutions applying multiple policies to multiple risks – but not addressing all key tasks, nor all important risks, nor all affected groups, nor accounting for all the important risk–risk interactions, and hence falling short of the best opportunities to reduce overall risk and to engage all affected groups.

The current governance framework for climate change, including the Framework Convention on Climate Change (FCCC),[34] the Paris Agreement,[35] other international agreements and multiple national laws, is already a "regime complex" with multiple institutions addressing multiple facets.[36] Governance of SRM could also take such a multi-institutional approach.[37] Here we describe the current array of governance of SRM, after which we suggest steps to advance toward better multi-risk governance of SRM.

Along a spectrum of potential multi-risk governance institutions, from highly fragmented to highly cohesive, these multiple institutions could be:

(1) uncoordinated, acting independently (and with some gaps in coverage); or
(2) coordinated with each other (acting separately but interdependently, in communication and seeking to cover gaps and address multi-risk interactions); or
(3) comprehensive, with a single regulator (or oversight body) to orchestrate all the key tasks for the full multi-risk portfolio.

Moving along this spectrum from fragmented uncoordinated, to more coordinated, and toward comprehensive governance frameworks, may improve multi-risk governance, by better addressing the multiple risks and their potential interactions, including the ancillary risks (co-benefits and countervailing risks) of policy measures, thereby improving overall outcomes – but such a move also faces obstacles and raises concerns about centralisation of regulatory power.[38]

Wiener, "Built to Learn: From Static to Adaptive Environmental Policy" in DC Esty (ed), *A Better Planet: Forty Big Ideas for a Sustainable Future* (New Haven CT, Yale University Press 2019) pp 353–60; LE McCray, KA Oye and AC Petersen, "Planned Adaptation in Risk Regulation" (2010) 77 Technological Forecasting and Social Change 951.

[34] U.N. Framework Convention on Climate Change (May 9, 1992), 1771 UNTS 107 (hereafter "FCCC").

[35] Paris Agreement to the U.N. Framework Convention on Climate Change (April 22, 2016), TIAS No. 16-1104.

[36] *See* Intergovernmental Panel on Climate Change (IPCC), 5th Assessment Report, *Climate Change 2014: Mitigation of Climate Change,* WG III, ch. 13, p 1012, available at https://www.ipcc.ch/site/assets/uploads/2018/02/ipcc_wg3_ar5_chapter13.pdf; RO Keohane and DG Victor, "The Regime Complex for Climate Change" (2011) 9 Perspectives on Politics 7. https://doi.org/10.1017/S1537592710004068; M Jänicke, "The Multi-Level System of Global Climate Governance – the Model and Its Current State" (2017) 27 Environmental Policy & Governance 108. https://doi.org/10.1002/eet.1747.

[37] For another view of the current complex array, see D Ruddigkeit, H Bruggink, A Gupta and F Biermann, "Multi-Institutional Global Governance of Solar Geoengineering" (2025) (this volume).

[38] See PH Sand and JB Wiener, "Towards a New International Law of the Atmosphere?" (2016) 7 Göttingen Journal of International Law 195, available at http://www.gojil.eu/72-abstract-sand-wiener.

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**Table 2.** Governance regimes for climate response options[39]

| Time | Governance Regimes | | |
|---|---|---|---|
| | Mitigation | Adaptation | Reflection |
| 1960s–2000s | Framework Convention on Climate Change (FCCC) (1992) | FCCC, article 4 | Possibly applicable to SRM, depending on type of technique and impact:<br>• International Civil Aviation Convention (1944) and ICAO regulation<br>• Outer Space Treaty (OST) (1967) and its Liability Convention (1972)<br>• London Convention (1972) & Protocol (1996) on ocean pollution<br>• Environmental Modification (ENMOD) Convention (1977)<br>• Long-Range Transboundary Air Pollution (LRTAP) (1979) agreement<br>• United Nations Convention on the Law of the Sea (UNCLOS) (1982)<br>• Vienna Convention (1985) & Montreal Protocol (1987) on stratospheric ozone<br>• Convention on Biological Diversity (CBD) (1992) |
| | Kyoto Protocol (1997) | Kyoto Protocol, article 10 | |
| 2010s–2020s | Paris Agreement (2015) pursuant to FCCC | Funding pledges for adaptation, e.g. the Green Climate Fund | Reports on SRM from:<br>• Intergovernmental Panel on Climate Change (IPCC)<br>• Climate Overshoot Commission<br>• United Nations Environment Programme (UNEP)<br>• U.S. National Academies of Science, Engineering & Medicine (NASEM)<br>• U.S. Office of Science & Technology Policy (OSTP)<br>• European Commission science advisors<br><br>United Nations Environment Assembly (UNEA): Swiss proposals (not adopted) |
| | Kigali Amendment (2016) to Montreal Protocol | Paris Agreement, Article 7 on adaptation, Article 8 on Loss & Damage | |
| | ICAO/CORSIA on Aviation GHG Emissions (2016) | | |
| 2030s–2050s? | More ambitious goals and targets? | Infrastructure for adaptation? | Assessment of SRM by e.g. IPCC, WMO, WCRP? |
| | More CDR (such as enhancing forests, direct air capture (DAC), carbon capture and storage (CCS), or marine CDR such as ocean fertilisation)? | Litigation requiring adaptation? | New accords on monitoring and governance of SRM? |
| | New energy sources (e.g., solar, wind, geothermal, nuclear fission, fusion)? | | |

[39] For a related table with more detail on Mitigation measures, but less detail on Reflection (SRM), see JB Wiener and T Felgenhauer, Texas A&M Law Review (2024), *supra* n 9, at 474–5.

In Table 2, we attempt to describe the current approach to governance of SRM, which is highly fragmented, with scattered authorities for different aspects, and significant gaps.[40] Although governance has been developed for mitigation, and somewhat for adaptation, there is little or no well-developed or coordinated governance for reflection (SRM). Each ancillary risk of each type of SRM may be addressed (if at all) by a separate treaty or accord "in piecemeal fashion."[41] For example, the climate treaties (FCCC and Paris Agreement) say essentially nothing about SRM. FCCC article 4(1)(f) calls for impact assessments of mitigation measures, but the FCCC has no comparable requirement for impact assessments of reflection measures (SRM).[42] The Paris Agreement adds a temperature-based goal (limiting global warming to 2°C above a preindustrial average), which might implicitly embrace limiting temperatures via SRM, but it has no provisions to assess, employ or govern SRM. The Ozone treaties (the Vienna Convention[43] and Montreal Protocol[44]) may regulate harms to the stratospheric ozone layer due to SAI, and the Long-Range Transboundary Air Pollution treaty (LRTAP)[45] may address acid deposition from sulfate SAI. The UN Convention on the Law of the Sea (UNCLOS)[46] and the Convention on Biological Diversity (CBD)[47] might apply to ocean- and land-based strategies, respectively, for carbon dioxide removal (CDR).[48] The Environmental Modification (ENMOD) Convention restricts "hostile" and military modifications, and although an actor deploying SRM would presumably deny any hostile animus,[49] perhaps reckless disregard of harms to others could be construed as "hostile." For PSS, the Outer Space Treaty (OST)[50] calls on its parties to avoid "harmful interference" with each other (article IX), and it imposes strict liability on national governments for damages caused on Earth (article VII) (amplified by its 1972

[40] See Wiener and Felgenhauer, "The Evolving International Climate Change Regime" (2024), *supra* n 9, Table 1 and Part III, pp 474–85. On the gaps and lack of coordination in current governance frameworks for SRM, see also Felgenhauer et al, "SRM: A Risk-Risk Analysis" (2022), *supra* n 20, section 4.1; JL Reynolds, *The Governance of Solar Geoengineering: Managing Climate Change in the Anthropocene* (Cambridge, Cambridge University Press 2019). https://doi.org/10.1017/9781316676790; JL Reynolds, "Solar Geoengineering to Reduce Climate Change: A Review of Governance Proposals" (2019) 475 Proceedings of the Royal Society – A, Mathematical, Physical, and Engineering Sciences 20190255. https://doi.org/10.1098/rspa.2019.0255; A-M Hubert, "International Legal and Institutional Arrangements Relevant to the Governance of Climate Engineering Technologies" in M-V Florin, et al, (eds), *International Governance Issues on Climate Engineering,* pp 48–71 (Lausanne, EPFL, International Risk Governance Center (IRGC) 2020); MB Gerrard and T Hester, eds, *Climate Engineering and the Law* (Cambridge, Cambridge University Press 2018) p 328: "neither international nor domestic laws offer a governance framework which explicitly addresses the large-scale policy and legal questions posed by SRM regulation.").

[41] See JB Horton, "Does International Law Prohibit SRM?" *SRM360* (Nov. 26, 2024) (arguing that the FCCC, CBD, London Convention and Protocol, and ENMOD treaties do not currently govern SRM), available at https://srm360.org/article/does-international-law-prohibit-srm/.

[42] See Gerrard and Hester (2018), *supra,* pp 330–1, comparing views of e.g., Burns, Nicholson, and Virgoe on whether the FCCC can govern SRM.

[43] Vienna Convention for the Protection of the Ozone Layer (March 22, 1985), 1513 UNTS 293, 26 ILM 1529.

[44] Montreal Protocol on Substances that Deplete the Ozone Layer (Sept. 16, 1987), 1522 UNTS 3, 26 ILM 1541.

[45] Convention on Long-Range Transboundary Air Pollution (LRTAP) (November 13, 1979), 1302 UNTS 217.

[46] UN Convention on the Law of the Sea (UNCLOS) (Dec. 10, 1982), 1833 UNTS 397.

[47] Convention on Biological Diversity (CBD) (June 5, 1992), 1760 UNTS 79, 31 ILM 818.

[48] The parties to the CBD have adopted decisions (but not treaty amendments) urging parties to prevent geoengineering affecting biodiversity, see https://www.cbd.int/climate/geoengineering; meanwhile, the London Protocol to the London Convention has proposed a provision on marine CDR and is considering action on MCB. See Horton (2024), *supra* n 40. Note that the United States is not a party to the CBD or the London Protocol.

[49] See A Eliason, "Avoiding Moonraker: Averting Unilateral Geoengineering Efforts" (2022) 43 University of Pennsylvania Journal of International Law 429, 447–8.

[50] Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies (Outer Space Treaty (OST)) (Jan. 27, 1967), 18 UST 2410, 610 UNTS 205, 6 ILM 386.

Liability Convention[51]), though it is unclear if the OST would apply to the induced climate effects of a space-based planetary sunshade system (PSS).[52]

In short, there are separate governance regimes for some of the ancillary risks of SRM, but "none of these bodies has a mandate that would include control of SRM, or the capacity to control it effectively."[53] In the view of Parson and Keith, "[p]rogress on governance [of SRM] may pose even greater challenges. The range of plausible governance needs for SRM is vast: It might be manageable by adjusting present international law and institutions, or it might require unprecedented new global governance authority."[54]

Constructing a single comprehensive regulatory regime for the global multi-risk portfolio of SRM has its appeal. A more integrated[55] and holistic approach to SRM could conceivably embrace the full system scale,[56] undertaking all of the key functional tasks noted above, with oversight of multiple risks, comprehensive analysis to weigh multi-risk tradeoffs and reduce overall risk, prospective and retrospective impact assessments, and more inclusive participation and voice by those affected.[57] It could foster ongoing monitoring and adaptive learning and updating on SRM, with a multi-risk scope.[58]

On the other hand, creating such a new comprehensive regime could entail significant cost and time. The political adoption of such a comprehensive regime for SRM might be quite difficult, especially in light of the difficulty of engaging key countries in international agreements on climate mitigation. For example, although the United States (US) joined the FCCC in 1992 and remains a party, the US did not ratify the 1997 Kyoto Protocol (with the Senate voting 95-0 not to do so), and the US signed the 2015 Paris Agreement but then withdrew starting in 2017, rejoined in 2021, and withdrew again in 2025. Several other countries have also been politically ambivalent about the climate mitigation accords, including Canada and Australia; Russia joined the Kyoto Protocol only after a long delay and concessions; and China joined Kyoto without quantitative emissions limitations, and later announced its future emissions targets while rising to be the world's largest emitter. Moreover, the incentives to be a first-mover on SRM[59] may make agreement on a governance framework difficult, and its legal authority limited or contested. Still, if they can agree on SRM, perhaps the US and China could cooperate to lead others to join a dual superpower regime on SRM.[60] As this example augurs, however, concerns about a single

[51] Convention on International Liability for Damage Caused by Space Objects (March 29, 1972), 24 UST 2389.

[52] See Eliason, *supra,* at 448–50; JB Horton, A Parker and D Keith, "Liability for Solar Geoengineering: Historical Precedents, Contemporary Innovations, and Governance Possibilities" (2015) 22 New York University Environmental Law Journal 225, 233–4.

[53] Parson and Keith, *ARER* (2024), *supra* n 9, at 340.

[54] Ibid, at 359.

[55] See L Guruswamy, "The Case for Integrated Pollution Control" (1991) 54 Law and Contemporary Problems 41, available at https://scholarship.law.duke.edu/lcp/vol54/iss4/3. For example, some experts have called for the creation of a "World Commission on SRM" (while also calling for "leveraging existing institutions"), see S Jinnah et al, "Governing Climate Engineering: A Proposal for Immediate Governance of Solar Radiation Management" (2019) 11 Sustainability 3954. https://doi.org/10.3390/su11143954.

[56] See Liu et al, "Systems Integration" (2015), *supra* n 4; Anastas and Zimmerman, " . . . systems design" (2019), *supra* n 4.

[57] See Graham and Wiener, *Risk vs Risk* (1995), *supra* n 4; Sand and Wiener, "Law of the Atmosphere" (2016), *supra* n 38; Wiener, "Disregard" (2021), *supra* n 16.

[58] See Bennear and Wiener (2019), *supra* n 33. A recent study testing a multivariate learning approach to improving SRM is: H Quan, D Koll, N Lutsko and J Yuval, "Solar Geoengineering Strategies Based on Reinforcement Learning" (April 21, 2025), available at https://d197for5662m48.cloudfront.net/documents/publicationstatus/254929/preprint_pdf/9406db96406cba0164d0d2c3395c3d47.pdf.

[59] See Barrett (2014), *supra* n 20; Barrett (2008), *supra* n 21; ML Weitzman, "A Voting Architecture for the Governance of Free-Driver Externalities, with Application to Geoengineering" (2015) 117 (4) Scandinavian Journal of Economics 1049–68. https://doi.org/10.1111/sjoe.12120.

[60] See Horton, Smith and Keith, *supra* n 23; see also J Nielsen, "The Big Green Button: Stratospheric Aerosol Injection as a Geopolitical Dilemma During Strategic Competition between the United States and China, and

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comprehensive and centralised regulatory regime include that it could add delays to policy analyses and decision making, could promote concentration of power, and could magnify the errors of policy decisions.[61]

By contrast, a multi-institutional governance framework could rely more on existing institutions, each with specialised expertise in one area of risk. This could entail more narrowly targeted regulation, with policy differences across regulatory institutions (and across countries). These differences could pose inconsistencies across risks, and barriers to trade. But these differences can also enable learning from policy variation.[62]

Fragmentation – especially if not coordinated – can leave gaps in which risks are unregulated, and pose conflicts and risk–risk tradeoffs, without oversight or comprehensive weighing to reduce overall risk. These dysfunctions may increase overall risk, and exacerbate "disregard" and "omitted voice" of underrepresented affected groups, discussed above.[63] Fragmented and uncoordinated multiple institutions may be a serious mismatch for a systemic multi-risk challenge like SRM, leaving the world vulnerable to the unaddressed risk-risk impacts of an emerging technology with little capacity to assess or manage these risks and to develop adaptive learning and updating.

## *2. Toward more coordinated and comprehensive multi-risk governance of SRM*

Given these constraints and tradeoffs, how can we make progress? A middle way is to start with existing multiple fragmented institutions, and enhance their coordination. The problems of fragmentation can themselves spur uncoordinated policy actors to grope toward coordination, such as in the European response to Covid-19,[64] and the continuing debate over the four-decades old US "Coordinated Framework" for multi-agency biotechnology policies (with occasional attempts at a new consolidated biotechnology law).[65] Such a coordinated framework of multi-treaty and multi-agency governance could be attempted for SRM.[66] If multiple institutions can coordinate to address multi-risk interactions, their specialised expertise and legal authorities can be employed to collaborate on comprehensive analyses and "joined up" policies – more quickly than trying to create a new comprehensive institution, and with fewer concerns about concentrated power or magnifying errors.[67] Timing is important because key governance tasks are

Implications for Expanding Aerosol Injection Near-Term Research" (2025) 5 Oxford Open Climate Change kgaf009. https://doi.org/10.1093/oxfclm/kgaf009.

[61] On the pros and cons of planetary-scale governance, see JS Blake and N Gilman, *Children of a Modest Star: Planetary Thinking for an Age of Crises* (Stanford CA, Stanford University Press 2024); JB Wiener and C Hamilton, "Interplanetary Risk Regulation" (2025) 26 Chicago Journal of International Law 73–106, at https://cjil.uchicago.edu/print-archive/interplanetary-risk-regulation. More generally, comprehensive decision making can yield delays due to more complex policy analysis, so the optimal extent of analysis should be *proportionate* to its value in improving policy options, see Graham and Wiener, *Risk vs. Risk* (1995), *supra* n 4, ch 1; JB Wiener, "Modernizing Regulatory Review" (2023), *supra* n 7; JD Graham and JB Wiener, "Co-Benefits, Countervailing Risks, and Cost-Benefit Analysis" (2024), *supra* n 7. Neglecting risks does not make them disappear, so some time to conduct more comprehensive analyses can be worthwhile (without undue delay), including by reducing countervailing risks, augmenting co-benefits, developing risk-superior policy options, and avoiding subsequent problems and backlashes.

[62] See Wiener and Alemanno, "Future of IRC" (2015), *supra* n 33.

[63] See Graham and Wiener, *Risk vs Risk* (1995), *supra* n 4; Sand and Wiener, "Law of the Atmosphere" (2016), *supra* n 38; Wiener, "Disregard" (2021), *supra* n 16.

[64] See A Alemanno, "The European Response to Covid-19: From Regulatory Emulation to Regulatory Coordination?" (2020) 11 European Journal of Risk Regulation 307.

[65] See J Kuzma, "A Missed Opportunity for U.S. Biotechnology regulation" (2016) 353 Science 1211.

[66] See Gerrard and Hester (2018), *supra* n 39, p 329 ("Integrate existing international and domestic legal authorities into a consistent and logical governance framework for SRM."); G Weil, "Global Climate Governance in 3D: Mainstreaming Geoengineering within a Unified Framework" (2021) 81 University of Pittsburgh Law Review 507.

[67] See Graham and Wiener, *Risk vs Risk* (1995), *supra* n 4, ch 11.

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needed before any unilateral (or multilateral) deployment of SRM.[68] Such coordination may entail a coordinating institution to link other more specialised bodies, at least for information sharing and possibly for collaboration policy making. In the case of SRM – recognising that any suggestions will be imperfect and face critiques – candidates for coordinating roles might include the World Meteorological Organization (WMO) or its affiliates for risk assessment (e.g., the IPCC and the WCRP), the Ozone treaties and the FCCC for risk management of SAI, the OST and FCCC for risk management of PSS, or even the UN Security Council for risk management of geopolitical relations. This tentative menu itself indicates how difficult it may be to find suitable existing coordinating institutions. Creating a new coordinating body – toward a more comprehensive multi-risk oversight regime – has its appeal, as noted above, but would also take time and diplomacy and raise concerns about centralised decision-making.

Failure to coordinate across current institutions, to address regulatory gaps, and to resolve risk–risk tradeoffs may lead to sudden demand for new rules and institutions spurred by a crisis.[69] But waiting for a crisis to spur new policy, rather than proactively improving coordination and moving toward comprehensive analysis and oversight, poses risks of skewed policies with narrow targets spawning further risk–risk tradeoffs.[70]

The spectrum from uncoordinated multi-institutional, to coordinated multi-institutional, to a single comprehensive institution, leaves open the question of what regulatory policies should be applied by any such institutions. Some of the options advanced in the debate include (a) a ban (or "non-use" stance) on all SRM deployment and research,[71] (b) a non-deployment stance that allows some research,[72] (c) a moratorium on deployment (temporary, to be revisited in the future) with affirmative support for research (and mitigation),[73] (d) ex post liability for attributable harm, or (e) no restrictions. Calls for a moratorium on deployment lead to questions about when, on what criteria, and by whom, decisions could be taken in the future to revise that stance. (Reflecting the difficulty of naming a coordinating institution, when the Climate Overshoot Commission issued its

[68] See S Jinnah et al (2019), *supra* n 55. Rushing to deploy SRM unilaterally, or even to prevent climate tipping points, can hasten or exacerbate countervailing risks, see Sovacool et al (2023), *supra* n 19.

[69] Parson and Keith, ARER (2024), *supra* n 9, p 360 ("New global governance capacity [for SRM] will be needed to manage deployment-related challenges but may more likely arise in reaction to a triggering event than be developed prospectively.").

[70] See T Birkland, *Lessons of Disaster: Policy Change after Catastrophic Events* (Washington DC, Georgetown University Press 2006); E Balleisen, LS Bennear, K Krawiec and JB Wiener, eds, *Policy Shock* (Cambridge, Cambridge University Press 2017), ch.1 p 28 and ch.18 p 552.

[71] See F Biermann et al, "Solar Geoengineering: The Case for an International Non-Use Agreement" (2022) 13 WIREs Climate Change e754. https://doi.org/10.1002/wcc.754 (calling for no public funding, no outdoor experiments, no patents, no deployment, and no support in international institutions). Banning most research (as well as deployment) may be advocated to prevent a slippery slope into use and moral hazard deterrence of mitigation, but banning research could turn out to invite hasty unwise use in a crisis, before the countervailing risks are fully understood; if so, conducting responsible research in advance, to understand the full scope of important impacts, could reduce overall risk. See S Jinnah et al, "Do Small Outdoor Geoengineering Experiments Require Governance?" (2024) 387 Science 600 (favoring research along with a proactive, public-engaging, standardised governance approach, coordinated among governments).

[72] See D McLaren and O Corry, "Solar Geoengineering Research Faces Geopolitical Deadlock" (2024) 387 Science 28. https://doi.org/10.1126/science.adr9237.

[73] See C Wieners, B Hofbauer, I de Vries, M Honegger, D Visioni, H Russchenberg and T Felgenhauer, "Solar Radiation Modification Is Risky, But So Is Rejecting It: A Call for Balanced Research" (2023) 3 (1) Oxford Open Climate Change kgad002. https://doi.org/10.1093/oxfclm/kgad002; Climate Overshoot Commission (2023), *supra*, ch.8; Parson and Keith, ARER (2024), *supra* n 9, pp 357–358 (a "moratorium is a temporary or conditional prohibition, adopted to provide time to assess and control a shared risk or to negotiate sharing and management of a contested resource." … "We conjecture that major powers facing domestic controversy over SRM might manage that controversy by adopting a moratorium in parallel with establishing SRM research programs and tightening mitigation.").

report in September 2023, it did not specify which if any institutions should promote the moratorium and research strategy that it recommended on SRM.)

Before these debates must be resolved, we suggest a near-term opportunity for two significant mechanisms that can help build up from the current fragmented array toward more coordinated (or even comprehensive) multi-risk governance of SRM. These mechanisms could help avoid the downsides of the current uncoordinated and fragmented regime, with regulatory gaps and unaddressed risk–risk interactions, and build toward better governance. These two mechanisms could offer "no regrets" benefits, that is, measures that can gain support from SRM advocates, observers, and critics alike, whether one favors or opposes SRM deployment. And they could be advanced without waiting for unanimous agreement – perhaps by a coalition of key countries. We suggest:

1) A series of iterative and transparent international *assessments* of SRM science, social science and policy.[74] These assessments could help build toward comprehensive understanding of the multiple risks affected by SRM options, including both climate and non-climate risks, both biophysical and sociopolitical risks, and both favorable and unfavorable impacts (see Table 1). These assessments should include analyses of:
   - the multi-risk portfolios
   - of an array of SRM techniques and policy options (including SAI with various particle types, MCB, and PSS)
   - under a range of scenarios of future climate change, mitigation effort, international relations, and other factors

   These more multi-risk comprehensive assessments would help overcome disregard of important impacts, inform multi-risk policy decisions to reduce overall risk (including by the multiple governance regimes indicated in Table 2), and identify affected groups whose voices should not be omitted.

2) A transparent international *monitoring* system for both unilateral and multilateral SRM activities, to be developed even before broader governance institutions, and to address the lifecycle of potential SRM activities from preparation to deployment to impacts to attribution. This monitoring system (or set of systems) could:
   - help identify preparations toward SRM deployment, thereby reducing the risks of unilateral surprise and international conflict;
   - help observe and estimate the multi-risk impacts of any SRM deployments (unilateral/non-cooperative or multilateral/cooperative), such as the types of SAI particles used, their atmospheric dynamics and reactions, and their effects on climate and non-climate risks (or the relevant factors for MCB or PSS);
   - help enforce any agreements on SRM (such as moratoria, or limitations on types of field testing);
   - help advance adaptive learning by assessing experience with intended and unintended (multi-risk) outcomes over time; and
   - help attribute (or distinguish) any subsequent adverse events asserted to have been caused by SRM (e.g., extreme weather or shifting precipitation patterns) and inform potential remedies for those harmed.

Beyond these two mechanisms, more will be needed to develop coordinated, or even comprehensive, governance frameworks for SRM. Some approach to collective

[74] Proposals for international scientific assessments of SRM include UNEP, One Atmosphere (2023); S Tilmes et al, "Research Criteria Towards an Interdisciplinary Stratospheric Aerosol Intervention Assessment" (2023) 4 Oxford Open Climate Change kgae010. https://doi.org/10.1093/oxfclm/kgae010.

international decision-making about deployment will be needed – whether in a multilateral treaty such as the FCCC or the Vienna Ozone convention (for SAI) or the OST (for a space-based PSS), or a new agreement, or the UN Security Council, or in another way. If not, a unilateral/non-cooperative deployment by one or a few actors may be met by unilateral/non-cooperative sanctions or reprisals by others.

Governance of SRM, and of climate change in general, requires a multi-risk approach. Focusing only on one or a few risks will not make the other risks disappear, and will entail gaps and tradeoffs. A multi-risk approach helps overcome neglect and disregard of important impacts, and of affected groups, enhancing both overall well-being and distributional equity. Monitoring and adaptive learning can help improve policies in light of experience. Yet multi-risk governance can be complex. To make good decisions, we need to identify and catalog the multiple risks affected by climate policy options (including mitigation, adaptation, and reflection [SRM]), estimate and compare these risks in order to reduce overall risk, and seek new risk-superior options. Better information, through assessments and monitoring, will be crucial.

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