# Solar Radiation Modification: A Risk-Risk Analysis

March 2022

C2G Carnegie Climate Governance Initiative

An initiative of CARNEGIE COUNCIL for Ethics in International Affairs

Duke Center on Risk in SCIENCE & SOCIETY

## Authors

Tyler Felgenhauer, Duke Center on Risk, Duke University, USA
Govindasamy Bala, Centre for Atmospheric and Oceanic Sciences, Indian Institute of Science, India
Mark E. Borsuk, Pratt School of Engineering and Duke Center on Risk, Duke University, USA
Matthew Brune, Duke Center on Risk, Duke University, USA
Inés Camilloni, Universidad de Buenos Aires, Facultad de Ciencias Exactas y Naturales, Departamento de Ciencias de la Atmósfera y los Océanos and CONICET – Universidad de Buenos Aires. Centro de Investigaciones del Mar y la Atmósfera, Argentina
Jonathan B. Wiener, Law School, Nicholas School, Sanford School, and Duke Center on Risk, Duke University, USA
Jianhua Xu, Department of Environmental Management, College of Environmental Sciences and Engineering and Institute for Global Health and Development, Peking University, China

## Publishing information

This report was commissioned and funded by the Carnegie Climate Governance Initiative (C2G) which is an initiative of the Carnegie Council for Ethics and International Affairs (CCEIA). Any views expressed in this report are solely those of its authors, and do not reflect any official positions of the authors' organisations, nor those of C2G, CCEIA, reviewers, or other contributors.

## Suggested citation

Felgenhauer, T., Bala, G., Borsuk, M., Brune, M., Camilloni, I., Wiener, J.B., Xu, J. (2022). *Solar Radiation Modification: A Risk-Risk Analysis*, Carnegie Climate Governance Initiative (C2G), March, New York, NY: www.c2g2.net

## Acknowledgements

The authors thank the generous contributions of time and insight from Nicholas Harrison, Janos Pasztor, Cynthia Scharf, and Kai-Uwe Schmidt at C2G and external reviewers Marie-Valentine Florin, International Risk Governance Center, and Matthias Honegger, Perspectives Climate Research and Copernicus Institute for Sustainable Development, Utrecht University. The authors are also thankful for additional helpful reviews from Simone Tilmes, National Center for Atmospheric Research (NCAR); Arden Rowell, University of Illinois College of Law; and John D. Graham, Paul H. O'Neill School of Public and Environmental Affairs, Indiana University.

For questions or corrections please contact: contact@c2g2.net

C2G Carnegie Climate Governance Initiative
An initiative of CARNEGIE COUNCIL for Ethics in International Affairs
Duke Center on Risk in SCIENCE & SOCIETY

# Contents

# Summary

## Solar radiation modification as an additional climate risk reduction strategy

Climate change poses multiple, interacting risks to human society and the environment which are only expected to worsen with additional warming. Managing these risks going forward requires a portfolio of policy responses. Mitigation strategies (which include both the reduction of greenhouse gas (GHG) emissions and the removal of carbon dioxide from the atmosphere (CDR)) must remain the policy focus, as they are the only means for addressing the root cause of climate change. However, it may be extremely difficult to meet the global warming temperature goals of 1.5 or 2°C stipulated in the Paris Agreement on climate with mitigation alone. Further, as $CO_2$ (the primary driver of current climate change) has a long lifetime in the atmosphere, $CO_2$ and temperatures are likely to remain elevated for hundreds of years in the absence of net-negative emissions. Adaptation may help reduce risks associated with a particular level of warming but is limited in its effectiveness and sustainability. For these reasons, solar radiation modification has been proposed as a complementary approach for quickly reducing many of the near-term risks of global warming and possibly helping to avoid irreversible climate tipping points while increased efforts are made to bring down atmospheric GHG concentrations.

Solar radiation modification (SRM) is an umbrella term for a suite of approaches that propose to reduce or stop global warming by intentionally increasing the amount of incoming sunlight that is reflected by the atmosphere back to space. The most-studied SRM options to date are stratospheric aerosol injection (SAI), the intentional release of highly reflective fine particles or their precursors into the stratosphere, and marine cloud brightening (MCB), the purposeful enhancement of the reflectivity of marine clouds. While other SRM approaches have also been proposed, in this report we focus on SAI and MCB, as they appear to be the most effective options, when employed with emissions mitigation and CDR, with the potential to help meet the Paris temperature goals.

As a proposed climate risk reduction option, SRM is categorically different from mitigation. Rather than addressing climate change at its source (via reduction in GHG emissions) or attempting to reverse climate change (via CDR), SRM is intentional climate change of another form. While still highly uncertain, its proposed benefits would be that, once the necessary technology and infrastructure are developed, it could be a fast, effective, and financially inexpensive means of cooling the Earth at a global scale. However, SRM is also imperfect as it would not completely offset climate change in all regions and seasons. Further, both SAI and MCB would need to be deployed continuously, as their effects are only expected to be temporary. These new technologies may also be risky, both in their interactions with the climate, and in their potential for exacerbating existing risks and introducing new biophysical and societal risks, including novel governance challenges. These fundamental tradeoffs—between SRM's potential to reduce climate risks and its likelihood of introducing its own countervailing risks—are the focus of this report.

### The risk-risk tradeoff framework

In this paper, a risk-risk tradeoff framework is used to compare a world with SRM and a world without SRM in addressing climate change. The risk-risk tradeoff framework considers the full portfolio or scope of important consequences that may arise from a decision. In this framework, *risk* is measured by both the *magnitude* of undesired consequences and the *likelihood* of the occurrence of these consequences. In the risk-risk *tradeoff framework*, the particular risk that an action or policy aims to address is referred to as the target risk, the additional risks that are produced in addressing the target risk are called *countervailing risks*, and ancillary reductions in non-target risks and other gains are termed *co-benefits*. The framework then identifies key attributes for comparing these risks, including the type, magnitude, likelihood, timing, and distribution of consequences associated with various actions or policies. The risk-risk tradeoff framework is intended to improve outcomes by helping analysts think beyond the direct costs and benefits associated with reducing the target risk alone. As with all public policies, SRM, as well as other climate policy options, might encounter “non-rational” public responses that could strongly influence decision-making; this report offers the risk-risk framework in order to help guide policies toward socially desirable outcomes informed by science.

## Solar radiation modification within the risk vs. risk framework

Based on the latest research literature, the potential impacts of adding SRM to a hypothetical policy portfolio of mitigation and adaptation could include the following (in which most effects would come from a global deployment of SAI, except where noted that the effect is specific to MCB):

| | Impacts of adding SRM to mitigation and adaptation | |
|---|---|---|
| | positive | negative |
| **Impact of SRM on target risk:**<br>climate change impacts | **Climatic benefits**<br>SRM would be expected to quickly reduce the significant future risks associated with temperature rise in most regions of the world. The most important such benefits include:<br>• reduction in the frequency and intensity of extremes of temperature and precipitation<br>• slowed melting of Arctic sea ice and mountain glaciers<br>• reduced loss of the Greenland and Antarctic ice sheets slowed sea level rise<br>• reduced weakening of the Atlantic meridional overturning circulation reduction in the intensity of tropical cyclones<br>• reduced decline in soil moisture slight reduction in atmospheric carbon dioxide concentrations | **Climatic risks**<br>SRM does not reverse climate change, but rather is a different and additional type of climate change with distinct impacts, some of the most important of which include:<br>• unintended climate changes (unintended warming or excessive cooling due to uncertainty in our estimates of the amount of SAI needed)<br>• regional precipitation changes |

| | | |
|---|---|---|
| **Ancillary impacts of SRM:**<br>non-climate change impacts | **Co-benefits**<br>SRM could have the side benefits of reducing other risks or adding value, both biophysical and social. Examples include:<br>• reduced tropospheric ozone<br>• increase in water availability over land in the tropical regions (MCB) | **Countervailing risks**<br>Depending on the technology employed, SRM introduces some novel risks, both biophysical and social, including:<br>• increased acid deposition in pristine areas in the high latitudes<br>• effects on stratospheric ozone<br>• light diffusion and dimming<br>• potential for international conflict and other societal risks<br>• potential interactions with a major volcanic eruption<br>• shock of sudden termination<br>• increase in salt deposition over land (MCB) |
| | **Positive or negative impacts**<br>• influence on motivation for emissions abatement policy or behaviour<br>• light diffusion and dimming and its effects on human health, ecosystems, and agriculture<br>• effects on procedural and distributional justice, and other ethical concerns | |

Of course, SRM deployment would not occur in isolation, so its benefits and risks would depend on a number of other factors, including the particular goals of the SRM deployment, the background emissions pathway and adaptation plans being followed, sustainable development goals pursued, and the governance framework in place. Conceptually, the emissions pathway and anticipated adaptive capacity would determine the level of residual climate risk that might be addressed by SRM. SRM deployment and its governance would then seek to simultaneously minimize these climate risks, maximize additional gains, and limit its own added climate and countervailing risks. To make these tradeoffs explicit, in the full report we consider three specific climate risk management scenarios with different relative contributions of mitigation and SRM.

# Key insights

**1) Employing a risk-risk framework in policy analysis and decision-making concerning SRM would enable a more comprehensive assessment, comparison, and management of risks associated with climate change, emissions reductions, CDR, adaptation, and SRM.** This risk-risk framework would include identifying and weighing impacts on the target risk, countervailing risks, and co-benefits, recognizing that they may interrelate in complex ways. The public and policymakers may encounter heuristics and biases that influence decision making, and a risk-risk framework can help strengthen deliberation addressing the full portfolio of important impacts. Attempts to identify measures that minimize overall risk can help reduce the single target risk but also limit or reduce multiple countervailing risks in concert.

**(2) The target risk that SRM seeks to address is the risk of climate change, taking into account the emission scenario and the effects of emissions reduction, CDR, and adaptation.** Depending on the policy pathway, these risks may be large.

**(3) As a target risk reduction strategy (along with emissions reductions, CDR, and adaptation), SRM deployment may have the potential to reduce climate risks, yielding large direct benefits to humans and natural ecosystems.** By reducing the global mean temperature increase (or by stabilizing temperature at a given target) SRM could potentially lessen the near-term damages of climate change and lower the chances of crossing irreversible climate tipping points.

**(4) SRM could pose countervailing risks to biophysical systems.** These could include (depending on the SRM approach) changes in stratospheric ozone and surface UV radiation, acid rain, and unintended climate changes such as altered temperature and precipitation patterns or excessive cooling. The level of many of these risks would be partially affected by the design and governance of an SRM deployment.

**(5) SRM could also pose countervailing risks to societal systems.** These could include (depending on the approach) the risk of international conflict over deployment (especially in cases of ungoverned and unilateral deployment, the prospect or threat of deployment, or perceived harms between deployment and local/regional unexpected impacts), the risk of rapid climate change resulting from sudden termination (which is also a biophysical risk), and the risk that SRM could displace GHG emissions mitigation, among other concerns. Again, the level of many of these risks would be partially affected by the design and governance of an SRM deployment.

**(6) SRM could present some co-benefits.** The co-benefits of some SRM approaches may include an increase in diffuse solar radiation (sunlight), which may be beneficial to some ecosystems and crops, and slightly reduced tropospheric ozone in the mid and high latitudes. However, these uncertain effects are likely to be small and are not expected to play a significant role in weighing risk-risk tradeoffs.

**(7) Policymaking regarding SRM should compare its effects on multiple risks (including target risk reductions, co-benefits, and countervailing harms), as part of a policy portfolio that also takes into account emissions reductions, CDR, and adaptation.** These interconnected effects should be assessed in terms of their likelihood, impact, timing, uncertainty, distribution, and related factors.

**(8) Different levels of SRM may pose different implications for overall risk depending on the technology, its deployment, and governance**. Higher levels of SRM may be expected to yield greater decreases in temperature-associated climate target risks, but also increases in SRM's own countervailing risks. The particular levels and response patterns of target and countervailing risks to varying levels of SRM would depend on the SRM technology, deployment strategy, and governance mechanisms employed. It is possible that the level of SRM that minimizes total risk may be a low-to-intermediate level of deployment designed to avoid the worst near-term climate impacts by shaving the peak warming while GHG emissions mitigation and CDR efforts take effect.

**(9) As larger GHG emissions reductions, CDR, and adaptation reduce overall risks, the less need there may be for SRM with its countervailing risks, thereby reducing overall risk exposure (subject to any countervailing risks of emissions mitigation options).** Further attention must be given to the interdependence among multiple risks that can be created by shared causes or policy interactions.

**(10) Risk-risk analysis can help focus climate change risk management on broader societal objectives, rather than on temperature goals alone.** While temperature goals may be an important objective, there are many climate impacts that do not scale directly with temperature, and many other ancillary risks beyond climate. The indicators used to evaluate the United Nations' Sustainable Development Goals (SDGs) offer measures of well-being that may be used to evaluate the multiple risks of SRM. This report presents a preliminary evaluation of how three hypothetical risk management portfolios supplementing GHG emissions mitigation, CDR, and adaptation with SRM might be expected to impact attainment of the SDGs relative to not using SRM.

**(11) New governance institutions or mechanisms may be needed to restrain harmful or unjust use of SRM, ensure that any deployment is beneficial and just, and assess and minimize any countervailing harms.** Existing international governance aimed at addressing climate change and its impacts may offer some useful mechanisms, but currently appears to be inadequately designed for addressing SRM and its distinctive characteristics. As an attempt to restrain the imposition of global risks through hasty or unwise action, governance of SRM may be more analogous to arms control agreements than environmental treaties.

# 1. Climate change as a risk management problem

## 1.1. Introduction

Human activities such as fossil fuel burning and deforestation are the primary drivers of climate change in the industrial era, and the rate of warming in recent decades that has affected every region of the globe is unprecedented in at least the last 2,000 years (IPCC 2021c).1 Unless drastic cuts in greenhouse gas (GHG) emissions are implemented, the global mean warming is likely to exceed 2°C above the pre-industrial level within this century. Such warming could exacerbate the increases in the frequency and intensity of heat and precipitation extremes, tropical cyclones, melting of polar and glacial ice, and sea level rise (IPCC 2021c). These changes are already occurring and are projected to produce multiple negative, and in some cases irreversible, impacts on human society and the environment, including floods and droughts, biodiversity loss and species extinctions, severe wildfires, and inundation of coastal areas. Impacts are likely to fall disproportionately on the world's poorest, compromising the ability to meet the UN Sustainable Development Goals (SDGs) (WMO 2021). The ensuing migration crises could affect the very stability of nation-states and international security (Lieven 2020). These impacts are likely to only worsen with additional warming (IPCC 2021c).

## 1.2. Existing risk management strategies: Emissions mitigation, carbon dioxide removal, and adaptation

Climate change presents a problem of managing diverse risks (Kunreuther et al. 2013), which requires a portfolio of policy responses. Mitigation (which includes both the reduction of GHG emissions and the removal of carbon dioxide from the atmosphere (CDR)) must remain the policy focus, as it is the only means available to address the root cause of climate change. Adaptation can help reduce the risks associated with a particular level of warming (Pelling 2011; Kahn 2010; F. Schipper and Burton 2009). Yet societies can only adapt so much, as there are limits to adaptation's physical effectiveness and financial sustainability (Felgenhauer 2015). Both emission mitigation and CDR strategies work over the long term, but in the near term they are unlikely to significantly reduce impacts, as the effects of mitigation and CDR  on global warming would only be felt after multiple decades because of the long timescale associated with carbon cycle processes (IPCC 2021c: 41). It would be extremely challenging to meet the global warming temperature goals of 1.5 or 2°C that are stipulated in the Paris Agreement on Climate (UNFCCC 2015) with emissions reduction and CDR alone. The atmospheric carbon dioxide concentration will stop rising only after net-zero emissions are reached. For a 66% chance of staying below 1.5 or 2°C of warming by the end of this century, net global emissions in 2030 must be reduced to either 25 or 39 GtCO$_2$e (gigatons of carbon dioxide equivalent), respectively. The most optimistic set of mitigation pledges issued just before the COP26 climate meeting in Glasgow had the world on track for 50 GtCO$_2$e by 2030, corresponding to an end-of century temperature of 2.6°C (UNEP 2021). During COP26, a number of new pledges were

---

[1] This latest report of the Intergovernmental Panel on Climate Change (IPCC 2021b) builds upon several recent assessments of the world's international scientific community, including the IPCC's three special reports on global warming of 1.5°C above pre-industrial levels (IPCC 2018), climate change and land (IPCC 2019a), and climate change and the ocean and cryosphere (IPCC 2019b), as well as the IPCC's 5th Assessment Report (IPCC 2014).

made which brought that number down to 2.4°C (Climate Action Tracker 2021). Combining these “conditional” nationally determined contributions (NDCs) with additional net zero and other long-term pledges leads to an optimistic possible end-of-century warming of 1.8°C (ibid.; Meinshausen et al. 2021). It should be noted, however, that these optimistic pledges are not backed up by policies, and that earlier pledges have not been fully met.

## 1.3. Solar radiation modification as an additional risk management strategy

Solar radiation modification (SRM) is defined by the IPCC as *“… a range of radiation modification measures not related to greenhouse gas (GHG) mitigation that seek to limit global warming. Most methods involve reducing the amount of incoming solar radiation reaching the surface, but others also act on the longwave radiation budget by reducing optical thickness and cloud lifetime (IPCC 2021a)*"[2] SRM could lower climate change risks but could also create both new climatic risks as well as new harmful biophysical and societal side-effects. While other SRM approaches have also been proposed (see Box 1), in this report we focus on stratospheric aerosol injection (SAI) and marine cloud brightening (MCB), as they appear to be the only methods with the potential to help meet the Paris temperature goals (Lawrence et al. 2018).

**Stratospheric Aerosol Injection (SAI)**

Stratospheric aerosol injection is the most-studied SRM approach to counteract global warming. It would involve injection of highly reflective aerosols (or their precursors) into the stratosphere to deflect more sunlight back to space and cool the climate (the tropical stratosphere extends ~18–50 km above the Earth’s surface; most SAI studies look at injections between ~20–25 km). Most research has focused on the injection of sulphate precursor gases such as sulphur dioxide (i.e.,$SO_2$, which would then be oxidized to sulfuric acid ($H_2SO_4$ droplets) or the direct injection of droplets of sulfuric acid. Injection of other types of aerosol particles such as calcite ($CaCO_3$), titanium dioxide ($TiO_2$), aluminium oxide ($Al_2O_3$), and engineered nanoparticles has also been proposed (Keith 2010; Ferraro, Highwood, and Charlton-Perez 2011; Pope et al. 2012; Keith et al. 2016), though the potential use of these alternate particles is much less studied compared to sulphates. SAI can potentially produce a radiative forcing (a net change in the energy balance of the Earth system) of sufficient magnitude, i.e. ~2–5 W/m$^2$ (Watts per square meter of Earth’s surface) to help achieve Paris temperature goals (Lawrence et al. 2018). This is equivalent to approximately 1–2% of the total solar radiation absorbed by our planet today (~240 W/m$^2$). The natural analogue for SAI is a major volcanic eruption such as that of Mount Pinatubo in 1991, which injected about 20 Tera (thousand billion) grams of $SO_2$ into the stratosphere (Bluth et al. 1992) and caused a global mean cooling of ~0.3–0.5°C over the following two years (Soden et al. 2002).

**Marine Cloud Brightening (MCB)**

The next most-studied SRM approach is marine cloud brightening, which would involve adding suitable cloud condensation nuclei (CCN; sub-microscopic particles that facilitate the condensation of water vapor in the atmosphere to form cloud droplets), likely sea salt, into the low-level (~0-2 km) marine cloud layer, using, for example, ship-mounted sprayers. Evaporation of water from the droplets then results in suspended sea salt particles which can act as CCN. For the same cloud liquid water content, an increase in CCN would produce both a higher number of cloud droplets and droplets of smaller size, which would increase the reflectivity of clouds. The direct scattering effect from injected particles might also play an important role in MCB’s cooling effect, but the relative contribution of aerosol-cloud and aerosol-radiation effects remains uncertain (Ahlm et al. 2017). MCB could potentially produce an estimated radiative forcing magnitude of 0.8–5.4 W/m$^2$, and the cooling associated with this would help achieve the Paris temperature goals (Lawrence et al. 2018). Aerosol

---

[2] In this report we follow the IPCC convention, using solar radiation modification (SRM) to denote the umbrella term for the techniques being discussed, which are also referred to as “solar geoengineering,” “climate engineering,” or “solar radiation management” in other literature.

emissions from ship exhaust (“ship tracks”), provide an analog to the cloud and radiative effect of MCB (Chen et al. 2012). As cloud feedbacks contribute the largest uncertainty to the estimation of climate sensitivity (the amount of warming for a doubling of carbon dioxide) (Vial, Dufresne, and Bony 2013), and MCB involves manipulation of clouds while SAI does not, it is expected that the climatic effects of MCB are likely associated with larger uncertainty compared to SAI.

**Box 1. Other SRM methods (in addition to SAI and MCB)**

### Cirrus cloud thinning (CCT)

Cirrus clouds are upper-level clouds (~10 km above sea level) consisting mostly of ice crystals. These clouds trap infrared (IR) radiation as GHGs do, and thus have a warming effect on the planet. The basic idea behind cirrus cloud thinning (CCT) is to decrease the amount of cirrus clouds by seeding them with ice nucleating particles (such as bismuth tri-iodide and sea salt), which would cause larger ice crystals to form and rapid fallout resulting in reduced lifetime and coverage of cirrus clouds (Muri et al. 2014; Gasparini et al. 2017). The reduced amount of clouds would allow more IR radiation to escape to space, resulting in cooling. CCT is included in the portfolio of SRM options in the IPCC’s two latest assessment reports (IPCC 2018, 2021b), even though it would cool the planet not by reflecting more sunlight like other SRM options but instead by increasing the emission of longwave radiation to space. With a maximum potential radiative forcing magnitude of 2–3.5 W/m$^2$ (Lawrence et al. 2018), CCT could potentially offset the warming from a doubling of carbon dioxide (from the pre-industrial level of 280 ppm to 560 ppm; radiative forcing for a doubling of carbon dioxide is ~3.5 W/m$^2$). However, a few studies have found that no seeding strategy achieves a significant cooling effect, due to complex microphysical mechanisms that limit the climate responses. Further, a higher than optimal concentration of ice nucleating particles could result in over-seeding with deleterious effects of prolonging cirrus lifetime and contributing to global warming (Gasparini and Lohmann 2016; Penner, Zhou, and Liu 2015). Because of this large uncertainty in its effectiveness, CCT is not considered in this report.

### Ground-based albedo modification (GBAM)

Ground-based options for SRM—also called ground-based albedo modification (GBAM)—include a suite of proposals that would increase the reflectivity of land, ocean, or ice surfaces. The increase in reflectivity could be achieved by creating microbubbles to increase ocean albedo (Evans et al. 2010; Kravitz et al. 2018; Seitz 2011); adding reflective material to increase desert albedo (Crook et al. 2015); painting the roofs of urban buildings white to increase their reflectivity (Zhang et al. 2016); increasing the albedo of agricultural lands via no-till farming, changing crops, or through bioengineering to make crop leaves more reflective (Seneviratne et al. 2018); or adding reflective material to increase sea ice albedo (Field et al. 2018). A radiative forcing of only a few tenths of a W/m$^2$ might be achieved via increases in surface albedo, but large-scale implementation is probably infeasible. The literature indicates a less than 0.5 W/m$^2$ radiative forcing for white roofs and crop albedo enhancement (Schäfer et al. 2015). Further, the cooling from these GBAM options would be highly localized, in particular with white roofs, no-till farming, and crop albedo modification. White roofs could bring positive local co-benefits such as reduced urban heat island effects and related energy use (Zhang et al. 2016). At scale, however, GBAM approaches are associated with substantial side effects, such as disruption of regional ecosystems, biodiversity, and food production (Seneviratne et al. 2018). As the global scale climatic benefits of GBAM are too small, we do not consider these options in this report.

### Space-based approaches

These proposals involve placing mirrors, shades, or reflecting particles in space between the sun and earth to reflect or block sunlight before it reaches the Earth. Blocking ~2% of incoming solar radiation would offset the warming from a doubling of atmospheric $CO_2$ concentrations (Govindasamy and Caldeira 2000). Several early climate modelling studies assessed the effectiveness and viability of space-based options by simply prescribing a reduced value for the amount of solar radiation that enters the planet in modelling experiments (e.g., ibid.). The G1 experiment in the Geoengineering Model Intercomparison Project (GeoMIP) also prescribes a reduction in the solar constant to mimic the effects of space-based options and the nearly uniform change in radiative forcing that would be achieved with such methods. Space-based approaches avoid biophysical side effects associated with the modification of the composition of the atmosphere (as with SAI, MCB, and CCT) or surface properties (GBAM). However, space-based proposals rely on large leaps in technological development and a dramatic reduction in material transport costs from Earth to space from ~$10,000/kg to less than $100/kg (Keith et al. 2020). Further, there are significant, poorly understood risks including impacts from space debris and technical or communications failures. Hence, although these space-based options are not assessed in this report, further research on the risk-risk tradeoffs posed by space-based SRM may be warranted if the costs of these techniques decline and their potential use appears more plausible in the future.

* * *

As a climate risk reduction strategy, SRM is categorically different from mitigation. Rather than addressing climate change at its source (via reduction in GHG emissions or CDR), SRM is intentional climate change of another form. The cooling from some SRM options such as SAI would be potentially fast and effective (de Coninck et al. 2018), able to reduce some hazards and risks associated with climate change in most regions of the world in a way that can be equitable for rich and poor nations (Irvine et al. 2019). When added to a mitigation pathway, SRM could also lower the chances that a climatic tipping point is crossed (Bickel 2013). It could also be cheap to deploy, for example, on the order of a few billion dollars a year for SAI once the necessary technology and infrastructure are developed (Smith and Wagner 2018). The offset of climate change by SRM is imperfect, however, with residual and overcompensated climate changes at regional and local domains (Lee et al. 2021). The deployment of both SAI and MCB would need to be constantly maintained as their effects are temporary (1–2 years for SAI and 1–2 weeks for MCB). Therefore, SRM should not be considered as a solution to climate change but rather a temporary remedy, a possible supplement to a portfolio focussed primarily on mitigation, carbon dioxide removal, and adaptation. Finally, this set of new potential technologies is risky, both in their interactions with the climate, and in their potential for exacerbating existing risks and introducing new biophysical and societal risks. There are uncertainties involved in quantifying these impacts, which may warrant further research. It is an investigation of this fundamental tradeoff—between SRM's potential to reduce climate change risks and its likelihood of introducing its own countervailing risks, with potential governance challenges—that is the focus of this report.

## 1.4. A risk-risk framework for climate change and SRM

The recent U.S. National Academies of Sciences, Engineering, and Medicine report on "Reflecting Sunlight: Recommendations for Solar Geoengineering and Research Governance," called explicitly for the use of a risk-risk analytical framework for evaluating SRM:

> *Risk-risk assessment (or risk trade-off analysis) provides a framework wherein the risks of one policy option are comparatively assessed in relation to the risks of others to identify options that maximize benefit. The relevant comparison would characterize the risk of climate change without [SRM] versus the risks of climate change with [SRM]—in both cases, looking across a range of greenhouse gas (GHG) concentration pathway scenarios and including an array of other climate response actions (NASEM 2021: 117-18).*

In fact, there have been multiple calls for taking a risk-risk approach to consideration of SRM. A recent paper in the journal Science, for example, by more than 20 co-authors (including some of the present authors of this report) advised that *“Policy makers would gain from assessments of SRM’s] costs and benefits … and risk-risk tradeoffs”* (Aldy et al. 2021). Other examples are given in Box 2 below.

**Box 2. A need for risk-risk assessment**

Considering a scenario with global GHG emissions cut to near zero after mid-century, and resulting radiative forcing (RF) peak of 4W/m2 in 2075, Keith (2017) notes:

> *The central question is, which version of 2075 is more dangerous? A world with 4W/m$^2$ of [RF] from greenhouse gases or a world with a net [RF] of 3W/m$^2$ but with additional risks from solar geoengineering? No one knows. … One must weight them, however, against the evidence that solar geoengineering could avert harm to some of the world’s most vulnerable people.*

SilverLining, an SRM-focused non-profit group, wrote in a report that research into SRM:

> *… has not been set in the context of consistent goals or a defined agenda, and it has not been framed as a holistic assessment of the relative risks and benefits of unmitigated climate change versus implementation of some degree of atmospheric climate intervention (geoengineering). The result has been a hesitancy to fund scientific research into interventions and to exacerbate concerns amongst the public and policymakers about these approaches (Wanser and Konar 2019: 44).*

In an examination of the potential implications of SRM for achievement of the Sustainable Development Goals, Honegger, Michaelowa, and Pan (2021) recognize that:

> *Use of SRM would create its own risks and would only make any sense in a world experiencing or expecting severe climate change impacts. As such, consideration of SRM takes place in a risk–risk context (whereby the risks of application are judged against the risks from climate change without SRM). Considering the impacts of SRM in isolation can be misleading, as SRM’s sole raison d’être is reduction or avoidance of climate impacts stemming from elevated greenhouses gas concentrations.*

And an article from the International Risk Governance Center (IRGC) asked

> *... how can we sufficiently compare the relative risks presented in a future with SRM against the risk faced in a future without it? (Harrison, Pasztor, and Barani Schmidt 2021)*

The risk-risk tradeoff framework recognizes that, in the face of multiple possible actions or policies and a variety of risks crossing multiple domains, decisions can be difficult. Yet decisions on risk, even if the comparisons across alternatives are sometimes difficult, must be made and policy paths must be chosen.[3] To make these tradeoffs explicit, we consider three specific climate risk management scenarios with different relative contributions of mitigation and SRM in Section 3.4. In considering SRM, which risks could we moderate at low financial cost (and hence reduce), and which instead are mostly unavoidable or very costly to control? Of those risks that we seek to control, how are they dependent on SRM deployment characteristics such as level (the amount used in relation to a goal-oriented deployment and background climate conditions), the technology (the type of SRM and the specifics of its engineering and implementation method), or the governance regime that may (or may not) be in place to help manage decision making? On this last point, how can we create governance mechanisms to make good decisions about managing and lowering the SRM risk profile?

---

[3] Davies (2010) notes that “The fact that assessing the risks and benefits of geoengineering, or alternative policy paths, will result in a mix of quantified and non-quantified factors does not exclude the possibility of decision making based on weighing policy options.”

The report is structured as follows. Having introduced the current natural and social science understanding of SRM—including its potential for both attenuating climate risks and introducing its own novel risks—we next outline the risk-risk analysis framework in Section 2. In Section 3 we place SRM within the risk-risk tradeoff framework, detailing the strategy's ancillary biophysical and social risks and how many current decision frameworks fail to comprehensively consider risk. Section 4 explores some existing and proposed governance approaches that could address these issues, thereby strengthening society's ability to make decisions regarding climate change and SRM-related policy. Section 5 summarizes our key findings and policy implications. This report builds on earlier work by others to frame the comparison of possible future worlds confronting climate change—those futures that include some form of SRM and those that do not (Harrison, Pasztor, and Barani Schmidt 2021; Honegger 2020)

# 2. The risk-risk tradeoff framework

## 2.1. Confronting risk-risk tradeoffs

Risks are ubiquitous. Societies and individuals face many risks every day, including risks to health, safety, the environment, and security. Some risks are too low to be attended, while some others are high and salient enough to warrant responsive actions. In both individual choices and in the public policy arena, the focus is often on addressing one risk at a time. Even if decision makers try to weigh the benefits against the costs of actions for addressing a single risk, they may err if they neglect that the decision could also have other effects. The reality of living in a multi-risk world (Wiener 2002, 2020) means that focusing narrowly on one risk at a time can lead to unintended consequences in complex interconnected systems, i.e., see Box 3 (Graham and Wiener 1995b; Anastas and Zimmerman 2019; Baldwin 2017; Liu et al. 2015). This is not a defect in all policies or precautions; the problem arises when narrow decision frameworks are applied to complex multi-risk systems. One solution is the use of comprehensive and holistic frameworks for multi-risk decision analyses (Wiener 2020).

**Box 3. Examples of unintended effects generated in addressing target risks.**

There are many examples in which policies aiming to solve one problem also affect others in the environmental, health, and safety domains. (The difficulty is not regulatory policy per se, but taking a narrow focus in a world of multiple risks; see Wiener (2020, 2021)). For example, new medicines may reduce diseases but may also induce unintended side effects (Eichler et al. 2013). Policies requiring airbags in cars to protect adult occupants from fatal collision impacts also, at least initially, raised mortality risks to children due to the force and position of the airbag—until superior options were deployed such as smart airbags and having kids sit only in the back seat (Graham et al. 1998). Policies to curb stratospheric ozone depletion by phasing out CFCs led to the use of non-ozone depleting substitutes such as HFCs, which turned out to be potent GHGs that are now being phased out as well (WMO 2018; Wiener 1995). Initial policies to address COVID-19 may have shifted medical resources away from treating other diseases and thus to increased mortality from these diseases, and social isolation to reduce transmission may have worsened mental health harms (Woolf et al. 2020; Hammad et al. 2021; Krendl and Perry 2020); meanwhile, mask wearing to reduce the spread of COVID-19 may have the co-benefit of also reducing transmission of other diseases such as influenza (Koutsakos et al. 2021). And policies to reduce some air pollutants, such as mercury, can have co-benefits in reductions of other pollutants, such as fine particulate matter (PM2.5) (Aldy et al. 2020; Livermore and Revesz 2020).

As a general principle, good policy analysis should move from a narrow focus on a single target risk to a broader assessment of all important impacts—the full portfolio or scope of important consequences that may arise from a decision (Graham and Wiener 1995b; Dudley and Mannix 2018; Livermore and Revesz 2020; Wiener 2020; Fang and Xu 2013). Disregard of important impacts or affected groups (Stewart 2014; Wiener 2021) could lead a decision maker to choose an option that disserves overall social well-being, causes undue harm, unfairly burdens a group, and breeds public frustration.

The set of full impacts includes not only the direct benefits and costs of reducing the target risk, but also the “side effects” or “ancillary impacts.” And the distribution of these impacts (target risks reductions, costs, and side effects) can be important as well as their aggregate magnitudes. In addition to confronting and weighing these side effects, optimal policy would seek superior solutions that reduce multiple risks in concert (Graham and Wiener 1995a).

Assessing and acting upon the full scope of important impacts is not always easy. It can pose challenges for human psychology and institutions. Wiener and Graham (1995) argued that neglect of side effects is often the result of bounded thinking, inadequate participation (omitted voice of those affected), and fragmented institutions. Sunstein (2000) argued that the key challenge is cognitive: failure to think through the full future consequences of actions. A broader analytical framework is needed to overcome these challenges, avoid adverse side effects, and devise superior solutions. At the same time, broader analysis can be costly, and some scholars suggest that the extent of multiple impacts assessed be subject to the balance between the benefits of improving policy outcomes and the cost of the added analysis (Graham, Wiener, and Robinson forthcoming 2022).

Graham and Wiener (1995a) proposed an analytical framework for identifying, understanding, and addressing risk-risk phenomena. In this framework, risk is defined as the combination of undesired consequences and the probability of the realization of the consequences; the risk that a policy aims to address is the target risk; and the additional risks that the policy induces are countervailing risks (and additional risks that the policy reduces are co-benefits). Recognizing that the populations who bear the target risk and the countervailing risks could be different, and the types of consequences of the various risks could be different, this framework classified four types of risk-risk tradeoffs: risk offset (same population, same type of risks), risk transfer (different population, same type of risks), risk substitution (same population, different type of risks), and risk transformation (different population, different type of risks) (Table 1). The framework then identified key attributes for comparing these risks, including magnitude, type of consequence, uncertainty, timing, and distribution (Graham and Wiener 1995a). There are ethical and normative concerns in this classification, relating to overall aggregate impacts, and distributional equity and justice across populations, with respect for different values of different types of risks. In addition, beyond weighing the tradeoffs across risks, this analytical framework suggests seeking “risk superior moves” that reduce the target risk and countervailing risks in concert.

**Table 1. The risk-risk tradeoff framework (Graham and Wiener 1995b).**

| | | Compared to the target risk, the countervailing risk or co-benefit is | |
|---|---|---|---|
| | | *same type* | *different type* |
| Compared to the target risk, the countervailing risk or co-benefit affects | *same population* | Risk offset | Risk substitution |
| | *different population* | Risk transfer | Risk transformation |

Table 2 is a template that illustrates the array of impacts to be considered when applying this framework. The objective of Tables 1 and 2 is to help equip and encourage decision makers to move beyond a narrow focus on a target risk and help them confront (be aware of) the multiple risks that may be affected by their decisions in a multi-risk world of complex interconnected systems. It is important to note that the impacts in Table 2 (target risk reduction, costs, countervailing risks, co-benefits, and distribution) would be associated with each policy option, not only with the target risk. That is, each target risk might be addressed by multiple policy options, and each of these policy options might affect multiple risks in different ways.

**Table 2. Template for assessing multi-risk impacts of each policy option.** Examples are detailed in Section 3 of this report.

| | Benefits (reduction in target risk) | Costs | Ancillary impacts: co-benefits | Ancillary impacts: countervailing risks | Distribution |
|---|---|---|---|---|---|
| Option 1 | - | - | - | - | - |
| Option 2 | - | - | - | - | - |
| Option 3<br>o<br>o<br>o<br>Option N | - | - | - | - | - |

The risk-risk tradeoff framework helps analysts think beyond the benefits (reduction in target risk) and costs (direct costs for reducing the target risk), and brings side effects or ancillary impacts (countervailing risks and co-benefits) into consideration. Beyond the direct and intended impact of a policy, it offers a more holistic approach to multiple risks in complex interconnected systems.

## 2.2. Challenges in applying the risk-risk tradeoff framework

Although the risk-risk tradeoff framework moves forward by adding consideration of the side effects (both co-benefits and countervailing risks) of decisions, its application faces challenges. These challenges are not characteristics of the risk-risk tradeoff framework per se. Many of them are inherent in any effort to gauge the pros and cons of policies for addressing risks. These challenges are largely associated with the identification, assessment, and comparison of risks.

First, there is no definitive answer for how to decide the scope of side effects. How many (and which) direct and indirect effects should be considered? In other words, how many “ripples” shall we consider when a stone is thrown into a pond? Graham and Wiener (1995b: 20-22 and 228) used the “ripples” metaphor to discuss the optimal extent of analysis of multiple effects. For example, in the context of SRM, injecting aerosols into the stratosphere would reflect sunlight back into space and thus help cool down the earth as a way to hedge against climate change. But SRM might also exacerbate stratospheric ozone depletion, increase acid deposition, whiten skies, risk termination shock, influence emissions mitigation choices, and cause other effects. Which of these, and other, effects should be assessed, and with what degree of analytic rigor? And which affected groups of populations should be assessed? Which spatial (geographic) and temporal scopes should be included? These questions apply to deciding the scope of all side effects, both benefits and harms. One point of reference for assessing the scope of multiple impacts is to consider the impacts of policy alternatives on the 17 UN Sustainable Development Goals (SDGs) (Pham-Truffert et al. 2020). At the same time that broader multi-risk analysis can improve policy outcomes (by avoiding adverse and increasing beneficial side effects), it can also be costly (including by delaying decisions). More ripples require more research, especially transdisciplinary research. One way to achieve this is by comparing the value of information versus the cost of information (VOI/COI), which balances the benefits of improving policy outcomes and the costs of the added analysis, including delay (Graham, Wiener, and Robinson forthcoming 2022).

Second, even if we have a clear idea for each policy option of the array of target risks, costs, side effects (co-benefits and countervailing risks) and distribution across spatial and temporal dimensions that we intend to cover—that is, even if we are clear about what to put in Table 2 for our specific policy options—identifying and assessing these impacts can be quite challenging. Gathering data, understanding causal relationships, and assessing how much each risk would change under each policy option (and for whom), and valuing these impacts, is challenging. The importance of side effects may be large or small (relative to the target risk); not every countervailing risk warrants rejecting a policy option, because the target risk reduction and co-benefits could justify the countervailing risks, when compared to the alternative policy options. But even a countervailing risk that is smaller than the target risk reduction and co-benefits could still be worth addressing in policy design, to reduce the countervailing risk even further and maximize the net benefits. In addition, there may always be unknown side effects that we do not yet identify or understand. For some emerging technologies it can be the fear of unknown (unidentified) risks which deter the public and decision makers from accepting their applications. Even if the countervailing risks are “known” in the sense of being conceptually identified, they might be highly uncertain. This is especially true for emerging technologies. Quite often, there is evidence on the existence of target risks, countervailing risks or co-benefits, but the evidence is inconclusive. Even if the countervailing risks or co-benefits are well known, costly efforts may still be needed to collect data to estimate the size and distribution of these effects.

Third, comparing target risks, countervailing risks, and co-benefits, and making tradeoffs among them can be challenging. Risks can be of different types, with different outcomes for health, safety, environmental, security, economic, and other impacts. As noted above, the risk-risk framework includes comparison of key attributes of risks, including magnitude, type of consequence, uncertainty, timing, and distribution (Graham and Wiener 1995b). Different risks may elicit different valuations and perceptions, including different feelings of familiarity, dread, or repugnance. Expert assessments may weigh every life equally, and may add a catastrophe premium for especially large losses or truly existential risks, while public opinion elicitations may show declining concern (compassion fade) for risks to large numbers of victims (Slovic 2007; Slovic et al. 2013). Even for the same mortality risks, different cultures may weigh them differently (Renn and Rohrmann 2000; Weber and Ancker 2011; Weber and Hsee 1999). This cross-cultural issue becomes even more prominent when global risks are concerned. Of course, all these risks can be converted to the same metrics by assigning a weight to each of them, and expressing them all in the same numeraire (such as value per statistical life, or years of life saved). But how shall weights be assigned? These are all value-laden decisions, and the risk-risk framework helps identify these value choices facing decision makers. When the distribution of risks among different populations is taken into account, the complexity of the comparison multiplies.

The key point of the risk-risk framework is that such comparisons and weightings are inescapable. Not comparing does not make the multiple risks go away. In order to navigate the multi-risk world successfully—to minimise overall risk in complex interconnected systems—the risk-risk framework offers an approach to confronting, comparing, and weighing multiple impacts, and to seeking risk-superior options that reduce multiple risks in concert. The public and policymakers may also encounter as well as introduce heuristics and biases that influence decision making (Kahneman 2011), and a risk-risk framework can help ensure sound deliberation addressing the full portfolio of important impacts. The risk-risk framework helps decision makers organize and structure these difficult but unavoidable analyses.

## 2.3. Alternative considerations and framing

In making decisions to cope with risks in the public arena, there are other decision frameworks which have been widely adopted. A risk-risk approach can help broaden and improve these frameworks as well. Benefit cost analysis (Sunstein 2018) and the precautionary principle (Wiener 2002) are among the most frequently used decision frameworks. If, however, benefit cost analysis or precautionary principle focus on a single risk and omit side effects, they will not be adequate frameworks for analysing complex multirisk decisions such as regarding SRM and climate change. In principle, sound benefit cost analysis would consider important side effects (Graham, Wiener, and Robinson forthcoming 2022). And a broader approach to “optimal precaution” (Wiener 2002) would include consideration of side effects. Another notable framework that could be applied to SRM rests on principles of human rights (Citro and Taylor Smith 2021); because both climate change and SRM could have effects on human rights, a risk-risk framework could help broaden the analysis to assess and weigh the conflicting impacts.

For example, in the context of deploying SRM technologies for coping with climate change, a narrow benefit cost analysis framework could focus on the climate benefits and the financial cost of deploying SRM technologies, and leave countervailing risks and co-benefits out of the decision framework. With the precautionary principle, if the precaution is against the target risks of climate change, then deployment of SRM technologies would be encouraged without considering their side effects. If instead the precaution is against the risks of emerging technologies such as SRM, then deployment of SRM technologies would be discouraged while the benefits of climate risk reduction and the co-benefits of the technologies may be left out of the decision framework. SRM and climate change present a case of "dueling precautions" where selection of the target risk can switch the precautionary posture, while an "optimal precaution" approach would take into account the broader multi-risk effects (Robbins 2021; Wiener 2002, 2016). Neither framework, if narrowly focused, would give a holistic optimal solution. The risk-risk framework would help both benefit cost analysis and precaution to assess the full portfolio of important impacts more comprehensively.

# 3. Solar radiation modification within the risk vs. risk framework

## 3.1. Climate change and SRM risks and risk tradeoffs

How can risks be compared between a future world using emissions reductions, CDR, and adaptation to address climate change, and a different world that uses emissions reductions, CDR, adaptation, along with SRM? The potential additional benefit of SRM in reducing negative climate change impacts must be weighed against the additional novel risks that SRM would bring. Table 3 shows how these risk impacts can be understood within the risk-risk framework.

**Table 3. Risk outcomes of adding SRM to a climate policy portfolio of mitigation, CDR, and adaptation.**

| | | **Outcomes** | |
|---|---|---|---|
| | | **positive** | **negative** |
| **risk** | target risk: climate change impacts | Climatic benefits.<br>See Table 4.SRM could reduce climate change hazards in most regions of the world, e.g., Irvine et al. (2019). | Climatic risks. See Table 4.<br>The offset of climate change by SRM is imperfect; SRM is a different and additional type of climate change with new effects, e.g., Muri et al. (2018). SRM could affect regions differently with a new distribution of climates. |
| | side effects: non-climate change impacts | Co-benefits. See Table 5.<br>For example, more diffuse sunlight with SAI could increase photosynthesis in some ecosystems, e.g., Xia et al. (2016). | Countervailing risks. See Table 5.<br>SRM creates novel ancillary risks, both biophysical (see Table 5) and societal (see Section 3.3). |

## 3.2. Biophysical risk-risk analysis for SRM

One of the key features of SRM is that it has the potential to cool the planet rapidly: in highly simplified scenarios that abruptly introduce and sustain SRM the desired level of global mean cooling can be achieved within a few years (Matthews and Caldeira 2007). A more realistic and policy-relevant approach would use a slow ramp up of SRM to offset further warming. However, detecting the climatic system response and its attribution to SRM deployment could be challenging because the effects of SRM on global mean surface temperature may not be attributable for 2–3 decades, a situation that is similar to the indistinguishability of future emissions scenarios in the near-term (next 2–3 decades (IPCC 2021c)). However, deployment of a small amount of SAI may be detectable in stratospheric chemistry observations, and MCB in tropospheric cloud observations.

In the past two decades more in-depth investigations into SAI and MCB and their climate effects have been conducted using Earth system models (ESMs), applying sophisticated physics and chemistry to model processes. SAI would provide a more globally uniform radiative forcing compared to MCB, because aerosols in the stratosphere can quickly spread around the globe and stay in the stratosphere for 1–2 years. As the added sea salt aerosols of MCB have a lifetime of only a few days, MCB would create a highly localized and hence heterogeneous radiative forcing, and potentially large regional disparities in both beneficial impacts as well as countervailing risks (Jones, Haywood, and Boucher 2011).

Modelling studies have consistently shown that both SAI and MCB have the potential to offset some effect of increasing GHGs on global and regional climates, but there could be substantial residual or overcompensating climate change at regional and seasonal scales (IPCC 2021b). Some studies have also shown that it is possible to meet multiple global and large-scale temperature targets (such as global mean surface temperature, equator to pole temperature gradient, and interhemispheric temperature difference) simultaneously by optimally designed SAI strategies (Kravitz et al. 2017; MacMartin et al. 2017; Visioni, MacMartin, et al. 2020; Tilmes et al. 2018). However, large uncertainties associated with aerosol microphysics, transport, and aerosol-cloud-radiation interactions persist in our current understanding of climate response to these aerosol-based options. Thus, SAI and MCB may offset global mean warming but they are imperfect solutions at the regional scale, where the effects, impacts and risks of climate change are experienced (Jones et al. 2018).

SRM options such as SAI and MCB contrast with climate mitigation activities, such as emission reductions and negative emission technologies, as they introduce a “mask” on the climate change problem, for example by adding an aerosol layer in the stratosphere in case of SAI and in the marine low cloud regions in case of MCB, rather than attempting to address its root cause, which is the increase in GHGs in the atmosphere. By only concealing the climate effects of GHG emissions, SAI and MCB do not address other issues related to atmospheric carbon dioxide increase such as ocean acidification. This masking of climate change, if not accompanied by mitigation, poses a major countervailing risk of termination shock, which is discussed in Section 3.3. A sudden and sustained termination of large amount of SAI or MCB under a high GHG emission background would cause a rapid increase in temperature and precipitation at a rate that far exceeds that predicted for future climate change without SRM. However, a gradual phase-out combined with mitigation and CDR is most likely to avoid large rates of warming. It should be also noted that many conclusions on SAI and MCB have been drawn from climate modelling studies which involve uncertainties related to aerosol-cloud-radiation interactions. Hence the climate response to their deployment and termination (whether sudden or gradual) is also associated with large uncertainties.

As many of the global and regional impacts and risks of climate change on human and ecosystems scale with global mean surface temperature, SAI and MCB would reduce several biophysical hazards associated with climate change including the increase in frequency and intensity of extremes of temperature and precipitation, melting of Arctic sea ice and mountain glaciers, loss of the Greenland and Antarctic icesheets, sea level rise, weakening of the Atlantic meridional overturning circulation, changes in the frequency and intensity of tropical cyclones, and a decrease in soil moisture (Table 4). However, there is large uncertainty and low confidence in how the potential hazard and risk reduction from SAI and MCB are understood at the regional scale. Due in part to limited research, there is also large uncertainty in projected benefits or risks to crop yields, human health, or ecosystems (Table 4). SAI may introduce additional countervailing risks such as stratospheric ozone depletion, increased acid deposition in pristine areas in the high latitudes, and altered regional rainfall patterns, as well as co-benefits such as reduced tropospheric ozone in the high latitudes and an increase in diffuse radiation that may be beneficial to some ecosystems (Table 5). With MCB, one of the countervailing risks could be an increase in salt deposition over land, which could be detrimental to terrestrial ecosystems, and a co-benefit is the likely increase in water availability over land areas in the tropical regions (Table 5). Other co-benefits from MCB and also SAI are an increase in carbon stocks over land and ocean because of a cooler climate and a slight corresponding reduction in atmospheric carbon dioxide concentrations.

In Table 4 we map the multiple biophysical risks from climate change and how they are expected to be altered through the possible use of either SAI or MCB. These risks may be measured by specific indicators for the Sustainable Development Goals (SDGs), and the relevant SDG's for each risk are listed in the left column. Impacts of climate change as well as SRM on the SDGs draw on WMO (2021), and are explored in further detail in Sections 3.7 and 3.8 and Table 6 in the Supplementary Materials. Table 5 explores how the deployment of these new SRM technologies would create additional and novel countervailing risks along with some potential co-benefits. In both tables it should be noted that the risk outcomes listed are specific to a particular SRM technology, deployment pathway, and timeframe, among other factors.

**Table 4. Biophysical hazards (and risks) associated with climate change and the change in hazard with the addition of SRM, along with new hazards**. A blank cell indicates that there is no published scientific research on the relevant topic.

| **Risk factor** (applicable SDGs) | **Hazard and risk from climate change** | **Change in hazard (and risk) if SRM is deployed** | |
|---|---|---|---|
| | | SAI | MCB |
| Atmosphere | | | |
| Atmospheric $CO_2$ concentrations<br>(2, 3, 13, 14) | Risk would increase because global mean temperature change scales with the log of $CO_2$ concentrations. | SRM-induced cooling could lead to more carbon storage over land and the ocean, with a consequent marginal reduction in atmospheric $CO_2$ concentrations (Muri et al. 2018; Tilmes et al. 2020). However, this reduction is small and not enough to alleviate ocean acidification (Canadell et al. 2021). | |
| Global mean surface temperature (GMST)<br>(1, 2, 3, 6, 7, 8, 9, 10, 11, 13, 14, 15, 16) | Risk would increase (most biophysical effects and impacts scale with GMST). | Global mean temperature change can be fully or partially offset (IPCC 2021b, 2013).<br>Abrupt introduction of SRM could bring GMST to desired levels with a few years (Matthews and Caldeira 2007) | Global mean temperature change can be fully or partially offset (IPCC 2021b; Latham, Bower, et al. 2012; IPCC 2013).<br>MCB in the Pacific could produce persistent La Niña-like conditions and associated weather regimes around the world (Hill and Ming 2012; Baughman et al. 2012). |

| | | | |
|---|---|---|---|
| Global water cycle<br>(1, 2, 3, 6, 7, 8, 9, 10, 11, 13, 14, 15, 16) | The global water cycle would intensify. Risk would increase because of an increase in extreme precipitation events, floods, and droughts. | The global water cycle would weaken compared to the scenario with no SAI when GMST is fully offset (Muri et al. 2018; Crook et al. 2015; Tilmes et al. 2013).<br>However, changes in water availability (P–E) over land would be small as both precipitation and evaporation decrease under SAI (IPCC 2021b).<br>The weakening of the global water cycle could be prevented by SAI at moderate intensity, for example by offsetting half of the global mean warming (Irvine and Keith 2020) or considering a peak shaving scenario (Tilmes et al. 2020). | The global water cycle would weaken compared to the scenario with no MCB (Muri et al. 2018; Crook et al. 2015; Stjern et al. 2018).<br>Land mean precipitation and runoff could increase (Stjern et al. 2018; Alterskjær et al. 2013; Bala et al. 2011). Large uncertainty exists in our assessment of regional and local precipitation pattern changes. |
| Extreme temperatures<br>(1, 2, 3, 6, 7, 8, 9, 10, 11, 13, 14, 15, 16) | Risk would increase because of increased frequency and intensity of extreme temperatures. | SAI and MCB would reduce the intensity and frequency of extreme temperatures (Aswathy et al. 2015; Pinto et al. 2020). | |
| Extreme precipitation<br>(1, 2, 3, 6, 8, 9, 10, 11, 14, 15, 16) | Risk would increase because of increased frequency and intensity of extreme precipitation. | Both SAI and MCB would reduce the intensity and frequency of extreme precipitation (Aswathy et al. 2015). | |
| Dry spells (consecutive dry days)<br>(1, 2, 3, 6, 15, 16) | Risk would increase because of increased frequency of dry spells. | Both SAI and MCB would reduce the frequency of dry spells (Aswathy et al. 2015). | |

| | | | |
|---|---|---|---|
| Global and regional monsoons<br>(1, 2, 3, 6, 8, 9, 10, 11, 14, 15, 16) | Mean monsoon rainfall would increase but the variability (wet and dry days or floods and droughts) increases, which could pose a risk. | Relative to a scenario without SAI, the summer monsoon precipitation over some regions could decrease (Da-Allada et al. 2020; Simpson et al. 2019).<br>Single point injections in the northern (southern) hemisphere could cause reduction (increase) in precipitation in the tropical monsoon regions in the northern hemisphere and increase (reduction) in the southern hemisphere monsoon regions (Krishnamohan and Bala 2022).<br>Arctic SAI would reduce precipitation in N. Hemisphere monsoon domains (Nalam, Bala, and Modak 2018). | |
| Tropical cyclones<br>(1, 2, 3, 6, 8, 9, 10, 11, 14, 15, 16) | Tropical cyclone intensity would increase, and hence the risk increases. | Tropical cyclone genesis potential would decrease relative to a scenario without SAI (Wang, Moore, and Ji 2018), and cyclone intensity could be reduced (Irvine et al. 2019). | By reducing sea surface temperatures, hurricane intensity could be reduced (Ghosh et al. 2016; Latham, Parkes, et al. 2012). |

| Cryosphere | | | |
|---|---|---|---|
| Arctic Sea ice<br>(1, 2, 6, 13, 14, 15, 16) | Risk would increase as reduction in sea ice amplifies warming. | Sea ice cover can be recovered (Muri et al. 2018; Jones et al. 2018; Tilmes et al. 2014). | Sea ice cover can be recovered (Muri et al. 2018; Rasch, Latham, and Chen 2009). |
| Antarctic Sea ice<br>(1, 2, 6, 13, 14, 15, 16) | Risk would increase as reduction in sea ice amplifies warming. | Sea ice loss can be reduced (Muri et al. 2018). | |
| Greenland icesheet melt<br>(1, 2, 6, 7, 8, 9, 11, 13, 15) | Risk would increase because of accelerated melt and sea level rise. | Melt rate could be slowed down and contribution to sea level rise can be reduced (Moore et al. 2019; Tilmes et al. 2020). | – |
| West Antarctic icesheet melt<br>(1, 2, 6, 7, 8, 9, 11, 13, 15) | Risk would increase because of accelerated melt and sea level rise. | Ice sheet basal melting in Antarctic ice shelves would not be completely offset by SAI (McCusker, Battisti, and Bitz 2015). | – |
| Ice sheet collapse<br>(1, 2, 6, 7, 8, 9, 11, 13, 15) | Risk would increase as ice sheet collapse leads to sea level rise. | The ability of SAI to reverse collapse once initiated may be limited (Irvine, Keith, and Moore 2018). | – |
| Himalayan glacial melt<br>(1, 2, 6, 7, 8, 9, 11, 13, 15) | Risk would increase because glacier volumes would shrink, which could lead to water shortages. Risk from glacial lake outburst flooding increases. | Partial offset of volume reduction is likely (glacial melt is a slow process) when GMST is nearly offset (Zhao et al. 2017). | – |

| Oceans | | | |
|---|---|---|---|
| Sea level rise<br>(1, 2, 3, 6, 8, 9, 10, 11, 14, 15, 16) | Risk would increase from the inundation of coastal areas and larger storm surges. | Sea level rise could be limited or delayed (Muri et al. 2018; Jones et al. 2018), but cannot be completely offset unless high-magnitude SAI is deployed (Moore, Jevrejeva, and Grinsted 2010).<br>Storm surges and flooding in coastal north Atlantic can be reduced by SAI (Jones et al. 2018; Moore et al. 2015). | Sea level rise could be reduced (Muri et al. 2018). |
| Atlantic Meridional Overturning Circulation (AMOC)<br>(1, 2, 3, 6, 8, 9, 10, 11, 14) | Risk would increase from a weakened AMOC, which could cause a colder climate in N. Europe and circulation changes in the atmosphere. | Slowdown in the AMOC could be reduced (Muri et al. 2018; Xie et al. 2021 (under review)).<br>Because of imperfect regional offset, the AMOC strengthens in one study, which could lead to an increase in ocean heat content and sea level rise (Fasullo et al. 2018). But this result is model-dependent as the strengthening is not simulated in another version of the same model (CESM$_2$) (Tilmes et al. 2020). | Slowdown in AMOC could be reduced (Muri et al. 2018; Xie et al. 2021 (under review)). |
| Ocean acidification<br>(1, 2, 8, 11, 14, 16) | This is not a risk from climate change but rather a risk from increasing CO$_2$ levels in the atmosphere. | Risk could be marginally reduced as SRM reduces atmospheric CO$_2$ levels slightly (Matthews, Cao, and Caldeira 2009; Keith, Wagner, and Zabel 2017; Zarnetske et al. 2021). | |

| Land | | | |
|---|---|---|---|
| Changes in soil moisture (drying in the subtropical regions)<br>(1, 2, 3, 6, 15, 16) | Risk would increase as soil moisture would decrease and hence drought conditions would increase in the subtropics. | SAI would restore the global mean soil moisture (Cheng et al. 2019) but soils would become drier over India and the Amazon.<br>Soil would become wet in the Mediterranean region (Simpson et al. 2019). | – |
| Floods<br>(1, 2, 3, 6, 8, 9, 10, 11, 14, 15, 16) | Risk from the frequency and intensity of flood events would increase. | In general, SAI would reduce flood risk in most cases (Wei et al. 2018).<br>Storm surges and flooding in coastal north Atlantic may be reduced by SAI (Moore et al. 2015; Jones et al. 2018). | – |
| Wildfires<br>(1, 2, 3, 6, 8, 9, 10, 11, 15, 16) | Risk would increase because of drier conditions. | Fire danger would be reduced by SAI (Burton et al. 2018) . | – |
| Water quality in rivers<br>(1, 2, 6, 11, 14) | Risk would increase as warming leads to less dissolved oxygen in river water. Reduced low flows during dry periods would lead to reduced water quality. | – | |

| Ecosystems | | | |
|---|---|---|---|
| Coral bleaching<br>(1, 2, 8, 11, 14, 16) | Risk would increase because of more frequent and intense marine heat waves. | Risk would be reduced (Kwiatkowski et al. 2015). | Risk would be reduced (Latham et al. 2013). |
| Carbon storage on land and in the ocean<br>(1, 2, 8, 11, 14, 16) | Risk would increase as stocks are reduced by warming, which would lead to an increase in $CO_2$ in the atmosphere. | Carbon stocks would increase over land and the ocean because of SAI-induced cooling. Atmospheric $CO_2$ concentrations would fall slightly (Muri et al. 2018; Sonntag et al. 2018; Tjiputra, Grini, and Lee 2016; Zarnetske et al. 2021). | Carbon stocks would increase over land and ocean because of cooling. Atmospheric $CO_2$ concentrations would also fall slightly (Muri et al. 2018). |
| Permafrost carbon<br>(2, 3, 13, 14) | Risk would increase as permafrost carbon could be released by warming, which can accelerate (provide a positive feedback) global warming. | SAI could slow the release of permafrost carbon ($CO_2$ and $CH_4$) (Chen, Liu, and Moore 2020) or otherwise slow the current rate of permafrost degradation (Lee et al. 2019). | – |
| Ecosystem productivity (net primary production NPP)<br>(1, 2, 3) | Risk would increase in low latitudes as NPP is reduced by warming but there could be benefit in high latitudes from increased NPP due to a longer growing season. | Risk would be reduced in low latitudes as SAI reduces heat stress, but cooling could also lead to reduced N-mineralization relative to a world without SAI (Zarnetske et al. 2021). In high latitudes, cooling would reduce the growing season NPP (Tilmes et al. 2020; Duan et al. 2020).<br>The photosynthetic rate could increase because of an increase in diffuse light at the surface (Xia et al. 2016). | Regional precipitation would change and sea salt deposition over land from MCB may increase or decrease primary production in tropical rainforests (Muri, Niemeier, and Kristjánsson 2015). |

| | | | |
|---|---|---|---|
| Crop yields<br>(1, 2, 3) | Risk would increase in low latitudes as crop yields decrease due to heat stress, but there could be benefit in high latitudes due to a longer growing season. | Cooling and the resulting higher relative humidity would alleviate water stress for rainfed crops (Fan et al. 2021).<br>Risk of reduced crop yields in low latitudes could be reduced from a reduction in heat stress (Pongratz et al. 2012). Rice yields could be increased by SAI-caused cooling in one SAI scenario in China (Zhan et al. 2019), but little change in rice yield and a large increase in maize yield is found in another SAI scenario (Xia et al. 2014).<br>Risk of reduced crop yields may also increase in places where rainfall is reduced because of SAI (Yang et al. 2016). SAI-induced cooling in a hilly region in India would help climate conditions for apple plantations to remain in the region instead of moving up the hill (Singh, Sahany, and Robock 2020).<br>The benefit from SAI-induced cooling would be nearly offset by reduced sunlight at the surface (Proctor et al. 2018).<br>Crops may be also affected by reduced tropospheric ozone and increased UV radiation (Xia et al. 2017), and the net effect is uncertain.<br>Because of the divergence in results, the overall confidence in risk change for crop yields is low. | Cooling and resulting higher relative humidity would alleviate water stress for rainfed crops (Fan et al. 2021).<br>MCB reduces crop failures in Northeastern China and West Africa (Parkes, Challinor, and Nicklin 2015). |

| Human Health (Diseases) | | |
|---|---|---|
| Infectious diseases<br>(3) | Risk would increase as warmer temperatures are predicted to facilitate the spread or re-emergence of vector-borne diseases such as malaria, dengue fever and Zika. | SRM, by reducing warming, is likely to reduce disease range expansions. Transmission may also increase in the tropics under cooler conditions. Reduced monsoon rainfall could cause cholera in India (Carlson and Trisos 2018). |

**Table 5. Novel biophysical countervailing risks and co-benefits (shaded) introduced by SRM. An empty cell indicates no research in the relevant topic.**

| Feature | SAI | MCB |
|---|---|---|
| Precipitation changes<br>(SDGs 1, 2, 3, 6, 8, 9, 10, 11, 14, 15, 16) | Intensification of the global water cycle from climate change could be reduced by SAI compared to the scenario with no SAI (Muri et al. 2018; Crook et al. 2015).<br>Single point injections in the northern (southern) hemisphere could cause reduction (increase) in precipitation in the tropical monsoon regions in the northern hemisphere and increase (reduction) in the southern hemisphere monsoon regions (Krishnamohan and Bala 2022).<br>Arctic SAI could lead to reduced monsoon precipitation in the Northern Hemisphere (Nalam, Bala, and Modak 2018).<br>Large uncertainty exists in altered regional precipitation pattern. | Intensification of the global water cycle from climate change could be reduced by MCB, compared to the scenario with no MCB (Muri et al. 2018; Crook et al. 2015).<br>Land mean precipitation and runoff could increase (Stjern et al. 2018; Alterskjær et al. 2013; Bala, Caldeira, and Nemani 2010).<br>Regional and local precipitation pattern changes are uncertain. |
| Excessive cooling | Uncertainty in estimates of the amount of SAI required could lead to excessive cooling. Uncertainty in the amount of SAI ramp-down in the event of a sudden major volcanic eruption could lead to excessive cooling (Laakso et al. 2016; Robock 2008). | – |
| Acid rain or other toxic material falling from the sky<br>(1, 2, 3, 6, 14, 15) | New risks could arise due to sulfuric acid from SAI, or proposed metallic aluminium or aluminium oxide aerosols (Effiong and Neitzel 2016), though other materials are being studied that could increase or decrease risks.<br>Under an extreme SAI scenario, acid deposition may increase in pristine high latitude areas, as stratospheric aerosols enter the troposphere mostly in the high latitude regions (Visioni, Slessarev, et al. 2020). | Sea salt deposition over land may increase or decrease primary production in tropical rainforests (Muri, Niemeier, and Kristjánsson 2015). |

| | | |
|---|---|---|
| Stratospheric ozone depletion<br>(3) | Ozone could be depleted in the polar stratosphere with little change in the tropics and mid-latitudes (low confidence). Antarctic ozone hole recovery could be delayed by 25–50 years, and the hole could become deeper in the first ten years of SAI (Tilmes et al. 2020; Tilmes et al. 2021). | – |
| Surface UV radiation increase<br>(3) | A decrease/increase in stratospheric ozone could lead to an increase/decrease in surface UV at high latitudes (Xia et al. 2017; Madronich et al. 2018). Resulting higher/lower UV exposure could have impacts on human heaths and ecosystems (Eastham 2018, Zarnetske et al. 2021). | – |
| Partition between direct and diffuse solar radiation at the surface<br>(1, 2, 3) | Some crops may not benefit from SAI (Proctor et al. 2018). Net radiation decreases, which would lead to reduced NPP and crop yields (Kalidindi et al. 2015; Krishnamohan et al. 2019).<br>Reduced direct radiation could also lead to reduced solar energy generation (Robock 2008), degraded ground-based optical astronomy (Robock 2020), negative effects on satellite remote sensing (ibid.), or sky whitening (Kravitz, MacMartin, and Caldeira 2012). | – |
| Stratospheric heating<br>(1, 2, 3, 6, 7, 8, 9, 10, 11, 13, 14, 15, 16) | Stratospheric heating could lead to water vapor increase in the stratosphere, which affects ozone chemistry. The heating also affects stratospheric circulation such as with the Quasi biennial oscillation (QBO), polar vortex, and Brewer Dobson Circulation (BDC), e.g., Richter et al. (2018) and Aquila et al. (2014). Strategic applications of SAI can reduce the impacts on the QBO. | – |
| Unintended warming instead of cooling<br>(1, 2, 3, 6, 7, 8, 9, 10, 11, 13, 14, 15, 16) | Stratospheric warming and its spread into the troposphere could result if black carbon were injected into the stratosphere (Kravitz et al. 2012).[4] | Particles that are either too small (0.04 micron) or oversized (2.5 micron) could lead to a warming instead of cooling (Alterskjær and Kristjánsson 2013; Pringle et al. 2012). |
| Tropospheric ozone decrease | SAI could cause tropospheric ozone in high latitudes to drop because of reduced downward transport of stratospheric ozone into the troposphere (Xia et al. 2017). | MCB would increase tropospheric chlorine and bromine, reduce OH and increase $CH_4$ lifetime, and reduce surface ozone pollution marginally (Horowitz et al. 2020). |

---

[4] Kravitz et al. (2012) note that, "...black carbon geoengineering likely carries too many risks to make it a viable option for deployment."

| | | |
|---|---|---|
| Biodiversity and other ecosystem services, including food security<br>(1, 2, 3) | Increase in diffuse sunlight at the surface from SAI could benefit some ecosystems, but the effect on crops is uncertain, and the net effect from SAI-induced cooling and decrease in net solar radiation at the surface may be negative (Proctor et al. 2018; Zarnetske et al. 2021). | – |

## 3.3. Novel societal countervailing risks introduced by SRM

As an emerging family of technologies, SRM presents multiple new potential societal risks in addition to its novel biophysical risks. Indeed, the 2009 UK Royal Society report on geoengineering made the observation that "The greatest challenges to the successful deployment of geoengineering may be the social, ethical, legal and political issues associated with governance, rather than scientific and technical issues" (Shepherd et al. 2009: xi). Several of these possible societal risks arising from the research, development, and deployment of SRM have been examined, including: 1) deployment error or irresponsible deployment that leads to error; 2) path dependence, slippery slope, or socio-technical lock-in, which leads to dependency on SRM or and erosion of democratic systems; and 3) capture and exploitation by private interests or oil states, among many other concerns (Keith 2021). The existence of possible harms is not a reason for rejecting further research into SRM (Parson 2021), though there are significant challenges to address with the governance of such research (McLaren and Corry 2021). Here we examine four larger categories of societal risks from deployment of SRM: international conflict, emissions abatement displacement, termination shock, and ethical concerns.

### International conflict

Notable among novel societal risks are the threats to international peace and security that deployment of some SRM options could create.[5] Because SRM—in particular SAI—apparently presents no insurmountable technological hurdles, and because it would be so inexpensive relative to the size of many national budgets (as well as to the costs already required for mitigation), several nation-states may be motivated to be the first in pursuing the development and deployment of SRM unilaterally, without the cooperation of the rest of the world (Weitzman 2015; Barrett 2008). Such a "free-driver" motivation would mean that an implementing nation could change the temperature of the entire globe without the consent of other countries. Even if a country were to deploy regionally, the intervention would create cross-border effects.

Unilateral SRM deployed without broad international agreement could lead to conflict (National Intelligence Council 2021; Corry 2017). With the potential for a unilateral global first mover, disagreements may arise over: 1) where the *"global thermostat"* is set, who has the power to set the thermostat, and how to account (and compensate) for heterogeneous regional impacts of the SRM (Stavins et al. 2014, Sec. 4.4); 2) national prestige and struggles over global leadership; 3) international distrust, especially of the deploying state; 4) motivations to maintain technological superiority or other competitive advantages; and 5) cross-border negative impacts of SRM and their attribution to that SRM deployment, whether real or perceived (National Intelligence Council 2021). Such conflict could manifest itself peacefully (i.e., with diplomacy, sanctions, etc.), via traditional military means (airstrikes, blockades, cyberattacks, invasion and war, etc.), or even with attempts at countermeasures (deploying secondary SRM in order to neutralize the SRM deployment of another

---

[5] It should be noted that climate change itself is seen as a "threat multiplier," an indirect but contributing factor for a higher risk of both international and intra-national conflict and crises (Lieven 2020; Koubi 2019; Cater 2021). To the extent that SRM could reduce the symptoms of climate change, it could reduce the likelihood of such conflict.

country, also known as *"counter-geoengineering"*) (Parker, Horton, and Keith 2018).[6]
The existence of multiple non-cooperative nations, with SRM capability and different preferences for their average temperature, could lead to strategic disputes and an overcooling of the planet (Abatayo et al. 2020).

## Emissions abatement displacement ("moral hazard")

Another concern derives from the assumption that SRM could lower the overall risks of climate change at much less cost than mitigation does. The worry is that decision makers might then act rationally to reallocate their efforts away from mitigation and towards SRM in a form of *"risk compensation."* This phenomenon has been termed geoengineering's *"moral hazard,"* but more accurately it can be seen as a concern over the possibility that SRM may cause emissions abatement displacement (Reynolds 2019, ch. 3).

If the use of SRM did in fact lower global mitigation efforts from what they otherwise would have been, several harms would arise, including: 1) exacerbated ocean acidification (as the atmosphere's carbon dioxide concentrations continue to rise), 2) a need for more SRM to be used in order to counteract continued rising GHG emissions (consequently raising the amount of SRM's negative side effects), and 3) relatedly, a higher risk of dependency on SRM and thus a higher risk of the consequences of termination shock. Yet in a list of ten studies compiled in Reynolds (2019, ch. 3), emissions abatement displacement does not manifest itself. In some cases a "reverse moral hazard effect" appears, for example in game theoretic modelling where an increased motivation to mitigate is exhibited when the prospect of SRM is characterized as risky compared to the risks of climate change (Fabre and Wagner 2020); relatedly, public opinion on mitigation efforts may decline if SRM is framed as a solution, but not decline if SRM is framed as part of a larger policy portfolio (Raimi et al. 2019). Further, the risk of emissions abatement could potentially be addressed through strategic linking of international mitigation and solar geoengineering policies, and other cooperation efforts (Reynolds 2021).

## Termination and resulting termination shock

Termination shock would be "a rapid and substantial risk in global temperatures following a cessation of [solar geoengineering] deployment" (Parker and Irvine 2018). Such a stoppage in SRM implementation could occur as a result of terrorism or economic collapse, or it could instead be accidental, mistaken, or even deliberate. Regardless of reason, a sudden halting of SRM—in particular, if GHG concentrations continued to rise in the interim—could have devastating effects on human and natural systems. An abrupt termination of global SAI would see a rapid rate of warming and drying of land areas in the first few years following cessation, with catastrophic effects on biodiversity and risk of species extinction (Muri et al. 2018; Jones et al. 2013; Moore, Jevrejeva, and Grinsted 2010; Trisos et al. 2018; McCusker et al. 2014). A sudden stoppage of MCB would also see rapid warming and likely similar negative effects as well (Muri et al. 2018; Stjern et al. 2018; Alterskjær et al. 2013).

The risk of termination shock—both the likelihood that a deployed SRM program would suddenly stop, as well as the consequences of such an event—has been deemed very low, as both risk components can be addressed with relatively straightforward approaches such as building redundancy (Parker and Irvine 2018). Consequences of a termination can be further limited by maintaining high levels of mitigation throughout any SRM deployment, such that the SRM does not comprise a large share of the cooling during its use. Reducing the likelihood of termination could come from building SRM infrastructure resiliency and security (ibid.; Lockley 2019), along with creating appropriate governance systems (Rabitz 2019).

## Ethical concerns

Environmental ethicists have to date tended to focus on the countervailing risks of SRM, rather than on its risk-attenuation potential and the associated ethics warranting or even requiring

---

[6] A discussion also exists on whether or not SRM can be weaponized, e.g., Horton and Keith (2021) (no) and Chalecki (2021) (yes).

its examination (Svoboda 2017). It is understandable why many environmentalists may be opposed to SRM in general, when approaches such as SAI could in effect pollute the stratosphere with sulphate aerosols in order to counteract and conceal the effects of society's historical and current GHG pollution. For example, U.S. environmental advocacy groups are split in their positions on whether the technologies should be researched further, as explored in Felgenhauer, Horton, and Keith (2021).

Several ethical objections to the research, development, and possible use of SRM are related to the justice of both procedures and implementation (who is deploying the SRM, for what purpose, and how is decision making governed) as well as outcomes (who is helped, who is harmed, and is there a viable attribution, liability, and compensation mechanism). The possibility that the effects of an SRM deployment could be distributed heterogeneously across the globe—with some regions hurt by the deployment while others are helped—is of particular concern, not just because such an outcome is unjust, but also because there are no viable means or possibilities of redress.

These types of concerns highlight the fact that many of the possible negative side effects of SRM are not inherent to the technology but are rather a function of political efforts, governance, and the specifics of any deployment scenario. We argue that many of these ethics-based concerns over the risks of SRM can be understood within a risk-risk analytical framework, even if their values cannot be explicitly calculated.

## 3.4. Three illustrative policy scenarios

In order to illustrate possible futures, in Figure 1 we present three different numbered climate and policy scenarios that combine mitigation with some level of SRM. For reference, mitigation-only scenarios are indicated along the bottom. Adaptation to climate change is not depicted in these three scenarios, but would represent additional choices depending on the level of climate change. The situation before the 2015 Paris Agreement is at the bottom right, in which the world expected to reach relatively high GHG levels and temperatures in 2100. The current trajectory of 2021, accounting for the official 2030 climate pledges made up to the COP26 climate conference in Glasgow, is at bottom centre. The Paris Agreement goal of 1.5°C is indicated at the bottom left. The scenarios that include SRM are then positioned accordingly along the horizontal axis, with vertical placement indicating the level of SRM and are as follows:

(1) Peak Shaving – high mitigation + some SRM
High mitigation moves background emissions down to a path aligned with the SSP53.4-OS scenario (Tilmes et al. 2020)7, in which global mean temperature overshoots the 1.5°C target briefly but CDR and deep mitigation bring down atmospheric carbon dioxide in the latter half of this century. SRM is deployed in 2040 with the goal of capping the temperature rise at 1.5°C, and SRM is ramped down as the temperature goes below 1.5°C. (This scenario is similar to that in Tilmes, Sanderson, and O'Neill (2016), in which global mean temperature is stabilized at 2°C instead of at 1.5°C as assumed here).

(2) Half-Warming – moderate mitigation + some SRM
Emissions follow the SSP2-4.5 pathway. SRM is deployed in 2040 when global warming reaches ~1.5°C. The amount of SRM is moderate but ongoing, with the goal of keeping the temperature rise half as great as it would be under SSP2-4.5 without SRM. This scenario is similar to the GeoMIP G4 experiment (Kravitz et al. 2015).

---

[7] Figure 1 utilizes the pairing of Shared Socioeconomic Pathways (SSPs) and Representative Concentration Pathways (RCPs) for scenario building. The SSPs describe a range of five plausible societal evolution pathways over this century, built from both qualitative and quantitative foundations, with implications for society's ability to both mitigate and adapt to climate change (O'Neill et al. 2014; O'Neill et al. 2017). The RCPs describe a series of emissions and concentrations pathways for climate forcers, each distinguished by the expected radiative forcing for that pathway at the end of the century, i.e., 1.9–8.5 W/m2 (Moss et al. 2010; van Vuuren et al. 2011). The two pathways can be paired (and abbreviated) to form a scenario, as for example with Scenario 2 in Figure 1 where SSP2-4.5 is a combination of SSP2 and RCP 4.5. Use of the SSPs and RCPs in the IPCC assessment reports explained further in Chen et al. (2021).

(3) SRM dependency – low mitigation + high SRM
Emissions follow the SSP5-8.5 pathway with very low mitigation. SRM is deployed in 2040 when global warming reaches ~1.5°C. The amount of SRM increases throughout the century with the goal of keeping temperatures stabilized at 1.5°C. (This scenario is somewhat similar to the GeoMIP G6sulfur experiment (Kravitz et al. 2015), and has been performed by the Geoengineering LargeEnsemble Simulations (GLENS) (Tilmes et al. 2018)

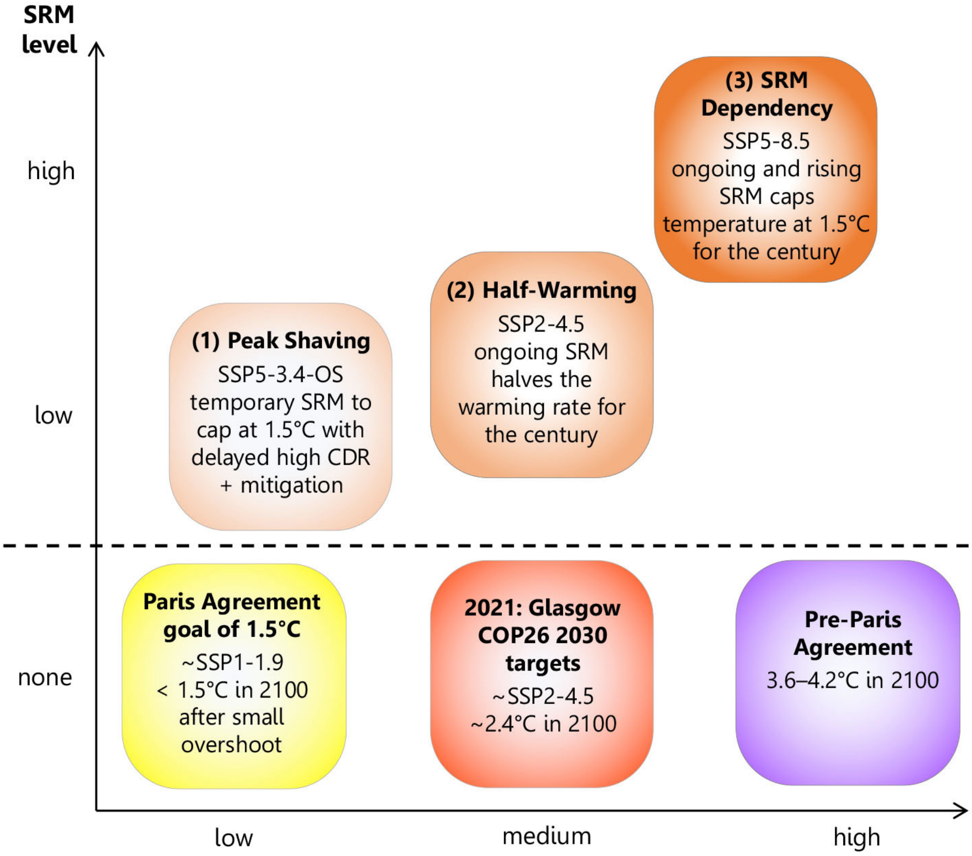

**Figure 1. Three mitigation + SRM policy scenarios in relation to three mitigation-only scenarios.** All SRM scenarios assume that SRM is deployed in 2040 (when the world is at roughly 1.5°C of warming). Assumptions on mitigation pledges and temperature outcomes are from two analyses by Climate Action Tracker (2021) and Climate Resource (Meinshausen et al. 2021). Axes are not to scale.

## 3.5. Risk tradeoffs with additional dimensions

Given different SRM approaches, how are risk-risk tradeoffs affected and complicated by additional factors? Accurate understanding of the risk profile of any SRM implementation depends on its interaction with a large set of other relevant factors, including the policy goals of any implementation, the amount of SRM needed (in relation to both the goals as well as the background climatic conditions), the technological and methodological details of an implementation, and the governance mechanism that is established for the entire process.

Comparisons can be made between a mitigation-only scenario and scenarios that incorporate some level of SRM. Conceptually, the emissions pathway followed in a mitigation-only scenario will determine the level of residual climate change risk that might yet be addressed by SRM. Lower emissions pathways will leave less climate risk remaining. The specific choice of SRM deployment level then comes down to managing a tradeoff between further reduction of these climate change risks and tolerance for the countervailing risks of SRM (Figure 2). It is believed that increasing levels of SRM can be expected to decrease global temperature—and therefore climate risk—sublinearly (Keith and MacMartin 2015). This means that the total effectiveness of SRM is not expected to increase in proportion to the level of SRM deployment. Further, it can be expected that most countervailing risks will increase with higher SRM levels. Together, these features imply that the level of SRM that minimizes total risk will be less than the level that minimizes climate change risk alone. Identifying the "total-risk minimizing" SRM deployment scenario depends on knowing how the various ancillary impacts of SRM depend on the level of deployment. Some may be expected to increase superlinearly with increasing SRM level (Keith and MacMartin 2015). This means that the level of impact is expected to grow more than in proportion to the level of SRM deployment. Others, such as the risk of international conflict, for example, might be expected to increase only sublinearly if the likelihood, but not the magnitude, grow at higher levels of SRM deployment (see Figure 2). Determining whether increases in ancillary impacts, in aggregate, will be sublinear (Figure 2, curve A), linear (curve B), or superlinear (curve C) in relation to SRM level, along with how these patterns depend on the specifics of SRM implementation (e.g., the technology used, the deployment strategy, the policy objective, and the governance mechanism) are important research questions

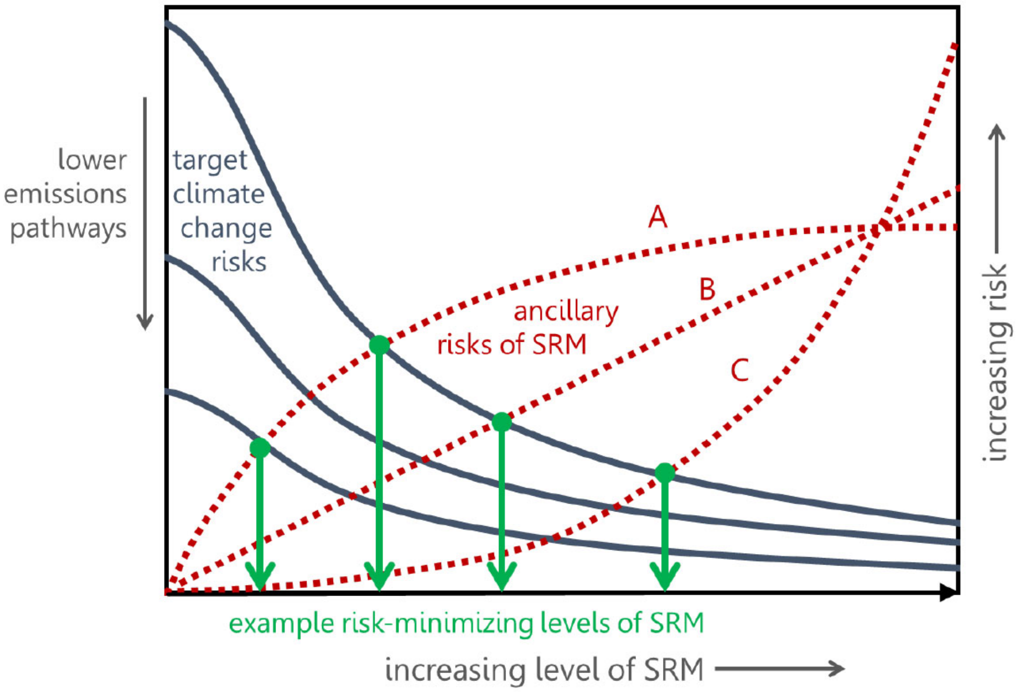

**Figure 2. The fundamental risk-risk tradeoff of SRM between climate change risks and ancillary risks.** With increasing SRM level, the ability of SRM to reduce global temperature, and therefore the risks of climate change, is widely believed to decrease sublinearly (solid blue curves shown for various emissions pathways). However, it is currently unknown whether aggregated ancillary risks (dashed red curves) should be expected to increase sublinearly (Curve A), linearly (B), or superlinearly (C) with increasing SRM. Green arrows show the locations of some examples of risk-minimizing levels of SRM for various combinations of emissions pathways and hypothetical ancillary risk curves. The offsetting intended and ancillary benefits of SRM are not shown here.

## 3.6. Relative severity of ancillary impacts of SRM

While all the potential ancillary impacts of SRM, both positive and negative, are highly uncertain, it is useful to attempt to position them on a risk matrix to prioritize further investigation (Figure 3). Some ancillary risks, such as acid deposition if sulphuric aerosols are used, are fairly certain (Visioni, Slessarev, et al. 2020; Kravitz et al. 2009), although the consequences may be less severe. Others, such as international conflict (Corry 2017) or termination shock (Parker and Irvine 2018) could be disastrous if they were to occur. In anticipating these risks their likelihood could be reduced, by developing and putting into place robust international governance structures prior to any development, or by limiting the amount of SRM. Further, these latter two risks might be hypothesized to respond differently to greater levels of SRM. While the consequences of unexpectedly terminating SRM would likely increase along with the level of SRM, most of the hypothesized causes of termination are not believed to be more likely at higher SRM levels (ibid.). On the other hand, it seems that the likelihood of international conflict could be greater with more SRM (Heyen, Horton, and Moreno-Cruz 2019), although the consequences of such a conflict would not necessarily depend on the level of SRM deployment. At this point, the expected responses of these risks to SRM level are speculative and would need to be informed by research and expertise from the appropriate disciplines.

The influence of SRM on future emissions abatement is highly uncertain, both in its likelihood and especially its magnitude, including some possibility of SRM even promoting abatement due to a perception that SRM poses an even greater risks than GHGs (Fabre and Wagner 2020). Both the likelihood and magnitude of a possible emissions abatement effect might be expected to increase at higher SRM levels (Lin 2013). Ancillary benefits of carbon sink enhancement and reduction in tropospheric ozone are highly likely, but are of only marginal consequence, with the likelihood and magnitude of each likely to increase with higher SRM Table 5. The greatest risks, posing potentially significant, even disastrous, consequences paired with moderate to high likelihood, are expected to be regional changes in precipitation patterns, especially the Asian monsoon (Krishnamohan and Bala 2022), and other unintended climate changes. Such surprises could result, for example, from unintended warming or excessive cooling due to uncertainty in estimates of the amount of SRM required or due to a sudden major volcanic eruption when SRM is already occurring (Table 5). The position of these risks in the matrix suggests that they warrant attention in future climate modelling research.

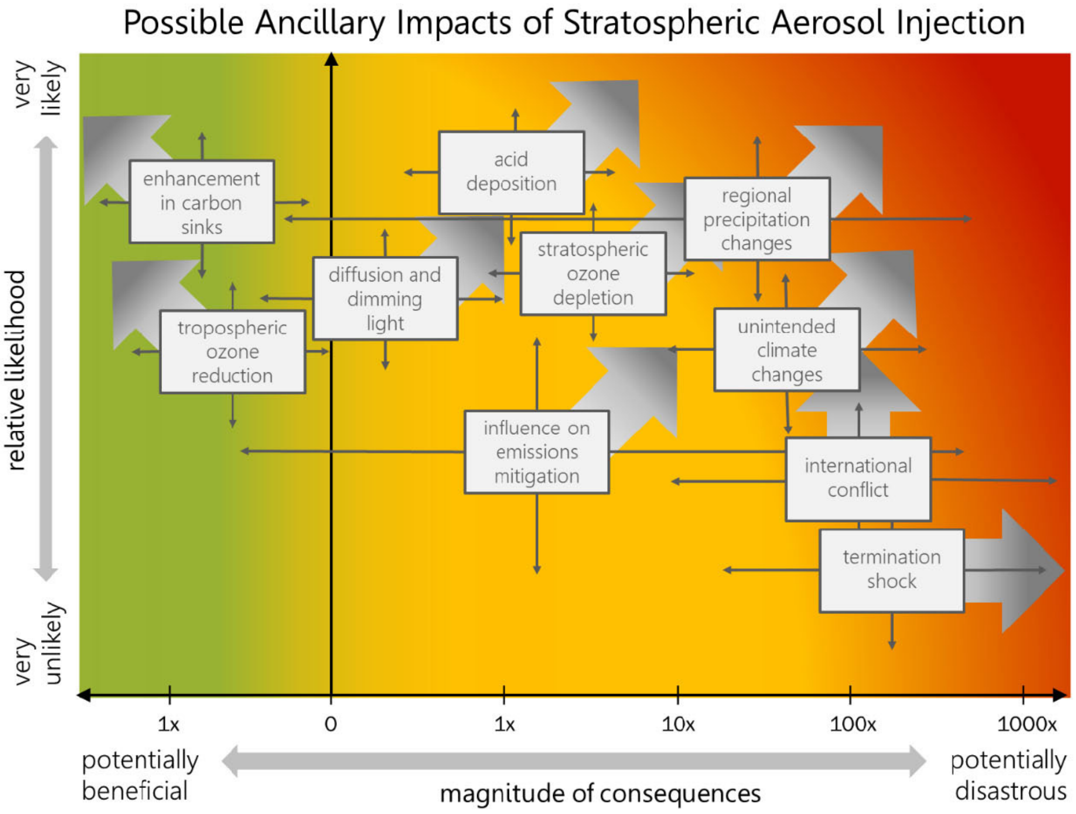

**Figure 3. A comparison of the relative likelihood and magnitude of consequences of the ancillary impacts of the SRM option SAI.** Boxes represent speculative estimates by the authors of the likelihood and consequences of impacts resulting from a “low” level of SAI (e.g., peak-shaving scenario), with “error bars” suggesting the extent of uncertainty in these estimates. Thick shaded arrows indicate the hypothesized direction and extent of the shift in likelihood and consequences associated with higher levels of SAI. With increasing application of SRM, many ancillary impacts might be hypothesized to increase, in either likelihood or magnitude of consequences, or both.

## 3.7. Correlated risks

To this point, this assessment of risk-risk tradeoffs has focused on whether the severity of multiple risks can be expected to increase or decrease in tandem according to the SRM strategy deployed (see Figure 2). Another, somewhat more subtle, issue is whether there might be joint increases or decreases across multiple risks due to common causes that are extrinsic to SRM deployment, or causal relations among risk factors—both within a given scenario and across multiple scenarios. This may be caused, for example, by 1) an uncertain biophysical effect of long-term SRM deployment that is propagated to multiple biophysical risk factors, 2) natural variability in the biophysical system that subsequently impacts multiple risk factors simultaneously, 3) an uncertain relationship between the biophysical system and more than one societal risk factor, and 4) uncertainty or variability in the sensitivity of humans and the environment to risk factors.

For example, SAI deployment is expected to warm the tropical lower stratosphere, which would impact the amount of water vapor (a greenhouse gas), counter the surface cooling, and affect ozone chemistry. Further, a change in tropical lower stratospheric heating will affect stratospheric circulation and the Arctic oscillation, potentially increasing Arctic spring ozone loss. Thus, if the effect of SAI on stratospheric heating is different than expected, if the influence of stratospheric heating on stratospheric dynamics and chemistry is of unexpected magnitude, or if there are unexpected health and environmental effects from ozone change, then multiple risk factors will be impacted simultaneously. Thus, the chance of extreme values or “tail risks” of any given SRM scenario may be much greater (or less) than currently anticipated.

Accounting for correlations among multiple risk factors within SRM scenarios is also essential for understanding the differences in levels of risk between scenarios (Reichert and Borsuk 2005). If a lack of scientific understanding or underlying natural variability in key climate factors affects the assessment of risk for different climate management strategies in a similar way, then the difference in risk levels between the two strategies may be clear, even if the absolute level of risk for either strategy is not easy to assess. In other words, even when faced with uncertainty in the details of particular risks, it is possible to assess with confidence whether a particular strategy increases or decreases risk relative to another strategy. It is similarly important to consider that many risks can change over time, possibly in parallel. This suggests that comparisons between strategies that focus on cumulative or net present value measures of risk may help to distinguish among alternative strategies.

## 3.8. Measuring outcomes to achieve different objectives

When considering SRM and other strategies for addressing climate change, it can be easy for decision-makers to get overwhelmed by the many uncertainties and risks of each. This is especially true when there are differing modes of action and points of potential impact, making the strategies appear incommensurate. In such a situation, it can be extremely difficult to identify an appropriate course of action. Such paralysis is often a symptom of excessive focus on predefined alternatives, rather than the motivating objectives, involved in a decision. A focus on alternatives leads to insufficient attention being paid to the link between imaginable courses of action and the fulfilment of underlying objectives. It also promotes the adoption of decision criteria that are not accurate indicators of objectives, but rather incomplete proxies, often dictated by the fixed set of alternatives. Finally, concentrating on alternatives encourages dichotomous (i.e., all-or-nothing) thinking about immediately available choices, rather than creative thinking about how to achieve diverse objectives in an integrative way.

On the other hand, giving primary attention to the objectives of a decision, referred to as *“value-focused thinking”* (Keeney 1992), can lead to the creation of more attractive options and the discovery of compromise-based strategies. This is because disparate decision-makers often hold the same objectives in a decision situation, even if they do not initially agree on the best course of action. Thus, encouraging decision-makers to be proactive about finding ways to achieve their shared objectives collectively can reduce controversy and conflict. This will be especially important in addressing climate change when different strategies may be preferable for different parties.

In the context of decision-making, an objective is something specific that we want to achieve, often with a “direction” associated with it (e.g., reduce poverty). Most decisions have multiple objectives, some of which may be inherently conflicting. When explicitly articulating objectives, it is important to distinguish between fundamental objectives and means objectives. Fundamental objectives are the true motivations behind the decision (e.g., reduce hunger) and provide the basis for ultimately evaluating the success of alternative courses of action. Means objectives, on the other hand, are not necessarily important in themselves, but only because they contribute to achieving the fundamental objectives. Often means objectives are tightly linked to specific decision alternatives (e.g., provide food aid) and thus cannot be reliably used as decision criteria. Thus, while it may be helpful to articulate means objectives, they should typically be recognized and then set aside in order to focus attention on the fundamental objectives.

It is also useful to acknowledge the role of goals. Unlike objectives, which can be accomplished to varying degrees, a goal is either achieved or not. Goals can be useful for clearly communicating a particular level of an objective to strive toward (e.g., zero hunger). However, as it is typically required to find compromises that only partially achieve the desired ends, objectives provide more useful metrics for evaluation than goals.

Given the many and diverse risks associated with climate change and potential response strategies, it may be useful to give greater attention to the fundamental objectives of climate change management. This would support consideration of the best overall strategy (or portfolio of strategies) for practically achieving those objectives, rather than sparking debates over what could be false dichotomies among strategies. This raises the question of whether there are already widely accepted goals or metrics that fit the conditions required to be suitable fundamental objectives. These conditions include: 1) relevant, meaning that they are of direct and quantifiable importance to decision-makers; 2) measurable, meaning that we can estimate specific levels of achievement, or at least construct a probability distribution over possible levels, for various courses of action; and 3) comprehensive, meaning that if we have measures of the levels of all objectives, we will then have a clear understanding of the success of a particular course of action.

### The Paris temperature goals

To date, scientists and policymakers have largely framed the objectives of international climate policy as achievement of the Paris temperature goals of 1.5 and 2.0°C above pre-industrial levels. This may be a convenient shorthand, as many biophysical effects are expected to track (or scale with) global temperature. However, there are many biophysical and socioeconomic impacts that do not scale linearly with temperature and many impacts will continue to occur even if a particular temperature target is met. Therefore, the Paris goals may not meet the criteria of suitable fundamental objectives. They are more akin to means objectives, as they function essentially as indirect proxies of the broad extent to which we might avoid more specific impacts.

### Specific climate impacts

The more specific impacts being encapsulated by the Paris goals are those identified in Table 4, including ice sheet melt, extreme temperatures and precipitation, sea level rise, and ocean acidification. Moderating each of these impacts are objectives that meet the second condition of being measurable. However, they are not comprehensive in that they do not directly capture the extent of social impacts incurred by climate change, including those on employment, poverty, and equity. Biophysical factors also do not meet the first condition, as by themselves are not of direct importance to policy makers, but rather are seen as being the causes of more immediate problems, such as the need for economic aid, social relocation, and infrastructure repair.

### Global social welfare or other economic measurements

Maximization of social welfare is the objective used in many integrated assessments of climate change and attempts to aggregate the many salient socioeconomic impacts, both direct and indirect, into a single metric of social desirability. When expressed in terms of equivalent change in GDP per capita or the social cost of carbon, this objective meets the criteria of being relevant and measurable. Further, this objective can be made more comprehensive by employing extensions that can accommodate preferences for inequality and risk. This is particularly relevant for decisions involving climate change that confront complex and unequally distributed risk-risk tradeoffs. Nevertheless, there are significant limitations in using maximization of social welfare as the primary objective of climate policy. Perhaps most importantly, the measure of social welfare relies on a set of detailed assumptions (e.g., time discounting, marginal utility of money, risk attitude, inequality aversion) that are difficult to make and yet embed huge implications for the assessed level of desirability of alternative states of the world. Further, the relative importance of various climate risks to different subpopulations (e.g., nations, tribes, communities, cultures), is unlikely to be uniformly reflected by monetary measures. The educational, vocational, psychological, and cultural impact of confronting any particular risk is highly context specific. A risk that might be collectively manageable to one community could be mutually devastating to another. For these reasons, a set of objectives that are more highly resolved than a single measure of social welfare is likely to be more productive.

### The Sustainable Development Goals (SDGs)

The United Nations' Sustainable Development Goal (SDG) framework may represent a leading source of objectives for use in formulating and evaluating climate change management strategies (WMO 2021). In particular, each of the 17 SDGs have specific *"outcome"* and *"means of implementation"* targets. While the latter have the characteristics of means objectives, the former are close to being fundamental objectives. Yet, by presenting aspirational levels of achievement, the targets reflect absolute goals rather than partially achievable objectives. Associated with each target, however, are one or more indicators intended to measure progress toward each target. These outcome indicators have all the properties required of fundamental objectives: they are relevant, measurable, and collectively comprehensive. For each policy option, there may be tradeoffs or synergies among the 17 SDGs (Pham-Truffert et al. 2020). We therefore suggest that they represent appropriate criteria for assessing the risk-risk tradeoffs involved in climate response management. These tradeoffs are depicted in Figure 4, with their relation to the SDGs as fundamental social objectives.

In a recent evaluation of SRM, Honegger, Michaelowa, and Pan (2021) come to a similar conclusion. As in this report, they assert that, *"It would be wrong to judge SRM solely by its potential to influence global average temperature. In fact, if this was the sole metric that mattered, SRM would already have been deployed... To be relevant, assessment of SRM therefore needs to enhance our understanding of potential effects across a multitude of socially relevant parameters, rather than a single one."*They therefore proceed to report on the results of a literature review, supplemented by expert elicitation, of the implications of SRM for the Sustainable Development Goals. The results highlight the many possible interactions between the direct damages of climate change, the potential direct impacts of SRM intended to limit climate change damages, the indirect physical, social, economic, and political impacts of both climate change and SRM, and the diverse objectives reflected by the SDGs. The authors argue that further consideration of SRM as part of a climate change response strategy needs to take place in a risk–risk context. This means not only evaluating the degree to which the various SDG outcome indicators are advanced, nor the potential conflicts that arise in advancing multiple indicators, but also the tradeoffs involved in attempting to control the risks of unexpected reversion of indicators. Accomplishing such an evaluation will require transdisciplinary, inclusive, and geographically diverse research that is attentive to local adaptive, resilience, and governance capacities.

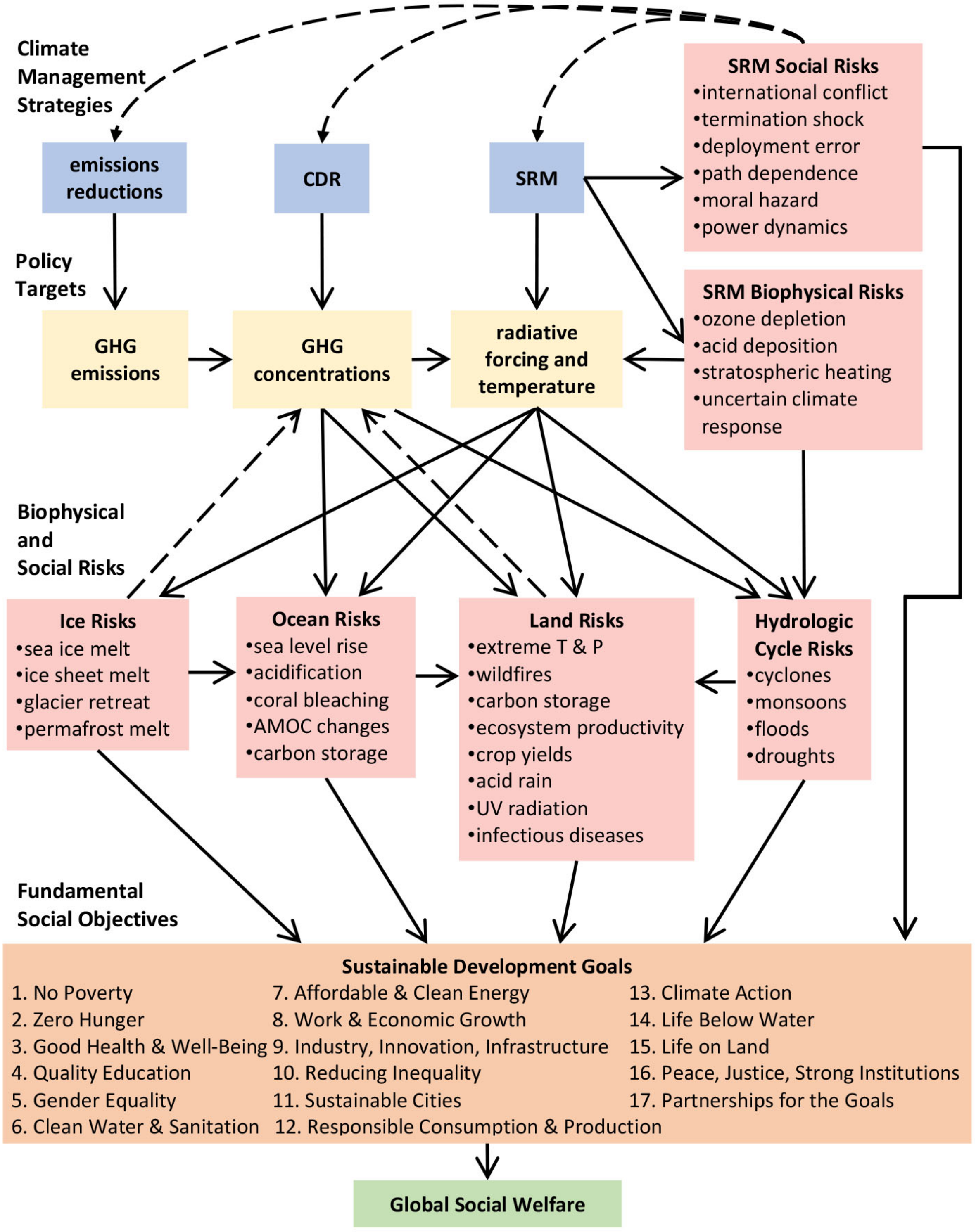

**Figure 4. Causal relations between climate management strategies, policy targets, biophysical and social risks, and fundamental social objectives.** Arrows represent causal influence; dashed arrows show feedback mechanisms

## 3.9. Decision making

If the SDG outcome target indicators are adopted as society's fundamental objectives in formulating a climate change response strategy, then one can work backwards from these objectives to proactively identify optimal courses of action. A starting point is to consider whether there is a course of action that would allow all objectives to be met simultaneously. This is rarely the case, but as a counterfactual, such a construct clarifies which objectives are in conflict and why. For example, climate change itself is clearly detrimental to many of the outcome targets of the SDGs. So a thought exercise would be to ask, "*Would mitigation, in the form of significant carbon dioxide emissions reductions, advance all the outcome targets (i.e., meet all our fundamental objectives)?"* Fujimori et al. (2020) address this question and find, at least for Asia, most, but not all, SDGs are advanced with mitigation. Further, the marginal emissions reduction values of SDG indicators are found to be ubiquitously less than 1, meaning that a 1% reduction in emissions can be expected to lead to less than a 1% improvement in SDG indicators. Additionally, many improvements in SDGs do not occur for decades after mitigation is well underway.

Alternatively, one can ask, *"Would SRM, if responsibly applied, advance all the SDG outcome targets?"* As SRM is expected to reduce global mean surface temperature relatively quickly, it would be expected to directly advance the outcome targets of the SDGs that are linked to temperature, weather extremes, and sea level rise. These include increases in food security and economic development (SDG 1 & 2), reductions in forced climate migration/climate refugees (1 & 8), improved equality among genders (5), peoples, and nations (10), and more sustainable economic growth and employment (8). Additionally, as co-benefits SRM in the form of SAI would create more diffuse light, possibly increasing the productivity of some agricultural yields and supporting the zero hunger and poverty SDGs (1 & 2).

Other targets, however, are subject to additional risks. For example, the potential disruptions in agriculture and fishing due to changes in precipitation and temperature impact the zero hunger and poverty SDGs (1 & 2). Increased acid deposition may negatively impact health and well-being (3), freshwater supplies and ecosystems (6), and marine resources (14). Finally, the differences in regional climates created by SRM deployment may decrease geopolitical security and lead to conflicts (16). A full comparison of how the SDGs may change under the three different SRM scenarios from Figure 1 is presented in the Supplementary Material, Table 6.

It is clear that all objectives cannot be achieved with either mitigation or SRM alone. Yet, the complementarity of the two strategies suggests that, if implemented together, the vast majority of SDGs could be advanced. Although highly uncertain, it may be that low or moderate SRM combined with high mitigation (our Scenario #1) could advance even further all the SDGs advanced by either alone, while limiting the negative impacts of acid deposition, unexpected changes in temperature and precipitation, and the risk of international conflict. The key remaining risk tradeoffs associated with SRM deployment include: the net health effects of fewer temperature extremes but potentially reduced stratospheric ozone and greater acid deposition (SDG 3), the net effect on marine resources (14) and freshwater systems (15) of reduced sea level rise and greater acid deposition, and the net effect on international conflict of reduced climate change but possible disagreement over SRM implementation. Of course, climate policies—such as emissions mitigation, CDR, adaptation and/or SRM—would not fully address all the SDGs; other actions would also be needed to advance them.

# 4. Governance

The potential for SRM to affect multiple risks raises the question of governance mechanisms to avoid negative impacts and enhance positive impacts. Because the multi-risk impacts of SRM may span multiple domains—such as global climate change, stratospheric ozone, regional climate and weather patterns, precipitation, SDGs, and international conflict—the appropriate governance mechanisms may also span several domains, time horizons, and different levels or scales of governance. Some of these governance mechanisms may already exist, but others may not yet and may need to be established.

## 4.1. Existing governance mechanisms that may address SRM risk-risk tradeoffs

Several existing governance mechanisms may be relevant to addressing the risk-risk tradeoffs posed by SRM. These are covered in Hubert (2020) and Reynolds (2020), and for further discussion see: (C2G 2021; Grieger et al. 2019; NASEM 2021; Reynolds 2019; Stavins et al. 2014, Sec. 13.4.4; Stavins and Stowe 2019; Burns, Dana, and Nicholson 2021; Weil 2021). The existence of such mechanisms does not necessarily imply their adequacy (and there are no current international mechanisms that could oversee the full risk-risk management approach advocated in this paper).

For example:

- The UN Framework Convention on Climate Change (UNFCCC), Article 4.1(f), calls on parties to undertake impact assessments of their climate policies and measures. Some national governments have impact assessment systems for regulatory and other policy making, but these may need to be adjusted to apply to decisions about SRM. And some national governments may not yet have well developed impact assessment systems.
- Other UNFCCC provisions may also be relevant to SRM, such as provisions on mitigation, adaptation, financial assistance, and loss and damage.
- The UN Convention on the Law of the Sea may apply to marine-based actions.
- The Convention on Biological Diversity (CBD) has in the past sought to address and restrain geoengineering activities that may affect biodiversity.
- The UN Convention on the Prohibition of Military or any Other Hostile Use of Environmental Modification Techniques (the ENMOD Convention) restricts “hostile” actions to modify the environment. Although SRM may have benevolent motivations, it could be that reckless disregard of the countervailing risks of SRM might rise to the type of actions addressed by the ENMOD Convention.
- The UN Convention on Environmental Impact Assessment in a Transboundary Context (under the UN Economic Commission for Europe, 1991) calls for parties to undertake environmental impact assessment, potentially including for SRM activities.
- The 1967 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), and the associated 1972 Convention on International Liability for Damage Caused by Space Objects, may apply to SRM activities if they are conducted in space (such as space mirrors, not analysed in thisreport), or if they use space satellites to monitor modification of the Earth’s atmosphere, or in other ways addressed by these treaties.
- The UN Security Council and related international security mechanisms and treaty organizations might address SRM activities that pose threats to the security of other nations or the international community. For example, perhaps the UN Security Council, if its members agreed (including its permanent members with veto power), might adopt resolutions and impose sanctions (even by military force) for unilateral SRM activities where they pose countervailing risks to international security.

- International human rights law might be applied to both the impacts of climate change (e.g., refugee migration) and the risks of SRM (e.g., regional climate impacts) (Citro and Taylor Smith 2021).

  Other international agreements and principles, and national laws, depending on the specific technique of SRM employed and its array of multiple risks.
- Non-state actors and social norms may also play a role in the broader governance of SRM. For example, non-state actors might help identify and alert others to unilateral SRM activities,for to the impacts of SRM on affected populations. As another example, societal norms among international epistemic networks of scientists (such as through codes of conduct) might share research on risk-risk tradeoffs of SRM and help constrain experiments that pose higher overall risk.

Basic principles of international treaty law rest on the sovereignty of states and their consent to be bound to international obligations. When the behaviours of sovereign states pose negative externalities, mutually-agreed informal and/or formal rules may be needed to govern those behaviours (which in turn regulate domestic entities—both state and non-state actors—within their jurisdiction). In the absence of international agreements on rules for the deployment of SRM, there may be customary international law rules or norms that are applicable to the decisions on the deployment of SRM technologies (Hubert 2020). These include a duty of international cooperation, a duty to prevent transboundary environmental harm, an obligation to do due diligence to prevent transboundary impacts, and a duty to exchange information, notify, and consult. In the absence of formal international rules for governing the deployment of SRM technologies, these customary international rules may provide a basis for at least discussing and shaping norms on SRM.

## 4.2. Potential governance gaps, conflicts, and options for additional governance mechanisms to address SRM risk-risk tradeoffs

Existing governance institutions aimed at mitigation of GHG emissions, such as the UNFCCC and its follow-on agreements, have attempted to mobilize collective action to deliver shared global benefits for present and future generations. These international regimes and associated domestic policies have sought to overcome the potential incentives for actors to avoid costly mitigation actions while free riding on the mitigation actions taken by others.

By contrast, governance of the risk-risk tradeoffs of SRM may involve the converse problem of restraining the incentives for actors to undertake hasty or unwise SRM projects. “Solar radiation management poses the converse of the collective action and governance challenges arising from emissions-reduction efforts: rather than mobilizing hesitant action to limit emissions, SRM governance involves restraining hasty unilateral action” (Stavins et al. 2014: 1023, Sec. 13.4.4).

Although the global community has developed successful treaties for addressing issues like stratospheric ozone depletion (e.g., the Montreal Protocol), that does not necessarily imply that it would be simple to develop similar treaties governing decisions for deploying SRM technologies. Many international or transboundary environmental issues are problems of overuse of common resources, and international rules are then developed to restrict the shared harms of these activities. The direct costs are largely born by the state where the activities occur, while the benefits are shared by all entities sharing the commons. Still these agreements are difficult to make and enforce.

By contrast, for the deployment of SRM technologies, the cost benefit calculation and distribution may be more complicated, because actors may face incentives not to free ride and wait for action by others, but rather to launch first (free driver or first mover incentives). Thus the challenge may be to restrain hasty or unwise or unilateral use of SRM (Stavins et al. 2014: 1023). The international agreements for this purpose may bear greater analogy to arms control agreements or non-proliferation regimes, with challenges of monitoring and restraining acquisition and deployment of technologies that are perceived as self-protective but also posing shared risks. And even if SRM is governed through multilateral consensus, there will remain questions of how much SRM to deploy to yield how much temperature change, and how to address those adversely affected.

Options for new governance mechanisms could include, e.g.:

- adding SRM provisions to the UNFCCC and/or its follow-on agreements,
- negotiating a new agreement on SRM, and
- establishing a new international body such as a global Solar Geoengineering Organization, as proposed in Reynolds (2019, ch. 13).

Any or all of these governance approaches would need to address key questions including how to decide: the desired degree of SRM, if any, to yield the desired temperature change; ways to prevent unwise deployment; the optimal timing of starting and ending any SRM; and ways to address those adversely affected by SRM (Victor 2008; Bodle 2010; Parson and Ernst 2013; Stavins et al. 2014: 1023; Reichwein et al. 2015; Reynolds 2019; Reynolds 2020; Grieger et al. 2019; Lin 2019; Stavins and Stowe 2019; Hubert 2020; C2G 2021; Burns, Dana, and Nicholson 2021; Florin 2021; NASEM 2021; Weil 2021).

To address the risks of SRM, such mechanisms could include requirements such as:

- multilateral, majoritarian, or consensus decision making on SRM
- commitments to "no first use" or unilateral deployment of SRM[8]
- commitments to avoid or minimize harm to those adversely affected by SRM
- liability and compensation for harms due to SRM
- impact assessment before testing or deployment—including use of the risk-risk framework
- commitments to advance notification of deployment
- means for the technical monitoring, reporting and verification (MRV) of SRM activities, and attributing any deployment to specific nations or actors, and attributing any impacts to specific SRM activities (the latter may be more difficult)
- agreements on transparency, data sharing, research cooperation
- a global communications network to determine and share information on whether suspected deployment has occurred, with what methods and impacts

One approach to achieve some or many of the above mechanisms could be a formal international governance framework for deciding and supervising the deployment of SRM technologies, e.g., Reynolds (2019, ch. 13). But it is not clear what type of international governance scheme could or would be built, and further research is needed (Aldy et al. 2021). Dai et al. (2021) compared climate experts' opinions on the research, governance, and deployment of SRM between the United States and China, asking 13 randomly selected IPCC experts from each country their preference on how the deployment of SRM technologies should be governed. Experts from both countries preferred an international governance scheme, but their preferred approaches differed. While the Chinese experts prefer an extension to the UNFCCC, the U.S. experts prefer a new form of UN treaty.

As experience with past international negotiations on subjects such as climate change and arms control indicates, reaching agreement—and effective monitoring and implementation—can be difficult. Monitoring, reporting and verification (MRV) can serve narrow or broad objectives, with a broader scope of MRV corresponding to greater attention to risk-risk effects (Wiener 2015).

---

[8] To the extent that SRM would reduce some risks and increase other risks—posing risk-risk tradeoffs—then governance of SRM could involve partial restrictions that seek to avoid its countervailing risks while fostering its target benefits and co-benefits. Governance options that lean all the way in either direction—to fully deploy large scale SRM, or to fully prohibit any SRM, e.g., Biermann et al. (2022)—could incur larger risk tradeoffs, and would be warranted only where the risks they prevent would dominate the risks they incur.

## 4.3. Ensuring that governance of SRM risk-risk tradeoffs is effective, efficient, fair, and transparent

Applying the risk-risk framework to SRM could help increase the likelihood that decisions on SRM are effective, efficient, fair, and transparent. By considering all important impacts, the risk-risk framework could help ensure that affected groups and interests are considered. As discussed above (section 2), key sources of undesired ancillary impacts are the “bounded decision” narrow cognitive focus and the “omitted voice” of those affected (Graham and Wiener 1995b; Sunstein 2000). A more comprehensive risk-risk analysis brings those impacts into consideration so that fair and inclusive decision processes may consider them. The risk-risk framework itself could be incorporated into a new international agreement, to ensure that the ancillary impacts of SRM are not treated with disregard (Stewart 2014; Wiener 2021).

# 5. Key insights

**(1) Employing a risk-risk framework in policy analysis and decision-making concerning SRM would enable a more comprehensive assessment, comparison, and management of risks associated with climate change, emissions reductions, CDR, adaptation, and SRM.** This risk-risk framework would include identifying and weighing impacts on the target risk, countervailing risks, and co-benefits, recognizing that they may interrelate in complex ways. The public and policymakers may encounter heuristics and biases that influence decision making, and a risk-risk framework can help strengthen deliberation addressing the full portfolio of important impacts. Attempts to identify measures that minimize overall risk can help reduce the single target risk but also limit or reduce multiple countervailing risks in concert.

**(2) The target risk that SRM seeks to address is the risk of climate change, taking into account the emission scenario and the effects of emissions reduction, CDR,** and adaptation. Depending on the policy pathway, these risks may be large.

**(3) As a target risk reduction strategy (along with emissions reductions, CDR, and adaptation), SRM deployment may have the potential to reduce climate risks, yielding large direct benefits to humans and natural ecosystems.** By reducing the global mean temperature increase (or by stabilizing temperature at a given target) SRM could potentially lessen the near-term damages of climate change and lower the chances of crossing irreversible climate tipping points.

**(4) SRM could pose countervailing risks to biophysical systems.** These could include (depending on the SRM approach) changes in stratospheric ozone and surface UV radiation, acid rain, and unintended climate changes such as altered temperature and precipitation patterns or excessive cooling. The level of many of these risks would be partially affected by the design and governance of an SRM deployment.

**(5) SRM could also pose countervailing risks to societal systems.** These could include (again depending on the approach) the risk of international conflict over deployment (especially in cases of ungoverned and unilateral deployment, the prospect or threat of deployment, or perceived harms between deployment and local/regional unexpected impacts), the risk of rapid climate change resulting from sudden termination (which is also a biophysical risk), and the risk that SRM could displace GHG emissions mitigation, among other concerns. Again, the level of many of these risks would be partially affected by the design and governance of an SRM deployment.

**(6) SRM could present some co-benefits.** The co-benefits of some SRM approaches may include an increase in diffuse solar radiation (sunlight), which may be beneficial to some ecosystems and crops, and slightly reduced tropospheric ozone in the mid and high latitudes. However, these uncertain effects are likely to be small and are not expected to play a significant role in weighing risk-risk tradeoffs.

**(7) Policymaking regarding SRM should compare its effects on multiple risks (including target risk reductions, co-benefits, and countervailing harms), as part of a policy portfolio that also takes into account emissions reductions, CDR, and adaptation.** These interconnected effects should be assessed in terms of their likelihood, impact, timing, uncertainty, distribution, and related factors.

**(8) Different levels of SRM may pose different implications for overall risk depending on the technology, its deployment, and governance.** Higher levels of SRM may be expected to yield greater decreases in temperature-associated climate target risks, but also increases in SRM's own countervailing risks. The particular levels and response patterns of target and countervailing risks to varying levels of SRM would depend on the SRM technology, deployment strategy, and governance mechanisms employed. It is possible that the level of SRM that minimizes total risk may be a low-to-intermediate level of deployment designed to avoid the worst near-term climate impacts by shaving the peak warming while GHG emissions mitigation and CDR efforts take effect.

**(9) As larger GHG emissions reductions, CDR, and adaptation reduce overall risks, the less need there may be for SRM with its countervailing risks, thereby reducing overall risk exposure (subject to any countervailing risks of emissions mitigation options).** Further attention must be given to the interdependence among multiple risks that can be created by shared causes or policy interactions.

**(10) Risk-risk analysis can help focus climate change risk management on broader societal objectives, rather than on temperature goals alone.** While temperature goals may be an important objective, there are many climate impacts that do not scale directly with temperature, and many other ancillary risks beyond climate. The indicators used to evaluate the United Nations' Sustainable Development Goals (SDGs) offer measures of well-being that may be used to evaluate the multiple risks of SRM. This report presents a preliminary evaluation of how three hypothetical risk management portfolios supplementing GHG emissions mitigation, CDR, and adaptation with SRM might be expected to impact attainment of the SDGs relative to not using SRM.

**(11) New governance institutions or mechanisms may be needed to restrain harmful or unjust use of SRM, ensure that any deployment is beneficial and just, and assess and minimize any countervailing harms.** Existing international governance aimed at addressing climate change and its impacts may offer some useful mechanisms, but currently appears to be inadequately designed for addressing SRM and its distinctive characteristics. As an attempt to restrain the imposition of global risks through hasty or unwise action, governance of SRM may be more analogous to arms control agreements than environmental treaties.

# References

Abatayo, Anna Lou, Valentina Bosetti, Marco Casari, Riccardo Ghidoni, and Massimo Tavoni. 2020. 'Solar geoengineering may lead to excessive cooling and high strategic uncertainty', Proceedings of the National Academy of Sciences, 117: 13393-98.

Ahlm, L., A. Jones, C. W. Stjern, H. Muri, B. Kravitz, and J. E. Kristjánsson. 2017. 'Marine cloud brightening – as effective without clouds', Atmospheric Chemistry and Physics, 17: 13071-87.

Aldy, Joseph E., Tyler Felgenhauer, William A. Pizer, Massimo Tavoni, Mariia Belaia, Mark E. Borsuk, Arunabha Ghosh, Garth Heutel, Daniel Heyen, Joshua Horton, David Keith, Christine Merk, Juan Moreno-Cruz, Jesse L. Reynolds, Katharine Ricke, Wilfried Rickels, Soheil Shayegh, Wake Smith, Simone Tilmes, Gernot Wagner, and Jonathan B. Wiener. 2021. 'Social science research to inform solar geoengineering', Science, 374: 815-18.

Aldy, Joseph, Matthew Kotchen, Mary Evans, Meredith Fowlie, Arik Levinson, and Karen Palmer. 2020. 'Deep flaws in a mercury regulatory analysis', Science, 368: 247-48.

Alterskjær, K., and J. E. Kristjánsson. 2013. 'The sign of the radiative forcing from marine cloud brightening depends on both particle size and injection amount', Geophysical Research Letters, 40: 210-15.

Alterskjær, Kari, Jón Egill Kristjánsson, Olivier Boucher, Helene Muri, Ulrike Niemeier, Hauke Schmidt, Michael Schulz, and Claudia Timmreck. 2013. 'Sea-salt injections into the low-latitude marine boundary layer: The transient response in three Earth system models', Journal of Geophysical Research: Atmospheres, 118: 12,195-12,206.

Anastas, Paul T., and Julie B. Zimmerman. 2019. 'Environmental Protection through Systems Design, Decision-Making, and Thinking.' in Daniel C. Esty (ed.), A Better Planet: Forty Big Ideas for a Sustainable Future (Yale University Press).

Aquila, V., C. I. Garfinkel, P.A. Newman, L.D. Oman, and D.W. Waugh. 2014. 'Modifications of the quasi-biennial oscillation by a geoengineering perturbation of the stratospheric aerosol layer', Geophysical Research Letters, 41: 1738-44.

Aswathy, V. N., O. Boucher, M. Quaas, U. Niemeier, H. Muri, J. Mülmenstädt, and J. Quaas. 2015. 'Climate extremes in multi-model simulations of stratospheric aerosol and marine cloud brightening climate engineering', Atmospheric Chemistry and Physics, 15: 9593-610.

Bala, G., Ken Caldeira, Rama Nemani, Long Cao, George Ban-Weiss, and Ho-Jeong Shin. 2011. 'Albedo enhancement of marine clouds to counteract global warming: impacts on the hydrological cycle', Climate Dynamics, 37: 915-31.

Bala, Govindasamy, Ken Caldeira, and R Nemani. 2010. 'Fast versus slow response in climate change: implications for the global hydrological cycle', Climate Dynamics, 35: 423-34.

Baldwin, Robert. 2017. 'Regulatory excellence and lucidity.' in Cary Coglianese (ed.), Achieving Regulatory Excellence (Brookings Institution Press: Washington, DC).

Barrett, Scott. 2008. 'The Incredible Economics of Geoengineering', Environmental and Resource Economics, 39: 45-54.

Baughman, E., A. Gnanadesikan, A. Degaetano, and A. Adcroft. 2012. 'Investigation of the Surface and Circulation Impacts of Cloud-Brightening Geoengineering', Journal of Climate, 25: 7527-43.

Bickel, J. Eric. 2013. 'Climate engineering and climate tipping-point scenarios', Environment Systems & Decisions, 33: 152-67.

Biermann, Frank, Jeroen Oomen, Aarti Gupta, Saleem H. Ali, Ken Conca, Maarten A. Hajer, Prakash Kashwan, Louis J. Kotzé, Melissa Leach, Dirk Messner, Chukwumerije Okereke, Åsa Persson, Janez Potočnik, David Schlosberg, Michelle Scobie, and Stacy D. VanDeveer. 2022. 'Solar geoengineering: The case for an international non-use agreement', WIREs Climate Change: e754.

Bluth, Gregg J. S., Scott D. Doiron, Charles C. Schnetzler, Arlin J. Krueger, and Louis S. Walter. 1992. 'Global tracking of the $SO_2$ clouds from the June, 1991 Mount Pinatubo eruptions', Geophysical Research Letters, 19: 151-54.

Bodle, Ralph. 2010. 'Geoengineering and International Law: The Search for Common Legal Ground', Tulsa Law Review, 46: 305-22.

Burns, Wil, David Dana, and Simon James Nicholson (ed.) 2021. Climate Geoengineering: Science, Law and Governance (Springer Nature: Cham, Switzerland).

Burton, C., R. A. Betts, C. D. Jones, and K. Williams. 2018. 'Will Fire Danger Be Reduced by Using Solar Radiation Management to Limit Global Warming to 1.5 °C Compared to 2.0 °C?', Geophysical Research Letters, 45: 3644-52.

C2G. 2021. "C2G Evidence Brief. Stratospheric Aerosol Injection and its Governance." New York, NY: Carnegie Climate Governance Initiative (C2G).

Canadell, J.G., P.M.S. Monteiro, M.H. Costa, L. Cotrim da Cunha, P.M. Cox, A.V. Eliseev, S. Henson, M. Ishii, S. Jaccard, C. Koven, A. Lohila, P.K. Patra, S. Piao, J. Rogelj, S. Syampungani, S. Zaehle, and K. Zickfeld. 2021. 'Global Carbon and other Biogeochemical Cycles and Feedbacks.' in V. Masson-Delmotte, P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu and B. Zhou (eds.), 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. In Press).

Carlson, Colin J., and Christopher H. Trisos. 2018. 'Climate engineering needs a clean bill of health', Nature Climate Change, 8: 843-45.

Cater, Charles. 2021. "Toward New Policies for the Climate Change and Violent Extremism Nexus in Africa." In Extremism InFocus. United Nations Development Programme (UNDP), Regional Service Centre for Africa, Oslo Governance Centre.

Chalecki, Elizabeth L. 2021. "When Assessing Geopolitical Risks of Geoengineering, Don’t Assume the Future Will Look Like the Past." In The Internationalist. New York, NY: Council on Foreign Relations.

Chen, D., M. Rojas, B.H. Samset, K. Cobb, A. Diongue Niang, P. Edwards, S. Emori, S.H. Faria, E. Hawkins, P. Hope, P. Huybrechts, M. Meinshausen, S.K. Mustafa, G.-K. Plattner, and A.-M. Tréguier. 2021. 'Framing, Context, and Methods.' in V. Masson-Delmotte, P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu and B. Zhou (eds.), 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. In Press).

Chen, Y. C., M. W. Christensen, L. Xue, A. Sorooshian, G. L. Stephens, R. M. Rasmussen, and J. H. Seinfeld. 2012. 'Occurrence of lower cloud albedo in ship tracks', Atmos. Chem. Phys., 12:8223-35.

Chen, Yating, Aobo Liu, and John C. Moore. 2020. 'Mitigation of Arctic permafrost carbon loss through stratospheric aerosol geoengineering', Nature Communications, 11: 2430.

Cheng, Wei, Douglas G. MacMartin, Katherine Dagon, Ben Kravitz, Simone Tilmes, Jadwiga H. Richter, Michael J. Mills, and Isla R. Simpson. 2019. 'Soil Moisture and Other Hydrological Changes in a Stratospheric Aerosol Geoengineering Large Ensemble', Journal of Geophysical Research: Atmospheres, 124: 12773-93.

Citro, Brian, and Patrick Taylor Smith. 2021. 'A Human Rights Framework for Climate Engineering: A Response to the Limits of Cost-Benefit Analysis.' in Wil Burns, David Dana and Simon James Nicholson (eds.), Climate Geoengineering: Science, Law and Governance (Springer International Publishing: Switzerland).

Climate Action Tracker. 2021. "Glasgow's 2030 credibility gap: net zero's lip service to climate action. Wave of net zero emissions goals not matched by action on the ground." In Warming Projections Global Update. Climate Analytics and NewClimate Institute.

Corry, Olaf. 2017. 'The international politics of geoengineering: The feasibility of Plan B for tackling climate change', Security Dialogue, 48: 297-315.

Crook, J. A., L. S. Jackson, S. M. Osprey, and P. M. Forster. 2015. 'A comparison of temperature and precipitation responses to different Earth radiation management geoengineering schemes', Journal of Geophysical Research: Atmospheres, 120: 9352-73.

Da-Allada, C. Y., E. Baloïtcha, E. A. Alamou, F. M. Awo, F. Bonou, Y. Pomalegni, E. I. Biao, E. Obada, J. E. Zandagba, S. Tilmes, and P. J. Irvine. 2020. 'Changes in West African Summer Monsoon Precipitation Under Stratospheric Aerosol Geoengineering', Earth's Future, 8: e2020EF001595.

Dai, Zhen, Elizabeth T. Burns, Peter J. Irvine, Dustin H. Tingley, Jianhua Xu, and David W. Keith. 2021. 'Elicitation of US and Chinese expert judgments show consistent views on solar geoengineering', Humanities and Social Sciences Communications, 8: 18.

Davies, Gareth. 2010. 'Framing the Social, Political, and Environmental Risks and Benefits of Geoengineering: Balancing the Hard-to-Imagine Against the Hard-to-Measure', Tulsa Law Review, 46: 261-82.

de Coninck, H., A. Revi, M. Babiker, P. Bertoldi, M. Buckeridge, A. Cartwright, W. Dong, J. Ford, S. Fuss, J.C. Hourcade, D. Ley, R. Mechler, P. Newman, A. Revokatova, S. Schultz, L. Steg, and T. Sugiyama. 2018. 'Strengthening and implementing the global response.' in V. Masson-Delmotte, P. Zhai, H. O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor and T. Waterfield (eds.), Global warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty (in press).

Duan, Lei, Long Cao, Govindasamy Bala, and Ken Caldeira. 2020. 'A Model-Based Investigation of Terrestrial Plant Carbon Uptake Response to Four Radiation Modification Approaches', Journal of Geophysical Research: Atmospheres, 125: e2019JD031883.

Dudley, S.E., and B.F. Mannix. 2018. 'Improving Regulatory Benefit-Cost Analysis', Journal of Law & Politics, XXXIV: 1-20.

Effiong, Utibe, and Richard L. Neitzel. 2016. 'Assessing the direct occupational and public health impacts of solar radiation management with stratospheric aerosols', Environmental Health, 15: 7.

Eichler, Hans-Georg, Brigitte Bloechl-Daum, Daniel Brasseur, Alasdair Breckenridge, Hubert Leufkens, June Raine, Tomas Salmonson, Christian K. Schneider, and Guido Rasi. 2013. 'The risks of risk aversion in drug regulation', Nature Reviews Drug Discovery, 12: 907-16.

Evans, J.R.G., E.P.J. Stride, M.J. Edirisinghe, D.J. Andrews, and R.R. Simons. 2010. 'Can oceanic foams limit global warming?', Climate Research, 42: 155-60.

F. Schipper, E. Lisa, and Ian Burton (ed.) 2009. The Earthscan Reader on Adaptation to Climate Change (Earthscan: London, UK).

Fabre, Adrien, and Gernot Wagner. 2020. "Risky Geoengineering Option Can Make An Ambitious Climate Mitigation Agreement More Likely." In NYU Wagner Research Paper. New York, NY: NYU.

Fan, Yuanchao, Jerry Tjiputra, Helene Muri, Danica Lombardozzi, Chang-Eui Park, Shengjun Wu, and David Keith. 2021. 'Solar geoengineering can alleviate climate change pressures on crop yields', Nature Food, 2: 373-81.

Fang, Bo, and Jianhua Xu. 2013. 'Introducing a Risk-Risk Tradeoff Analysis into the Policy-making Process', China Public Administration Review, 14: 9-25.

Fasullo, John T., Simone Tilmes, Jadwiga H. Richter, Ben Kravitz, Douglas G. MacMartin, Michael J. Mills, and Isla R. Simpson. 2018. 'Persistent polar ocean warming in a strategically geoengineered climate', Nature Geoscience, 11: 910-14.

Felgenhauer, Tyler. 2015. 'Addressing the limits to adaptation across four damage–response systems', Environmental Science & Policy, 50: 214-24.

Felgenhauer, Tyler, Joshua Horton, and David Keith. 2021. 'Solar geoengineering research on the U.S. policy agenda: when might its time come?', Environmental Politics: 1-21.

Ferraro, A. J., E. J. Highwood, and A. J. Charlton-Perez. 2011. 'Stratospheric heating by potential geoengineering aerosols', Geophysical Research Letters, 38.

Field, L., D. Ivanova, S. Bhattacharyya, V. Mlaker, A. Sholtz, R. Decca, A. Manzara, D. Johnson, E. Christodoulou, P. Walter, and K. Katuri. 2018. 'Increasing Arctic Sea Ice Albedo Using Localized Reversible Geoengineering', Earth's Future, 6: 882-901.

Florin, Marie-Valentine. 2021. "Using stratospheric aerosol injection to alleviate global warming: When?" In Spotlight on Risk. Lausanne, Switzerland: International Risk Governance Council (IRGC).

Fujimori, Shinichiro, Tomoko Hasegawa, Kiyoshi Takahashi, Hancheng Dai, Jing-Yu Liu, Haruka Ohashi, Yang Xie, Yanxu Zhang, Tetsuya Matsui, and Yasuaki Hijioka. 2020. 'Measuring the sustainable development implications of climate change mitigation', Environmental Research Letters, 15: 085004.

Gasparini, B., S. Münch, L. Poncet, M. Feldmann, and U. Lohmann. 2017. 'Is increasing ice crystal sedimentation velocity in geoengineering simulations a good proxy for cirrus cloud seeding?', Atmospheric Chemistry and Physics, 17: 4871-85.

Gasparini, Blaž, and Ulrike Lohmann. 2016. 'Why cirrus cloud seeding cannot substantially cool the planet', Journal of Geophysical Research: Atmospheres, 121: 4877-93.

Ghosh, S., A. Sharma, S. Arora, and G. Desouza. 2016. 'A geoengineering approach toward tackling tropical cyclones over the Bay of Bengal', Atmospheric Science Letters, 17: 208-15.

Govindasamy, Bala, and Ken Caldeira. 2000. 'Geoengineering Earth's radiation balance to mitigate CO2-induced climate change', Geophysical Research Letters, 27: 2141-44.

Graham, J.D., J.B. Wiener, and L.A. Robinson. forthcoming 2022. 'Co-Benefits, Countervailing Risks, and Cost-Benefit Analysis.' in Dennis J. Paustenbach (ed.), Human and Ecological Risk Assessment: Theory and Practice (John Wiley & Sons).

Graham, John D., Sue J. Goldie, Maria Segui-Gomez, Kimberly M. Thompson, Toben Nelson, Roberta Glass, Ashley Simpson, and Leo G. Woerner. 1998. 'Reducing Risks to Children in Vehicles With Passenger Airbags', Pediatrics, 102: e3-e3.

Graham, John D., and Jonathan Baert Wiener. 1995a. 'Confronting Risk Tradeoffs.' in John D. Graham and Jonathan Baert Wiener (eds.), Risk vs. Risk: Tradeoffs in Protecting Health and the Environment (Harvard University Press: Cambridge, MA).

Graham, John D., and Jonathan Baert Wiener. (ed.) 1995b. Risk vs. Risk: Tradeoffs in Protecting Health and the Environment (Harvard University Press: Cambridge, MA).

Grieger, Khara D., Tyler Felgenhauer, Ortwin Renn, Jonathan Wiener, and Mark Borsuk. 2019. 'Emerging risk governance for stratospheric aerosol injection as a climate management technology', Environment Systems and Decisions.

Hammad, Tarek A., Melanie Parikh, Nour Tashtish, Cynthia M. Lowry, Diane Gorbey, Farshad Forouzandeh, Steven J. Filby, William M. Wolf, Marco A. Costa, Daniel I. Simon, and Mehdi H. Shishehbor. 2021. 'Impact of COVID-19 pandemic on ST-elevation myocardial infarction in a non-COVID-19 epicenter', Catheterization and Cardiovascular Interventions, 97: 208-14.

Harrison, Nicholas, Janos Pasztor, and Kai-Uwe Barani Schmidt. 2021. "A risk-risk assessment framework for solar radiation modification." In. Lausanne, Switzerland: International Risk Governance Center (IRGC).

Heyen, Daniel, Joshua Horton, and Juan Moreno-Cruz. 2019. 'Strategic implications of counter-geoengineering: Clash or cooperation?', Journal of Environmental Economics and Management, 95: 153-77.

Hill, Spencer, and Yi Ming. 2012. 'Nonlinear climate response to regional brightening of tropical marine stratocumulus', Geophysical Research Letters, 39.

Honegger, Matthias. 2020. 'Addressing risks and trade-offs in governance.' in Marie-Valentine Florin, Paul Rouse, Anna-Maria Hubert, Matthias Honegger and Jesse Reynolds (eds.), International governance issues on climate engineering: Information for policymakers (EPFL, International Risk Governance Center (IRGC): Lausanne, Switzerland).

Honegger, Matthias, Axel Michaelowa, and Jiahua Pan. 2021. 'Potential implications of solar radiation modification for achievement of the Sustainable Development Goals', Mitigation and Adaptation Strategies for Global Change, 26: 21.

Horowitz, Hannah M., Christopher Holmes, Alicia Wright, Tomás Sherwen, Xuan Wang, Mat Evans, Jiayue Huang, Lyatt Jaeglé, Qianjie Chen, Shuting Zhai, and Becky Alexander. 2020. 'Effects of Sea Salt Aerosol Emissions for Marine Cloud Brightening on Atmospheric Chemistry: Implications for Radiative Forcing', Geophysical Research Letters, 47: e2019GL085838.

Horton, Joshua, and David Keith. 2021. "Can Solar Geoengineering Be Used as a Weapon?" In The Internationalist. New York, NY: Council on Foreign Relations.

Hubert, Anna-Maria. 2020. 'International legal and institutional arrangements relevant to the governance of climate engineering technologies.' in Marie-Valentine Florin, Paul Rouse, Anna-Maria Hubert, Matthias Honegger and Jesse Reynolds (eds.), International governance issues on climate engineering: Information for policymakers (EPFL, International Risk Governance Center (IRGC): Lausanne, Switzerland).

IAEG-SDGs. 2017. "Global indicator framework for the Sustainable Development Goals and targets of the 2030 Agenda for Sustainable Development." In, edited by Inter-Agency and Expert Group on SDG Indicators (IAEG-SDGs). New York, NY: United Nations Statistics Division (UNSD), Department of Economic and Social Affairs (DESA).

IPCC. 2013. Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (Cambridge University Press: Cambridge, UK and New York, NY).

IPCC. 2014. Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC: Geneva, Switzerland).

IPCC. 2018. Global warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty.

IPCC. 2019a. Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems (in press).

IPCC. 2019b. IPCC Special Report on the Ocean and Cryosphere in a Changing Climate.

IPCC. 2021a. 'Annex VII: Glossary.' in J.B.R. Matthews, J. S. Fuglestvedt, V. Masson-Delmotte, V. Möller, C. Méndez, R. van Diemen, A. Reisinger and S. Semenov (eds.), Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (Cambridge University Press).

IPCC. 2021b. 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, in press: Cambridge, UK).

IPCC. 2021c. 'Summary for Policymakers.' in V. Masson-Delmotte, P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu and B. Zhou (eds.), 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: Cambridge, UK).

Irvine, P. J., D. W. Keith, and J. Moore. 2018. 'Brief communication: Understanding solar geoengineering's potential to limit sea level rise requires attention from cryosphere experts', The Cryosphere, 12: 2501-13.

Irvine, Peter, Kerry Emanuel, Jie He, Larry W. Horowitz, Gabriel Vecchi, and David Keith. 2019. 'Halving warming with idealized solar geoengineering moderates key climate hazards', Nature Climate Change.

Irvine, Peter J., and David W. Keith. 2020. 'Halving warming with stratospheric aerosol geoengineering moderates policy-relevant climate hazards', Environmental Research Letters, 15: 044011.

Jones, Andy, Jim Haywood, and Olivier Boucher. 2011. 'A comparison of the climate impacts of geoengineering by stratospheric SO2 injection and by brightening of marine stratocumulus cloud', Atmospheric Science Letters, 12: 176-83.

Jones, Andy, Jim M. Haywood, Kari Alterskjær, Olivier Boucher, Jason N. S. Cole, Charles L. Curry, Peter J. Irvine, Duoying Ji, Ben Kravitz, Jón Egill Kristjánsson, John C. Moore, Ulrike Niemeier, Alan Robock, Hauke Schmidt, Balwinder Singh, Simone Tilmes, Shingo Watanabe, and Jin-Ho Yoon. 2013. 'The impact of abrupt suspension of solar radiation management (termination effect) in experiment G2 of the Geoengineering Model Intercomparison Project (GeoMIP)', Journal of Geophysical Research: Atmospheres, 118: 9743-52.

Jones, Anthony C., Matthew K. Hawcroft, James M. Haywood, Andy Jones, Xiaoran Guo, and John C. Moore. 2018. 'Regional Climate Impacts of Stabilizing Global Warming at 1.5 K Using Solar Geoengineering', Earth's Future, 6: 230-51.

Kahn, Matthew E. 2010. Climatopolis: How Our Cities will Thrive in the Hotter Future (Basic Books: New York, NY).

Kahneman, Daniel. 2011. Thinking, Fast and Slow (Farrar, Straus and Giroux: New York, NY).

Kalidindi, Sirisha, Govindasamy Bala, Angshuman Modak, and Ken Caldeira. 2015. 'Modeling of solar radiation management: a comparison of simulations using reduced solar constant and stratospheric sulphate aerosols', Climate Dynamics, 44: 2909-25.

Keeney, Ralph L. . 1992. Value-Focused Thinking: A Path to Creative Decisionmaking (Harvard

University Press: Cambridge, MA).

Keith, David, Oliver Morton, Yomay Shyur, Pete Worden, and Robin Wordsworth. 2020. "Reflections on a Meeting About Space-Based Solar Geoengineering." In SGR Blog, edited by Holly Buck, Peter Irvine, Ben Kravitz, Andy Parker and Gernot Wagner. Cambridge, MA.

Keith, David W. 2010. 'Photophoretic levitation of engineered aerosols for geoengineering', Proceedings of the National Academy of Sciences, 107: 16428-31.

Keith, David W. 2017. "Toward a Responsible Solar Geoengineering Research Program." In Issues in Science and Technology.

Keith, David W. 2021. 'Toward constructive disagreement about geoengineering', Science, 374: 812-15.

Keith, David W., and Douglas G. MacMartin. 2015. 'A temporary, moderate and responsive scenario for solar geoengineering', Nature Climate Change, 5: 201-06.

Keith, David W., Gernot Wagner, and Claire L. Zabel. 2017. 'Solar geoengineering reduces atmospheric carbon burden', Nature Climate Change, 7: 617-19.

Keith, David W., Debra K. Weisenstein, John A. Dykema, and Frank N. Keutsch. 2016. 'Stratospheric solar geoengineering without ozone loss', Proceedings of the National Academy of Sciences, 113: 14910-14.

Koubi, Vally. 2019. 'Climate Change and Conflict', Annual Review of Political Science, 22: 343-60.

Koutsakos, Marios, Adam K. Wheatley, Karen Laurie, Stephen J. Kent, and Steve Rockman. 2021. 'Influenza lineage extinction during the COVID-19 pandemic?', Nature Reviews Microbiology.

Kravitz, B., P. J. Rasch, H. Wang, A. Robock, C. Gabriel, O. Boucher, J. N. S. Cole, J. Haywood, D. Ji, A. Jones, A. Lenton, J. C. Moore, H. Muri, U. Niemeier, S. Phipps, H. Schmidt, S. Watanabe, S. Yang, and J. H. Yoon. 2018. 'The climate effects of increasing ocean albedo: an idealized representation of solar geoengineering', Atmospheric Chemistry and Physics, 18: 13097-113.

Kravitz, B., A. Robock, S. Tilmes, O. Boucher, J. M. English, P. J. Irvine, A. Jones, M. G. Lawrence, M. MacCracken, H. Muri, J. C. Moore, U. Niemeier, S. J. Phipps, J. Sillmann, T. Storelvmo, H. Wang, and S. Watanabe. 2015. 'The Geoengineering Model Intercomparison Project Phase 6 (GeoMIP6): simulation design and preliminary results', Geoscientific Model Development, 8: 3379-92.

Kravitz, Ben, Douglas G. MacMartin, and Ken Caldeira. 2012. 'Geoengineering: Whiter skies?', Geophysical Research Letters, 39.

Kravitz, Ben, Douglas G. MacMartin, Michael J. Mills, Jadwiga H. Richter, Simone Tilmes, Jean-Francois Lamarque, Joseph J. Tribbia, and Francis Vitt. 2017. 'First Simulations of Designing Stratospheric Sulfate Aerosol Geoengineering to Meet Multiple Simultaneous Climate Objectives', Journal of Geophysical Research: Atmospheres, 122: 12,616-12,634.

Kravitz, Ben, Alan Robock, Luke Oman, Georgiy Stenchikov, and Allison B. Marquardt. 2009. 'Sulfuric acid deposition from stratospheric geoengineering with sulfate aerosols', Journal of Geophysical Research: Atmospheres, 114.

Kravitz, Ben, Alan Robock, Drew T. Shindell, and Mark A. Miller. 2012. 'Sensitivity of stratospheric geoengineering with black carbon to aerosol size and altitude of injection', Journal of Geophysical Research: Atmospheres, 117.

Krendl, Anne C, and Brea L Perry. 2020. 'The Impact of Sheltering in Place During the COVID-19 Pandemic on Older Adults’ Social and Mental Well-Being', The Journals of Gerontology: Series B, 76: e53-e58.

Krishnamohan, K. S., and Govindasamy Bala. 2022. 'Sensitivity of tropical monsoon precipitation to the latitude of stratospheric aerosol injections', Climate Dynamics.

Krishnamohan, K.P.S.P., G. Bala, L. Cao, L. Duan, and K. Caldeira. 2019. 'Climate system response to stratospheric sulfate aerosols: sensitivity to altitude of aerosol layer', Earth System Dynamics, 10: 885-900.

Kunreuther, Howard, Geoffrey Heal, Myles Allen, Ottmar Edenhofer, Christopher B. Field, and Gary Yohe. 2013. 'Risk management and climate change', Nature Climate Change, 3: 447.

Kwiatkowski, Lester, Peter Cox, Paul R. Halloran, Peter J. Mumby, and Andy J. Wiltshire. 2015. 'Coral bleaching under unconventional scenarios of climate warming and ocean acidification', Nature Climate Change, 5: 777-81.

Laakso, A., H. Kokkola, A. I. Partanen, U. Niemeier, C. Timmreck, K. E. J. Lehtinen, H. Hakkarainen, and H. Korhonen. 2016. 'Radiative and climate impacts of a large volcanic eruption during stratospheric sulfur geoengineering', Atmospheric Chemistry and Physics, 16: 305-23.

Latham, John, Keith Bower, Tom Choularton, Hugh Coe, Paul Connolly, Gary Cooper, Tim Craft, Jack Foster, Alan Gadian, Lee Galbraith, Hector Iacovides, David Johnston, Brian Launder, Brian Leslie, John Meyer, Armand Neukermans, Bob Ormond, Ben Parkes, Phillip Rasch, John Rush, Stephen Salter, Tom Stevenson, Hailong Wang, Qin Wang, and Rob Wood. 2012. 'Marine cloud brightening', Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, 370: 4217-62.

Latham, John, Joan Kleypas, Rachel Hauser, Ben Parkes, and Alan Gadian. 2013. 'Can marine cloud brightening reduce coral bleaching?', Atmospheric Science Letters, 14: 214-19.

Latham, John, Ben Parkes, Alan Gadian, and Stephen Salter. 2012. 'Weakening of hurricanes via marine cloud brightening (MCB)', Atmospheric Science Letters, 13: 231-37.

Lawrence, Mark G., Stefan Schäfer, Helene Muri, Vivian Scott, Andreas Oschlies, Naomi E. Vaughan, Olivier Boucher, Hauke Schmidt, Jim Haywood, and Jürgen Scheffran. 2018. 'Evaluating climate geoengineering proposals in the context of the Paris Agreement temperature goals', Nature Communications, 9: 3734.

Lee, Hanna, Altug Ekici, Jerry Tjiputra, Helene Muri, Sarah E. Chadburn, David M. Lawrence, and Jörg Schwinger. 2019. 'The Response of Permafrost and High-Latitude Ecosystems Under Large-Scale Stratospheric Aerosol Injection and Its Termination', Earth's Future, 7: 605-14.

Lee, J.Y., J. Marotzke, G. Bala, L. Cao, S. Corti, J.P. Dunne, F. Engelbrecht, E. Fischer, J. C. Fyfe, C. Jones, A. Maycock, J. Mutemi, O. Ndiaye, S. Panickal, and T. Zhou. 2021. 'Future Global Climate: Scenario Based Projections and Near-Term Information.' in V. Masson-Delmotte, P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu and B. Zhou (eds.), 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. In Press.).

Lieven, Anatol. 2020. Climate Change and the Nation State: The Case for Nationalism in a Warming World (Oxford University Press: New York, NY).

Lin, Albert C. 2013. 'Does Geoengineering Present a Moral Hazard?', Ecology Law Quarterly, 40: 673-712.

Lin, Albert C. 2019. 'The Relevance of the Climate Change Regime to Governance of Solar Geoengineering.' in Robert N. Stavins and Robert C. Stowe (eds.), Governance of the Deployment of Solar Geoengineering (Harvard Project on Climate Agreements: Cambridge, MA).

Liu, Jianguo, Harold Mooney, Vanessa Hull, Steven J. Davis, Joanne Gaskell, Thomas Hertel, Jane Lubchenco, Karen C. Seto, Peter Gleick, Claire Kremen, and Shuxin Li. 2015. 'Systems integration for global sustainability', Science, 347: 1258832.

Livermore, M.A., and R.L. Revesz. 2020. Reviving Rationality: Saving Cost-Benefit Analysis for the Sake of the Environment and Our Health (Oxford University Press: New York, NY).

Lockley, Andrew. 2019. 'Security of solar radiation management geoengineering', Frontiers of Engineering Management, 6: 102-16.

MacMartin, Douglas G., Ben Kravitz, Simone Tilmes, Jadwiga H. Richter, Michael J. Mills, Jean-Francois Lamarque, Joseph J. Tribbia, and Francis Vitt. 2017. 'The Climate Response to Stratospheric Aerosol Geoengineering Can Be Tailored Using Multiple Injection Locations', Journal of Geophysical Research: Atmospheres, 122: 12,574-12,90.

Madronich, Sasha, Simone Tilmes, Ben Kravitz, Douglas G. MacMartin, and Jadwiga H. Richter. 2018. 'Response of Surface Ultraviolet and Visible Radiation to Stratospheric SO2 Injections', Atmosphere, 9: 432.

Matthews, H. Damon, and Ken Caldeira. 2007. 'Transient climate–carbon simulations of planetary geoengineering', Proceedings of the National Academy of Sciences, 104: 9949-54.

Matthews, H. Damon, Long Cao, and Ken Caldeira. 2009. 'Sensitivity of ocean acidification to geoengineered climate stabilization', Geophysical Research Letters, 36.

McCusker, K. E., D. S. Battisti, and C. M. Bitz. 2015. 'Inability of stratospheric sulfate aerosol injections to preserve the West Antarctic Ice Sheet', Geophysical Research Letters, 42: 4989-97.

McCusker, Kelly E., Kyle C. Armour, Cecilia M. Bitz, and David S. Battisti. 2014. 'Rapid and extensive warming following cessation of solar radiation management', Environmental Research Letters, 9:

024005.

McLaren, Duncan, and Olaf Corry. 2021. 'The politics and governance of research into solar geoengineering', WIREs Climate Change, 12: e707.

Meinshausen, Malte, Jared Lewis, Zebedee Nicholls, and Rebecca Burdon. 2021. "COP26 Briefing paper: Updated warming projections for NDCs, long-term targets and the methane pledge. Making sense of 1.8°C, 1.9°C and 2.7°C." In. Melbourne, Australia: Climate Resource.

Moore, J. C., S. Jevrejeva, and A. Grinsted. 2010. 'Efficacy of geoengineering to limit 21st century sea-level rise', Proceedings of the National Academy of Sciences, 107: 15699-703.

Moore, John C., Aslak Grinsted, Xiaoran Guo, Xiaoyong Yu, Svetlana Jevrejeva, Annette Rinke, Xuefeng Cui, Ben Kravitz, Andrew Lenton, Shingo Watanabe, and Duoying Ji. 2015. 'Atlantic hurricane surge response to geoengineering', Proceedings of the National Academy of Sciences, 112: 13794-99.

Moore, John C., Chao Yue, Liyun Zhao, Xiaoran Guo, Shingo Watanabe, and Duoying Ji. 2019. 'Greenland Ice Sheet Response to Stratospheric Aerosol Injection Geoengineering', Earth's Future, 7: 1451-63.

Moss, Richard H., Jae A. Edmonds, Kathy A. Hibbard, Martin R. Manning, Steven K. Rose, Detlef P. van Vuuren, Timothy R. Carter, Seita Emori, Mikiko Kainuma, Tom Kram, Gerald A. Meehl, John F. B. Mitchell, Nebojsa Nakicenovic, Keywan Riahi, Steven J. Smith, Ronald J. Stouffer, Allison M. Thomson, John P. Weyant, and Thomas J. Wilbanks. 2010. 'The next generation of scenarios for climate change research and assessment', Nature, 463: 747-56.

Muri, H., J. E. Kristjánsson, T. Storelvmo, and M. A. Pfeffer. 2014. 'The climatic effects of modifying cirrus clouds in a climate engineering framework', Journal of Geophysical Research: Atmospheres, 119: 4174-91.

Muri, Helene, Ulrike Niemeier, and Jón Egill Kristjánsson. 2015. 'Tropical rainforest response to marine sky brightening climate engineering', Geophysical Research Letters, 42: 2951-60.

Muri, Helene, Jerry Tjiputra, Odd Helge Otterå, Muralidhar Adakudlu, Siv K. Lauvset, Alf Grini, Michael Schulz, Ulrike Niemeier, and Jón Egill Kristjánsson. 2018. 'Climate Response to Aerosol Geoengineering: A Multimethod Comparison', Journal of Climate, 31: 6319-40.

Nalam, Aditya, Govindasamy Bala, and Angshuman Modak. 2018. 'Effects of Arctic geoengineering on precipitation in the tropical monsoon regions', Climate Dynamics, 50: 3375-95.

NASEM. 2021. "Reflecting Sunlight: Recommendations for Solar Geoengineering Research and Research Governance." Washington, DC: National Academies of Sciences, Engineering, and Medicine.

National Intelligence Council. 2021. "Climate Change and International Responses Increasing Challenges to US National Security Through 2040." In National Intelligence Estimate. Office of the Director of National Intelligence.

O'Neill, Brian C., Elmar Kriegler, Kristie L. Ebi, Eric Kemp-Benedict, Keywan Riahi, Dale S. Rothman, Bas J. van Ruijven, Detlef P. van Vuuren, Joern Birkmann, Kasper Kok, Marc Levy, and William Solecki. 2017. 'The roads ahead: Narratives for shared socioeconomic pathways describing world futures in the 21st century', Global Environmental Change, 42: 169-80.

O'Neill, Brian C., Elmar Kriegler, Keywan Riahi, Kristie L. Ebi, Stephane Hallegatte, Timothy R. Carter, Ritu Mathur, and Detlef P. van Vuuren. 2014. 'A new scenario framework for climate change research: the concept of shared socioeconomic pathways', Climatic Change, 122: 387-400.

Parker, A., J. B. Horton, and D. W. Keith. 2018. 'Stopping Solar Geoengineering Through Technical Means: A Preliminary Assessment of Counter-Geoengineering', Earth's Future, 0:1058-1065.

Parker, Andy, and Peter J. Irvine. 2018. 'The Risk of Termination Shock From Solar Geoengineering', Earth's Future, 6: 456-67.

Parkes, B., A. Challinor, and K. Nicklin. 2015. 'Crop failure rates in a geoengineered climate: impact of climate change and marine cloud brightening', Environmental Research Letters, 10: 084003.

Parson, Edward A. 2021. 'Geoengineering: Symmetric precaution', Science, 374: 795-95.

Parson, Edward A., and Lia N. Ernst. 2013. 'International Governance of Climate Engineering', Theoretical Inquiries in Law, 14: 307-37.

Pelling, Mark. 2011. Adaptation to Climate Change: From Resilience to Transformation (Routledge: New York, NY).

Penner, Joyce E., Cheng Zhou, and Xiaohong Liu. 2015. 'Can cirrus cloud seeding be used for geoengineering?', Geophysical Research Letters, 42: 8775-82.

Pham-Truffert, Myriam, Florence Metz, Manuel Fischer, Henri Rueff, and Peter Messerli. 2020. 'Interactions among Sustainable Development Goals: Knowledge for identifying multipliers and virtuous cycles', Sustainable Development, 28: 1236-50.

Pinto, Izidine, Christopher Jack, Christopher Lennard, Simone Tilmes, and Romaric C. Odoulami. 2020. 'Africa's Climate Response to Solar Radiation Management With Stratospheric Aerosol', Geophysical Research Letters, 47: e2019GL086047.

Pongratz, J., D. B. Lobell, L. Cao, and K. Caldeira. 2012. 'Crop yields in a geoengineered climate', Nature Climate Change, 2: 101-05.

Pope, F. D., P. Braesicke, R. G. Grainger, M. Kalberer, I. M. Watson, P. J. Davidson, and R. A. Cox. 2012. 'Stratospheric aerosol particles and solar-radiation management', Nature Climate Change, 2: 713-19.

Pringle, K. J., K. S. Carslaw, T. Fan, G. W. Mann, A. Hill, P. Stier, K. Zhang, and H. Tost. 2012. 'A multi-model assessment of the impact of sea spray geoengineering on cloud droplet number', Atmospheric Chemistry and Physics, 12: 11647-63.

Proctor, Jonathan, Solomon Hsiang, Jennifer Burney, Marshall Burke, and Wolfram Schlenker. 2018. 'Estimating global agricultural effects of geoengineering using volcanic eruptions', Nature, 560: 480-83.

Rabitz, Florian. 2019. 'Governing the termination problem in solar radiation management', Environmental Politics, 28: 502-22.

Raimi, Kaitlin T., Alexander Maki, David Dana, and Michael P. Vandenbergh. 2019. 'Framing of Geoengineering Affects Support for Climate Change Mitigation', Environmental Communication, 13: 300-19.

Rasch, Philip J., John Latham, and Chih-Chieh Chen. 2009. 'Geoengineering by cloud seeding: influence on sea ice and climate system', Environmental Research Letters, 4: 045112.

Reichert, Peter, and Mark E. Borsuk. 2005. 'Does high forecast uncertainty preclude effective decision support?', Environmental Modelling & Software, 20: 991-1001.

Reichwein, David, Anna-Maria Hubert, Peter J. Irvine, Francois Benduhn, and Mark G. Lawrence. 2015. 'State Responsibility for Environmental Harm from Climate Engineering', Climate Law, 5: 142-81.

Renn, Ortwin, and Bernd Rohrmann (ed.) 2000. Cross-Cultural Risk Perception: A Survey of Empirical Studies (Springer-Science+Business Media, B.V.).

Reynolds, Jesse. 2020. 'Elements and steps for global governance.' in Marie-Valentine Florin, Paul Rouse, Anna-Maria Hubert, Matthias Honegger and Jesse Reynolds (eds.), International governance issues on climate engineering: Information for policymakers (EPFL, International Risk Governance Center (IRGC): Lausanne, Switzerland).

Reynolds, Jesse L. 2019. The governance of solar geoengineering: Managing climate change in the Anthropocene (Cambridge University Press: Cambridge, UK).

Reynolds, Jesse L. 2021. 'Linking Solar Geoengineering and Emissions Reductions: Strategically Resolving an International Climate Change Policy Dilemma', Climate Policy: 1-16.

Richter, Jadwiga, H., Simone Tilmes, Anne Glanville, Ben Kravitz, Douglas G. MacMartin, Michael J. Mills, Isla R. Simpson, Francis Vitt, Joseph J. Tribbia, and Jean-Francois Lamarque. 2018. 'Stratospheric Response in the First Geoengineering Simulation Meeting Multiple Surface Climate Objectives', Journal of Geophysical Research: Atmospheres, 123: 5762-82.

Robbins, Kalyani. 2021. 'Geoengineering and the Evolution of Dueling Precautions.' in Wil Burns, David Dana and Simon James Nicholson (eds.), Climate Geoengineering: Science, Law and Governance (Springer International Publishing: Switzerland).

Robock, Alan. 2008. '20 Reasons Why Geoengineering May Be a Bad Idea', Bulletin of the Atomic Scientists, 64: 14-18.

Robock, Alan. 2020. 'Benefits and Risks of Stratospheric Solar Radiation Management for Climate Intervention (Geoengineering)', The Bridge, 50: 59-67.

Schäfer, S., M. Lawrence, H. Stelzer, W. Born, S. Low, A. Aaheim, P. Adriázola, G. Betz, O. Boucher, A. Carius, P. Devine-Right, A. T. Gullberg, S. Haszeldine, J. Haywood, K. Houghton, R. Ibarrola, P. Irvine, J.-E. Kristjansson, T. Lenton, J. S. A. Link, A. Maas, L. Meyer, H. Muri, A. Oschlies, A. Proelß, T. Rayner, W. Rickels, L. Ruthner, J. Scheffran, H. Schmidt, M. Schulz, V. Scott,

S. Shackley, D. Tänzler, M. Watson, and N. Vaughan. 2015. "The European Transdisciplinary Assessment of Climate Engineering (EuTRACE): Removing Greenhouse Gases from the Atmosphere and Reflecting Sunlight away from Earth." Potsdam, Germany: Institute for Advanced Sustainability Studies Potsdam (IASS) e.V.

Seitz, Russell. 2011. 'Bright water: hydrosols, water conservation and climate change', Climatic Change, 105: 365-81.

Seneviratne, Sonia I., Steven J. Phipps, Andrew J. Pitman, Annette L. Hirsch, Edouard L. Davin, Markus G. Donat, Martin Hirschi, Andrew Lenton, Micah Wilhelm, and Ben Kravitz. 2018. 'Land radiative management as contributor to regional-scale climate adaptation and mitigation', Nature Geoscience, 11: 88-96.

Shepherd, John, Ken Caldeira, Peter Cox, Joanna Haigh, David Keith, Brian Launder, Georgina Mace, Gordon MacKerron, John Pyle, Steve Rayner, Catherine Redgwell, Andrew Watson, Rachel Garthwaite, Richard Heap, Andy Parker, and James Wilsdon. 2009. "Geoengineering the Climate: Science, Governance, and Uncertainty." London, UK: The Royal Society.

Simpson, I. R., S. Tilmes, J. H. Richter, B. Kravitz, D. G. MacMartin, M. J. Mills, J. T. Fasullo, and A. G. Pendergrass. 2019. 'The Regional Hydroclimate Response to Stratospheric Sulfate Geoengineering and the Role of Stratospheric Heating', Journal of Geophysical Research: Atmospheres, 124: 12587-616.

Singh, Jyoti, Sandeep Sahany, and Alan Robock. 2020. 'Can stratospheric geoengineering alleviate global warming-induced changes in deciduous fruit cultivation? The case of Himachal Pradesh (India)', Climatic Change, 162: 1323-43.

Slovic, P., D. Zionts, A.K. Woods, R. Goodman, and D. Jinks. 2013. 'Psychic Numbing and Mass Atrocity.' in Eldar Shafir (ed.), The Behavioral Foundations of Policy (Princeton University Press: Princeton, NJ).

Slovic, Paul. 2007. '‘If I Look at the Mass I Will Never Act’: Psychic Numbing and Genocide', Judgment and Decision Making, 2: 79-95.

Smith, Wake, and Gernot Wagner. 2018. 'Stratospheric aerosol injection tactics and costs in the first 15 years of deployment', Environmental Research Letters, 13: 124001.

Soden, Brian J., Richard T. Wetherald, Georgiy L. Stenchikov, and Alan Robock. 2002. 'Global Cooling After the Eruption of Mount Pinatubo: A Test of Climate Feedback by Water Vapor', Science, 296: 727-30.

Sonntag, Sebastian, Miriam Ferrer González, Tatiana Ilyina, Daniela Kracher, Julia E. M. S. Nabel, Ulrike Niemeier, Julia Pongratz, Christian H. Reick, and Hauke Schmidt. 2018. 'Quantifying and Comparing Effects of Climate Engineering Methods on the Earth System', Earth's Future, 6: 149-68.

Stavins, R., J. Zou, T. Brewer, M. Conte Grand, M. den Elzen, M. Finus, J. Gupta, N. Höhne, M.-K. Lee, A. Michaelowa, M. Paterson, K. Ramakrishna, G. Wen, J. Wiener, and H. Winkler. 2014. 'International Cooperation: Agreements and Instruments.' in O. Edenhofer, R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J.C. Minx (eds.), Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (Cambridge University Press: Cambridge, UK and New York, NY).

Stavins, Robert N., and Robert C. Stowe (ed.) 2019. Governance of the Deployment of Solar Geoengineering (Harvard Project on Climate Agreements: Cambridge, MA).

Stewart, Richard B. 2014. 'Remedying Disregard in Global Regulatory Governance: Accountability, Participation, and Responsiveness', American Journal of International Law, 108: 211-70.

Stjern, C. W., H. Muri, L. Ahlm, O. Boucher, J. N. S. Cole, D. Ji, A. Jones, J. Haywood, B. Kravitz, A. Lenton, J. C. Moore, U. Niemeier, S. J. Phipps, H. Schmidt, S. Watanabe, and J. E. Kristjánsson. 2018. 'Response to marine cloud brightening in a multi-model ensemble', Atmospheric Chemistry and Physics, 18: 621-34.

Sunstein, Cass R. 2000. 'Cognition and Cost-Benefit Analysis', The Journal of Legal Studies, 29: 1059-103.

Sunstein, Cass R. 2018. The Cost-Benefit Revolution (MIT Press: Cambridge, MA).

Svoboda, Toby. 2017. The Ethics of Climate Engineering: Solar Radiation Management and Non-Ideal Justice (Routledge: New York, NY and London, UK).

Tilmes, S., Alexandra Jahn, Jennifer E. Kay, Marika Holland, and Jean-Francois Lamarque. 2014. 'Can regional climate engineering save the summer Arctic sea ice?', Geophysical Research Letters, 41: 880-85.

Tilmes, S., D.G. MacMartin, J.T.M. Lenaerts, L. van Kampenhout, L. Muntjewerf, L. Xia, C.S. Harrison, K.M. Krumhardt, M.J. Mills, B. Kravitz, and A. Robock. 2020. 'Reaching 1.5 and 2.0°C global surface temperature targets using stratospheric aerosol geoengineering', Earth System Dynamics, 11: 579-601.

Tilmes, S., J. H. Richter, B. Kravitz, D. G. MacMartin, A. S. Glanville, D. Visioni, D. E. Kinnison, and R. Müller. 2021. 'Sensitivity of Total Column Ozone to Stratospheric Sulfur Injection Strategies', Geophysical Research Letters, 48: e2021GL094058.

Tilmes, S., B. M. Sanderson, and B. C. O'Neill. 2016. 'Climate impacts of geoengineering in a delayed mitigation scenario', Geophysical Research Letters, 43: 8222-29.

Tilmes, Simone, John Fasullo, Jean-Francois Lamarque, Daniel R. Marsh, Michael Mills, Kari Alterskjær, Helene Muri, Jón E. Kristjánsson, Olivier Boucher, Michael Schulz, Jason N. S. Cole, Charles L. Curry, Andy Jones, Jim Haywood, Peter J. Irvine, Duoying Ji, John C. Moore, Diana B. Karam, Ben Kravitz, Philip J. Rasch, Balwinder Singh, Jin-Ho Yoon, Ulrike Niemeier, Hauke Schmidt, Alan Robock, Shuting Yang, and Shingo Watanabe. 2013. 'The hydrological impact of geoengineering in the Geoengineering Model Intercomparison Project (GeoMIP)', Journal of Geophysical Research: Atmospheres, 118: 11,036-11,58.

Tilmes, Simone, Jadwiga H. Richter, Ben Kravitz, Douglas G. MacMartin, Michael J. Mills, Isla R. Simpson, Anne S. Glanville, John T. Fasullo, Adam S. Phillips, Jean-Francois Lamarque, Joseph Tribbia, Jim Edwards, Sheri Mickelson, and Siddhartha Ghosh. 2018. 'CESM1(WACCM) Stratospheric Aerosol Geoengineering Large Ensemble Project', Bulletin of the American Meteorological Society, 99: 2361-71.

Tjiputra, J. F., A. Grini, and H. Lee. 2016. 'Impact of idealized future stratospheric aerosol injection on the large-scale ocean and land carbon cycles', Journal of Geophysical Research: Biogeosciences, 121: 2-27.

Trisos, Christopher H., Giuseppe Amatulli, Jessica Gurevitch, Alan Robock, Lili Xia, and Brian Zambri. 2018. 'Potentially dangerous consequences for biodiversity of solar geoengineering implementation and termination', Nature Ecology & Evolution, 2: 475-82.

UNEP. 2021. "The Heat is On: A world of climate promises not yet delivered." In. Nairobi, Kenya: United Nations Environment Programme (UNEP).

UNFCCC. 2015. "Paris Agreement." COP 21. Le Bourget, France: United Nations Framework Convention on Climate Change (UNFCCC).

van Vuuren, Detlef P., Jae Edmonds, Mikiko Kainuma, Keywan Riahi, Allison Thomson, Kathy Hibbard, George C. Hurtt, Tom Kram, Volker Krey, Jean-Francois Lamarque, Toshihiko Masui, Malte Meinhausen, Nebjosa Nakicenovic, Steven J. Smith, and Steven K. Rose. 2011. 'The Representative Concentration Pathways: An Overview', Climatic Change.

Vial, Jessica, Jean-Louis Dufresne, and Sandrine Bony. 2013. 'On the interpretation of inter-model spread in CMIP5 climate sensitivity estimates', Climate Dynamics, 41: 3339-62.

Victor, David G. 2008. 'On the regulation of geoengineering', Oxford Review of Economic Policy, 24: 322-36.

Visioni, Daniele, Douglas G. MacMartin, Ben Kravitz, Jadwiga H. Richter, Simone Tilmes, and Michael J. Mills. 2020. 'Seasonally Modulated Stratospheric Aerosol Geoengineering Alters the Climate Outcomes', Geophysical Research Letters, 47: e2020GL088337.

Visioni, Daniele, Eric Slessarev, Douglas G. MacMartin, Natalie M. Mahowald, Christine L. Goodale, and Lili Xia. 2020. 'What goes up must come down: impacts of deposition in a sulfate geoengineering scenario', Environmental Research Letters, 15: 094063.

Wang, Q., J. C. Moore, and D. Ji. 2018. 'A statistical examination of the effects of stratospheric sulfate geoengineering on tropical storm genesis', Atmospheric Chemistry and Physics, 18: 9173-88.

Wanser, Kelly, and Manaswita Konar. 2019. "Ensuring a Safe Climate: A National Imperative for Research in Climate Intervention and Earth System Prediction." In. Washington, DC: Silver Lining.

Weber, Elke U., and Jessica S. Ancker. 2011. 'Cultural Differences in Risk Taking and Precaution:

The Relative Roles of Risk Perception and Risk Attitude.' in Jonathan B. Wiener, Michael D. Rogers, James K. Hammitt and Peter H. Sand (eds.), The Reality of Precaution: Comparing Risk Regulation in the United States and Europe (RFF Press/Routledge: Washington, DC).

Weber, Elke U., and Christopher K. Hsee. 1999. 'Models and mosaics: Investigating cross-cultural differences in risk perception and risk preference', Psychonomic Bulletin & Review, 6: 611-17.

Wei, L., D. Ji, C. Miao, H. Muri, and J. C. Moore. 2018. 'Global streamflow and flood response to stratospheric aerosol geoengineering', Atmospheric Chemistry and Physics, 18: 16033-50.

Weil, Gabriel. 2021. 'Global Climate Governance in 3D: Mainstreaming Geoengineering within a Unified Framework', University of Pittsburgh Law Review, 81.

Weitzman, Martin L. 2015. 'A Voting Architecture for the Governance of Free-Driver Externalities, with Application to Geoengineering', The Scandinavian Journal of Economics, 117: 1049-68.

Wiener, Jonathan B. 1995. 'Protecting the Global Environment.' in John D. Graham and Jonathan Baert Wiener (eds.), Risk vs. Risk: Tradeoffs in Protecting Health and the Environment (Harvard University Press: Cambridge, MA).

Wiener, Jonathan B. 2002. 'Precaution in a Multirisk World.' in Dennis Paustenbach (ed.), Human and Ecological Risk Assessment (John Wiley & Sons: New York, NY).

Wiener, Jonathan B. 2015. 'Towards an effective system of monitoring, reporting, and verification.' in Scott Barrett, Carlo Carraro and Jaime de Melo (eds.), Towards a Workable and Effective Climate Regime (Centre for Economic Policy Research (CEPR) Press and Fondation pour les études et recherches sur le développement international (Ferdi): London, UK and Clermont-Ferrand, France).

Wiener, Jonathan B. 2016. 'Precaution and Climate Change.' in Cinnamon P Carlarne, Kevin R Gray and Richard Tarasofsky (eds.), The Oxford Handbook of International Climate Change Law (Oxford University Press: Oxford, UK).

Wiener, Jonathan B. 2020. 'Learning to Manage the Multirisk World', Risk Analysis, 40: 2137-43.

Wiener, Jonathan B. 2021. 'Disregard and Due Regard', NYU Environmental Law Journal, 29: 437-69.

Wiener, Jonathan B., and John D. Graham. 1995. 'Resolving Risk Tradeoffs.' in John D. Graham and Jonathan Baert Wiener (eds.), Risk vs. Risk: Tradeoffs in Protecting Health and the Environment (Harvard University Press: Cambridge, MA).

WMO. 2018. "Scientific Assessment of Ozone Depletion: 2018." Geneva, Switzerland: World Meteorological Organization.

WMO. 2021. "Climate Indicators and Sustainable Development: Demonstrating the Interconnections." Geneva, Switzerland: World Meteorological Organization.

Woolf, Steven H., Derek A. Chapman, Roy T. Sabo, Daniel M. Weinberger, and Latoya Hill. 2020. 'Excess Deaths From COVID-19 and Other Causes, March-April 2020', JAMA, 324: 510-13.

Xia, L., P. J. Nowack, S. Tilmes, and A. Robock. 2017. 'Impacts of stratospheric sulfate geoengineering on tropospheric ozone', Atmospheric Chemistry and Physics, 17: 11913-28.

Xia, L., A. Robock, S. Tilmes, and R. R. Neely Iii. 2016. 'Stratospheric sulfate geoengineering could enhance the terrestrial photosynthesis rate', Atmospheric Chemistry and Physics, 16: 1479-89.

Xia, Lili, Alan Robock, Jason Cole, Charles L. Curry, Duoying Ji, Andy Jones, Ben Kravitz, John C. Moore, Helene Muri, Ulrike Niemeier, Balwinder Singh, Simone Tilmes, Shingo Watanabe, and Jin-Ho Yoon. 2014. 'Solar radiation management impacts on agriculture in China: A case study in the Geoengineering Model Intercomparison Project (GeoMIP)', Journal of Geophysical Research: Atmospheres, 119: 8695-711.

Xie, M., J. C. Moore, L. Zhao, M. Wolovick, and H. Muri. 2021 (under review). 'Impacts of three types of solar geoengineering on the North Atlantic Meridional Overturning Circulation', Atmospheric Chemistry and Physics Discussion (preprint), 2021: 1-28.

Yang, Huiyi, Steven Dobbie, Julian Ramirez-Villegas, Kuishuang Feng, Andrew J. Challinor, Bing Chen, Yao Gao, Lindsay Lee, Yan Yin, Laixiang Sun, James Watson, Ann-Kristin Koehler, Tingting Fan, and Sat Ghosh. 2016. 'Potential negative consequences of geoengineering on crop production: A study of Indian groundnut', Geophysical Research Letters, 43: 11,786-11,95.

Zarnetske, Phoebe L., Jessica Gurevitch, Janet Franklin, Peter M. Groffman, Cheryl S. Harrison, Jessica J. Hellmann, Forrest M. Hoffman, Shan Kothari, Alan Robock, Simone Tilmes, Daniele Visioni, Jin Wu, Lili Xia, and Cheng-En Yang. 2021. 'Potential ecological impacts of climate intervention by reflecting sunlight to cool Earth', Proceedings of the National Academy of Sciences, 118: e1921854118.

Zhan, Pei, Wenquan Zhu, Tianyi Zhang, Xuefeng Cui, and Nan Li. 2019. 'Impacts of Sulfate Geoengineering on Rice Yield in China: Results From a Multimodel Ensemble', Earth's Future, 7: 395-410.

Zhang, Jiachen, Kai Zhang, Junfeng Liu, and George Ban-Weiss. 2016. 'Revisiting the climate impacts of cool roofs around the globe using an Earth system model', Environmental Research Letters, 11: 084014.

Zhao, L., Y. Yang, W. Cheng, D. Ji, and J. C. Moore. 2017. 'Glacier evolution in high-mountain Asia under stratospheric sulfate aerosol injection geoengineering', Atmospheric Chemistry and Physics, 17: 6547-64.

# Supplementary Material

Table 6. Anticipated effects of three SRM scenarios on selected indicators for the United Nations Sustainable Development Goals. From left to right, the first two columns list a selected subset of UN SDGs along with relevant indicators for measuring progress toward each goal (which could be affected by SRM). The scenario columns use the three SRM scenarios developed in Figure 1 in the main text of the report. The effects of deploying SRM on each indicator are shown in the shaded cells, comparing expected outcomes for each SRM scenario to the baseline scenario of no SRM (2021: Glasgow COP26 2030 targets; bottom centre in Figure 1). Further work could include comparing the relative magnitude of changes in these indicators as well as the optimization of scenario selection by maximizing the net positive changes in SDG indicators (see Sections 3.7–3.8). The global indicator framework for the SDGs is from the UN Inter-Agency and Expert Group on SDG Indicators (IAEG-SDGs 2017). Tabulation of climate change impacts on the SDGs draws from WMO (2021).

| **Legend** | |
|---|---|
| Positive change in indicator | ✓ |
| Negative change in indicator | X |
| Tradeoffs in scenario between mitigation and SRM | – |

| | | **Scenarios** | | | |
|---|---|---|---|---|---|
| **Sustainable Development Goal** | **SRM-Relevant Indicators** | **(1) peak shaving (high mitigation + some SRM)** | **(2) half warming (moderate mitigation + some SRM)** | **(3) SRM dependency (low mitigation + high SRM)** | **rationale for indicator change** |
| 1. End poverty in all its forms everywhere | 1.1.1 Proportion of the population living below the international poverty line by sex, age, employment status and geographic location (urban/rural) | X | ✓ | ✓ | reduction of GMST and increase in diffuse light, but also risks of unexpected climate impacts |
| | 1.2.1 Proportion of population living below the national poverty line, by sex and age | ✓ | ✓ | ✓ | |
| | 1.2.2 Proportion of men, women and children of all ages living in poverty in all its dimensions according to national definitions | ✓ | ✓ | ✓ | |

| | | | | | |
|---|---|---|---|---|---|
| 1. End poverty in all its forms everywhere | 1.4.2 Proportion of total adult population with secure tenure rights to land, (a) with legally recognized documentation, and (b) who perceive their rights to land as secure, by sex and type of tenure | ✓ | ✓ | ✓ | reduction of GMST and increase in diffuse light, but also risks of unexpected climate impacts |
| | 1.5.1 Number of deaths, missing persons and directly affected persons attributed to disasters per 100,000 population | ✓ | ✓ | ✓ | |
| | 1.5.2 Direct economic loss attributed to disasters in relation to global gross domestic product (GDP) | ✓ | ✓ | ✓ | |
| 2. End hunger, achieve food security and improved nutrition and promote sustainable agriculture | 2.1.1 Prevalence of undernourishment | ✓ | ✓ | ✓ | reduction of GMST and increase in diffuse light, but also risks of unexpected climate impacts |
| | 2.1.2 Prevalence of moderate or severe food insecurity in the population, based on the Food Insecurity Experience Scale (FIES) | ✓ | ✓ | ✓ | |
| | 2.3.1 Volume of production per labour unit by classes of farming/pastoral/forestry enterprise size | ✓ | ✓ | ✓ | |
| | 2.3.2 Average income of small-scale food producers, by sex and indigenous status | ✓ | ✓ | ✓ | |
| | 2.4.1 Proportion of agricultural area under productive and sustainable agriculture | ✓ | ✓ | ✓ | |
| | 2.5.1 Number of (a) plant and (b) animal genetic resources for food and agriculture secured in either medium- or long-term conservation facilities | ✓ | ✓ | ✓ | |
| | 2.5.2 Proportion of local breeds classified as being at risk of extinction | ✓ | ✓ | ✓ | |

| | | | | | |
|---|---|---|---|---|---|
| 3. Ensure healthy lives and promote well-being for all at all ages | 3.3.3 Malaria incidence per 1,000 population | ✓ | ✓ | ✓ | vector-borne diseases |
| | 3.3.5 Number of people requiring interventions against neglected tropical diseases | ✓ | ✓ | ✓ | |
| | 3.4.1 Mortality rate attributed to cardiovascular disease, cancer, diabetes or chronic respiratory disease | ✓ | – | X | acid deposition + surface ozone + surface UV radiation |
| | 3.9.1 Mortality rate attributed to household and ambient air pollution | ✓ | – | X | |
| | 3.9.2 Mortality rate attributed to unsafe water, unsafe sanitation and lack of hygiene (exposure to unsafe Water, Sanitation and Hygiene for All (WASH) services) | X | X | X | acid deposition |
| | 3.9.3 Mortality rate attributed to unintentional poisoning | X | X | X | |
| 5. Achieve gender equality and empower all women and girls | 5.4.1 Proportion of time spent on unpaid domestic and care work, by sex, age and location | ✓ | ✓ | ✓ | reduction of GMST |
| | 5.a.1 (a) Proportion of total agricultural population with ownership or secure rights over agricultural land, by sex; and (b) share of women among owners or rights-bearers of agricultural land, by type of tenure | ✓ | ✓ | ✓ | |
| 6. Ensure availability and sustainable management of water and sanitation for all | 6.1.1 Proportion of population using safely managed drinking water services | X | X | X | acid deposition |
| | 6.3.2 Proportion of bodies of water with good ambient water quality | X | X | X | |
| | 6.4.2 Level of water stress: freshwater withdrawal as a proportion of available freshwater resources | ✓ | ✓ | ✓ | combat sea level rise via reduction of GMST |
| | 6.6.1 Change in the extent of water-related ecosystems over time | ✓ | ✓ | ✓ | |

| | | | | | |
|---|---|---|---|---|---|
| 7. Ensure access to affordable, reliable, sustainable, and modern energy for all | 7.1.1 Proportion of population with access to electricity | ✓ | – | – | mitigation level determines access to (clean) energy |
| | 7.1.2 Proportion of population with primary reliance on clean fuels and technology | ✓ | – | – | |
| 8. Promote sustained, inclusive, and sustainable economic growth, full and productive employment, and decent work for all | 8.8.1 Fatal and non-fatal occupational injuries per 100,000 workers, by sex and migrant status | ✓ | ✓ | ✓ | reduction of heat stress + climate migrants |
| | 8.8.2 Level of national compliance with labour rights (freedom of association and collective bargaining) based on International Labour Organization (ILO) textual sources and national legislation, by sex and migrant status | ✓ | ✓ | ✓ | |
| | 8.9.1 Tourism direct GDP as a proportion of total GDP and in growth rate | ✓ | ✓ | ✓ | reduction of GMST |
| 9. Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation | 9.4.1 CO$_2$ emission per unit of value added | ✓ | ✓ | X | mitigation level determines CO$_2$ emission efficiency |
| 10. Reduce inequality within and among countries | 10.2.1 Proportion of people living below 50 per cent of median income, by sex, age and persons with disabilities | ✓ | ✓ | ✓ | reduction of GMST |

| | | | | | |
|---|---|---|---|---|---|
| 11. Make cities and human settlements inclusive, safe, resilient, and sustainable | 11.3.1 Ratio of land consumption rate to population growth rate | ✓ | – | – | dependent on mitigation efforts |
| | 11.4.1 Total per capita expenditure on the preservation, protection and conservation of all cultural and natural heritage, by source of funding (public, private), type of heritage (cultural, natural) and level of government (national, regional, and local/municipal) | ✓ | – | X | |
| | 11.5.1 Number of deaths, missing persons and directly affected persons attributed to disasters per 100,000 population | ✓ | ✓ | ✓ | reduction of GMST |
| | 11.5.2 Direct economic loss in relation to global GDP, damage to critical infrastructure and number of disruptions to basic services, attributed to disasters | ✓ | ✓ | ✓ | |
| | 11.6.2 Annual mean levels of fine particulate matter (e.g., PM2.5 and PM10) in cities (population weighted) | – | X | X | sulphur deposition vs. emissions |
| 12. Ensure sustainable consumption and production patterns | 12.6.1 Number of companies publishing sustainability reports | ✓ | – | X | dependent upon level of mitigation |
| | 12.a.1 Installed renewable energy-generating capacity in developing countries (in watts per capita) | ✓ | – | X | |
| | 12.c.1 Amount of fossil-fuel subsidies (production and consumption) per unit of GDP | ✓ | – | X | |

| | | | | | |
|---|---|---|---|---|---|
| 13. Take urgent action to combat climate change and its impacts | 13.1.1 Number of deaths, missing persons and directly affected persons attributed to disasters per 100,000 population | ✓ | ✓ | ✓ | reduction of GMST |
| | 13.2.1 Number of countries with nationally determined contributions, long-term strategies, national adaptation plans and adaptation communications, as reported to the secretariat of the United Nations Framework Convention on Climate Change | ✓ | – | X | dependent upon mitigation efforts |
| | 13.2.2 Total greenhouse gas emissions per year | ✓ | – | X | |
| | 13.a.1 Amounts provided and mobilized in U.S. dollars per year in relation to the continued existing collective mobilization goal of the $100 billion commitment through to 2025 | ✓ | – | X | |
| | 13.b.1 Number of least developed countries and small island developing States with nationally determined contributions, long-term strategies, national adaptation plans and adaptation communications, as reported to the secretariat of the United Nations Framework Convention on Climate Change | ✓ | – | X | |
| 14. Conserve and sustainably use the oceans, seas, and marine resources for sustainable development | 14.3.1 Average marine acidity (pH) measured at agreed suite of representative sampling stations | ✓ | X | X | reduction of $CO_2$ emissions vs. acid deposition |
| | 14.4.1 Proportion of fish stocks within biologically sustainable levels | ✓ | – | – | reduction in sea level rise vs. acid deposition |
| | 14.5.1 Coverage of protected areas in relation to marine areas | ✓ | – | – | |

| | | | | | |
|---|---|---|---|---|---|
| 15. Protect, restore, and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss | 15.1.1 Forest area as a proportion of total land area | ✓ | – | – | CO2 emissions vs. reduction of GMST |
| | 15.1.2 Proportion of important sites for terrestrial and freshwater biodiversity that are covered by protected areas, by ecosystem type | ✓ | – | – | reduction in sea level rise vs. acid deposition |
| | 15.5.1 Red List Index | ✓ | ✓ | ✓ | reduction of GMST |
| 16. Promote peaceful and inclusive societies for sustainable development, provide access to justice for all and build effective, accountable, and inclusive institutions at all levels | 16.1.2 Conflict-related deaths per 100,000 population, by sex, age and cause | ✓ | – | X | SRM/ climate conflict |