Solar Radiation Modification: Governance gaps and challenges

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Contents

Key insights

1. **Solar radiation modification is being explored as a potential approach to reduce climate change impacts in addition to emissions reductions, removals, and adaptation.** Progress toward reducing the emissions of greenhouse gases that cause climate change remains insufficient, and emissions are on track to cause global warming to significantly overshoot the Paris Agreement's temperature goals. In this context, researchers are exploring additional approaches to reduce climate change impacts, beyond aggressive emissions reductions, carbon removals and adaptation. One such additional approach is solar radiation modification (SRM), a group of proposed techniques that would typically entail reflecting a small portion of incoming sunlight to cool the planet. SRM appears to have the potential to reduce—but not eliminate—some climate change impacts but could pose other risks, which would depend on the specifics of how it were implemented. Nevertheless, much remains uncertain.

2. **SRM may be able to reduce some climate risks but would also introduce new and novel risks of its own, so effective governance, especially at the international level, will be essential to minimise overall risk**. The research and potential use of SRM presents high-stakes risk-risk trade-offs with significant uncertainties. As such, governance—the full range of means for deciding, managing, implementing, and monitoring policies and measures—of SRM's research, evaluation, and possible use, is important. The governance of SRM has many dimensions, that arise at various stages. Key governance decisions include whether or not to undertake research of SRM's expected impacts, techniques, and more, and/or whether or not to consider or undertake deployment. Specific governance dimensions relating to indoor research include ensuring scientific quality and reliability and preventing SRM research and evaluation from undermining efforts to reduce greenhouse gas emissions. Among governance dimensions that manifest in relation to outdoor research are managing higher demands for transparency and legitimacy and regulating physical and environmental risks. Specific governance dimensions relating to consideration of SRM deployment include developing norms, objectives and institutions that could guide decision-making and prevent its use contrary to any international consensus. Finally, in the event of SRM deployment, further governance challenges would likely emerge, such as responding to claims of attribution, unfair impacts and sharing costs and burdens equitably.

3. **Some governance relevant to SRM exists but is limited.** The current governance landscape for SRM is limited but not vacant. Existing non-state, national, and international governance instruments, institutions, and processes partially address the governance dimensions to varying degrees. Non-state actors can provide some governance, particularly of small-scale SRM research and in the absence of action by countries and intergovernmental organisations. Indeed, several collections of scholars and others have put forth nonbinding principles for SRM research and possible use. These notably have several commonalities, among which are the research and governance of SRM for the wider public good, a role for the public in decision-making, transparency, cooperation, independent monitoring and assessment, governance before deployment, and the primacy of emissions reduction. National governance is diverse, but generally provides basic regulation of environmental risks through impact assessment, pollution, endangered species protection, and more. A handful of countries have issued official reports regarding SRM and/or publicly funded its research. Currently, there are no international legal instruments with binding obligations that are specific to SRM. Some international governance rules, processes, and norms are directly applicable, while other multilateral environmental agreements could be adapted to govern SRM.

4. **Many governance gaps exist around SRM, and one of the most salient issues is the current absence of comprehensive international governance frameworks.** This includes key questions on how decisions on any potential deployment would be made, by whom, and

in which forum or intergovernmental process. We identify numerous governance gaps that remain, and present examples of potential means by which decision-makers could address them. Through these, any research, evaluation, and possible use of SRM could be better aligned with widely held principles and objectives, such as the Sustainable Development Goals. As examples: If SRM research is to proceed (and this is itself a governance challenge), then governance could facilitate it and ensure responsibility. If outdoor tests and experiments are to take place and be perceived as legitimate, then the public could be engaged in some way. Some widespread and influential concerns about SRM could be addressed by integrating its governance with that of emissions reductions, removals, and adaptation to reduce climate change impacts. Commercial actors' interests could be balanced with those of the wider public. Finally, policymakers can consider how to resolve potential future international disputes.

5. **Conversations about SRM governance are needed sooner rather than later.** Governance gaps will likely evolve in the context of a rapidly warming world in which the risks faced are both known and unknown at this point. SRM is not yet available as a deployable technique and its research is still at an early stage, so it could be another decade or more before it could be ready to deploy. Similarly, although the high-stakes decisions surrounding whether to implement SRM remain distant, near-term steps could be taken so that future, highly consequential decisions are more likely to be relatively legitimate, effective, and less conflictual. Given that multilateral diplomacy takes time to develop, if governance gaps are to be addressed in time, then conversations between policymakers should begin now, not later.

1. Introduction

Sustainable development is a leading framework for organising action and guiding collective decision-making at the international, national, and subnational scales. States endorsed the ***Sustainable Development Goals (SDGs)***[1] in 2015 at the United Nations General Assembly in order to focus action toward poverty eradication, and economically, socially and environmentally sustainable development (United Nations General Assembly, 2015). However, human-caused *climate change* presents a major obstacle to fulfilling the goals. Indeed, one of the seventeen SDGs is combating climate change and its impacts (Goal 13) and, because of their interrelatedness, progress toward many of the other goals depends on limiting climate change.

The human influence on the climate is 'unequivocal' and 'unprecedented' (IPCC, 2021: SPM 5, 7)[2] and climatic change has had significant impacts on human and natural systems (IPCC, 2014a: 4–11). As emissions—mostly from human activities—of the ***greenhouse gases (GHGs)*** that cause climate change continue, these impacts are expected to worsen (IPCC, 2014a: 11–25).

Countries have taken collective and individual action to reduce GHG emissions, but these steps have been insufficient. Although the future is uncertain, if emissions continue on their current trajectory, global warming will very likely exceed 2°C (IPCC, 2021: SPM 18). Other approaches such as ***adaptation*** to a changed climate and ***carbon dioxide removal (CDR)*** could contribute to reducing climate change impacts and risks, but their feasible capacities and social, economic, and political constraints may limit their rate of scaling up.

Solar radiation modification (SRM) is an additional approach proposed to help lessen and manage climate change risks. This would typically entail reflecting a small portion of incoming sunlight. According to current evidence, SRM could rapidly and reversibly reduce climate change, but imperfectly so (IPCC, 2021: Ch.4 90). At least one suggested technique seems to be technically feasible and have relatively low direct costs (IPCC, 2018: 348–349). At the same time, SRM's research, evaluation, and possible use present numerous risks and diverse ***governance*** dimensions, some of which are challenging (IPCC, 2018: 347–348). Existing governance instruments, institutions, and processes address some, but not all, of these and various governance gaps remain (IPCC, 2018: 348).

This paper identifies the governance gaps associated with SRM. Section 2 describes, in the context of climate change, the leading proposed SRM techniques and, according to current evidence, its expected climatic effects, environmental risks, and wider effects on sustainable development. Section 3 explains the governance dimensions and challenges, organised as manifesting during indoor and outdoor research, and prior to and during SRM's potential implementation. Section 4 reviews some relevant existing nonstate, national, and international governance. Section 5 identifies the salient governance gaps. The paper finishes with a brief conclusion.

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1 Bold, italicized words are defined in the C2G Glossary: https://www.c2g2.net/glossary/

2 *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (*IPCC, 2021) has not yet been formatted as of the time of writing. Page numbers are thus given for the approved version that was published online 7 August 2021.

2. Climate change and solar radiation modification

Humans are changing the ***climate***. According to a recent report from the Intergovernmental Panel on Climate Change (IPCC), observed global warming is more than 1°C, and climatic change is 'already affecting many weather and climate extremes in every region across the globe' (IPCC, 2021: SPM 7, 10). As GHGs accumulate in the atmosphere, these trends—including 'increases in the frequency and intensity of hot extremes, marine heatwaves, and heavy ***precipitation***, agricultural and ecological droughts in some regions, and proportion of intense tropical cyclones, as well as reductions in Arctic sea ice, snow cover and permafrost'—will continue and worsen (IPCC, 2021: SPM 19). Some of the changes are expected to be irreversible for lengthy periods of time, and there are small chances of extreme climatic changes via feedback cycles, sometimes called ***'tipping points'*** (IPCC, 2021: TS 59–61). Among affected human and natural systems are water resources; agriculture and food systems; exposure to climate-related extremes, especially among people living in poverty; heat-related mortality; and species' ranges, activities, migration patterns, abundances, and interactions (IPCC, 2014a: 4–6). Furthermore, climate change may reduce economic growth, increase displacement of people, and contribute to violent conflicts (IPCC, 2014a: 19–20). These impacts are and will be disproportionately borne by low-latitude, developing, and small island countries and populations, as well as already threatened ecosystems (IPCC, 2014a: 6, 12–13, 19–20). Because those developing countries have relatively low per capita GHG emissions, and because today's emissions will cause impacts in the future, climate change raises serious intra- and inter-generational equity concerns. This is captured in the principle of common but differentiated responsibilities and respective capabilities, in the light of different national circumstances (UNFCCC: Article 3.1; Paris Agreement: Article 2.2). Climate change impacts are expected to worsen as GHGs accumulate in the atmosphere. For example, impacts associated with 1.5°C global warming are projected to be meaningfully less than those from 2°C warming (IPCC, 2018: 9–13).

Approaches to reduce climate change and its impacts

Countries have taken collective and individual action to reduce future climate change and its impacts, particularly by efforts toward reducing GHG emissions and atmospheric concentrations. Just two months after the world's countries approved the SDGs, they endorsed the Paris Agreement on Climate Change, which built on the previous 1992 UN Framework Convention on Climate Change (UNFCCC) and its 1997 Kyoto Protocol. In the Paris Agreement, state parties aim to, among other things, keep global warming to 'well below 2°C' and to 'pursu[e] efforts to limit the temperature increase to 1.5°C' (Paris Agreement: Article 2.1(a)). To do this, countries aim to reduce GHG emissions so that emissions peak as soon as possible and then decline to net zero in the second half of this century (Paris Agreement: Article 4.1).

Progress toward reducing GHG emissions has consistently been insufficient (United Nations Environment Programme, 2021). Global emissions have increased most years and have roughly followed a trajectory that is expected to lead to about 3°C global warming (SSP2-4.5 in IPCC, 2021: SPM 18), although future emissions, Earth system responses, and the amount of warming for a given increase in GHG concentrations are uncertain (IPCC, 2021: TS 21–23). Looking into the future, because ***carbon dioxide (CO_2)***—the most important GHG—accumulates, there is a remaining emissions 'budget' that would be likely to keep global warming within a given target. The most recent IPCC report estimated that this budget is 400 and 1,150 billion tons (gigatons) of CO_2 ($GtCO_2$) after 2020 to have a two-thirds chance of keeping warming within 1.5 and 2°C, respectively (IPCC, 2021: SPM 38). At the current rate of emissions of about 40 $GtCO_2$ per year (United Nations Environment Programme, 2021), these budgets would be depleted in approximately 2031 and 2050, respectively.

Given the increasing severity of expected climate change impacts as well as insufficient GHG emissions reduction, a wider range of approaches have been considered. First, although adaptation to actual or expected climate change and its effects is a component of the UNFCCC, it receives less emphasis and fewer obligations than emissions reduction in that agreement. In the late 1990s and early 2000s, developing countries led efforts to elevate adaptation (UNFCCC Adaptation Committee, 2019: 11–26). It is now, in principle, of equal importance in the Paris Agreement and UNFCCC institutional decision-making (Paris Agreement: Article 2.1). Second, CO_2 could be actively removed from the atmosphere and durably stored in geological, terrestrial, or ocean reservoirs, or in products. Techniques for such carbon dioxide removal (CDR) include building with biomass, afforestation and reforestation, restoring wetlands, macroalgal cultivation, soil carbon capture sequestration and biochar, bioenergy with carbon capture and storage, direct air CO_2 capture and storage, enhanced weathering and ocean alkalinisation, and ocean fertilisation (Mace et al., 2021). As GHG emissions have remained high, CDR has become essential to scenarios of future net GHG emissions that would be expected to keep warming within the 1.5 and 2°C goals. For example, pathways believed to be compatible with 1.5°C warming require from a couple of hundred, to over one thousand $GtCO_2$ of total CDR between now and 2100 to remove difficult-to-eliminate emissions and, in most cases, to reach net negative emissions, compensating for prior excessive emissions (IPCC, 2018: 19). Nevertheless, the magnitude assumed in some high-level scenarios is of unclear feasibility and would face multiple feasibility and sustainability constraints.

Solar radiation modification techniques

Solar radiation modification (SRM) is an additional approach proposed to help lessen and manage climate change risks. This would seek to limit global warming in ways not related to GHG emissions or atmospheric concentrations. This would typically entail reducing the amount of incoming solar radiation (roughly speaking, visible sunlight) reaching the surface (IPCC, 2021, Annex VII 56). Sometimes called 'solar geoengineering', it is often described as addressing the symptoms, but not the causes (that is, GHG emissions), of climate change.

Three SRM techniques have received the most attention among scientists.

- First, ***stratospheric aerosol injection (SAI)*** would introduce aerosols (small airborne solid or liquid particles) into the stratosphere (a layer of the atmosphere extending from about 10 km to about 50 km altitude) with the objective of scattering sunlight back to space and lowering surface temperatures. The leading candidate aerosol material is sulphates (or their precursors), as this is the substance that volcanic eruptions emit that naturally cool the planet (IPCC, 2021: Ch. 4 87). SAI appears to be efficacious in reducing global warming (IPCC, 2021: Ch. 4 87), with an IPCC report concluding 'with *high agreement* that it could limit warming to below 1.5°C' (IPCC, 2018: 350). Evidence also suggests that SAI would have relatively low direct financial deployment costs (in the order of a few billion

USD annually) (IPCC, 2018: 348) and is technically feasible (IPCC, 2018: 349). Because of these characteristics, SAI has received the most attention among SRM techniques (IPCC, 2021: Ch. 4 87).

- Second, ***marine cloud brightening (MCB)*** would spray sea-salt into low-lying clouds over the oceans, increasing the number of suspended particles. In turn, this would engineer the clouds to be brighter, boosting the amount of sunlight that is reflected out into space. Because MCB requires the presence of a specific type of cloud, its effects would vary across space and its efficacy would be limited (IPCC, 2021: Ch. 4 88–89). It might be able to alter the planet's energy balance up to about 2°C global cooling, but estimates vary (IPCC, 2021: Ch. 4 88).
- Third, ***cirrus cloud thinning (CCT)*** would add ice nuclei (a class of aerosols) to high-altitude cirrus clouds (the high, feathery ones), with the goal of reducing their density. Thinning these clouds would allow more longwave radiation (that is, infrared) to escape. Like MCB, CCT requires the presence of a specific type of cloud and its efficacy would consequently be limited. CCT might be able to achieve about 1°C global cooling, but this is quite uncertain (IPCC, 2021: Ch. 4 89). Although CCT does not satisfy the definition of SRM, it is often included therein due the similarity of the physical interventions and the lack of direct changes to atmospheric GHG concentrations.

Climatic effects

SRM could be efficacious but imperfectly so. The most recent IPCC report concludes: 'Modelling studies have consistently shown that SRM has the potential to offset some effect of increasing GHGs on global and regional climate (*high confidence*), but there would be substantial residual or overcompensating climate change at the regional scale and seasonal timescale (*high confidence*)' (IPCC, 2021: Ch. 4 90). In other words, SRM seems able to reduce human-caused climate change globally and regionally, but some areas at some times would still experience some effects of climate change while SRM might overcorrect in others. It would generally have global climate effects, although some desired regional variation might be possible (IPCC, 2021: Ch. 4 84). SRM's climatic effects would manifest rapidly (on the order of months to a few years) and be reversible (Kashimura et al., 2017). Moreover, it could pose serious risks to both human and natural systems, largely depending on the details of how it would be implemented, as described in the next subsection. Important scientific uncertainties remain (IPCC, 2021: Ch. 4 85). Like adaptation, SRM would not directly address the cause of climate change: GHG emissions. The following paragraphs expand on these characteristics.

According to the evidence from modelling and, to a lesser extent, natural analogues, the moderate and careful use of SRM would bring relevant climate metrics closer to their preindustrial values at the subregional scale. (SRM might not be used moderately and carefully, which is considered below.) These metrics include average and extreme global surface air temperature, average water availability (that is, precipitation minus evapotranspiration), extreme precipitation, tropical cyclones' frequency and intensity, the melting of polar ice and mountain glaciers, and the weakening of Atlantic meridional overturning circulation, an important set of ocean currents (IPCC, 2021: Ch. 4 86; Irvine et al., 2019).

Since GHGs and SRM operate differently (trapping outgoing longwave radiation and reflecting incoming shortwave radiation, respectively), SRM's compensation of these climate metrics would be imperfect. Specifically, SRM's countereffects would differ across space and time from GHGs' climatic changes, being more efficacious at particular locations and at particular times of year and less so at others (IPCC, 2021: Ch. 4 187–188). In one manifestation of this phenomenon, an intervention using SAI or MCB at a globally uniform intensity (that is, how strongly it would reflect incoming sunlight) would have stronger climatic effects near the equator than near the poles (IPCC, 2021: Ch. 4 86). (CCT, which is not 'true' SRM, may be able to more precisely offset GHG-induced climate change.) The inconsistencies are greater when SRM is used at a stronger intensity. This offers a key reason that SRM is generally considered only as a potential supplement to—not a replacement for—deep emissions reduction.

Thus, the residual, or persisting, climatic changes could be lessened but not eliminated. At the same time, multiple climate policy goals can be met in models in which SRM is optimised along multiple parameters, such as which technique(s) is/are used, at what intensity, when, and where (IPCC, 2021: Ch. 4 86–87). To extend the above example, a greater intensity of SAI or MCB near the poles would compensate for climate change more precisely than a simple globally uniform one. Furthermore, because CCT appears more effective near the poles, it may be able to be complementarily combined with SAI (IPCC, 2021: Ch. 4 89).

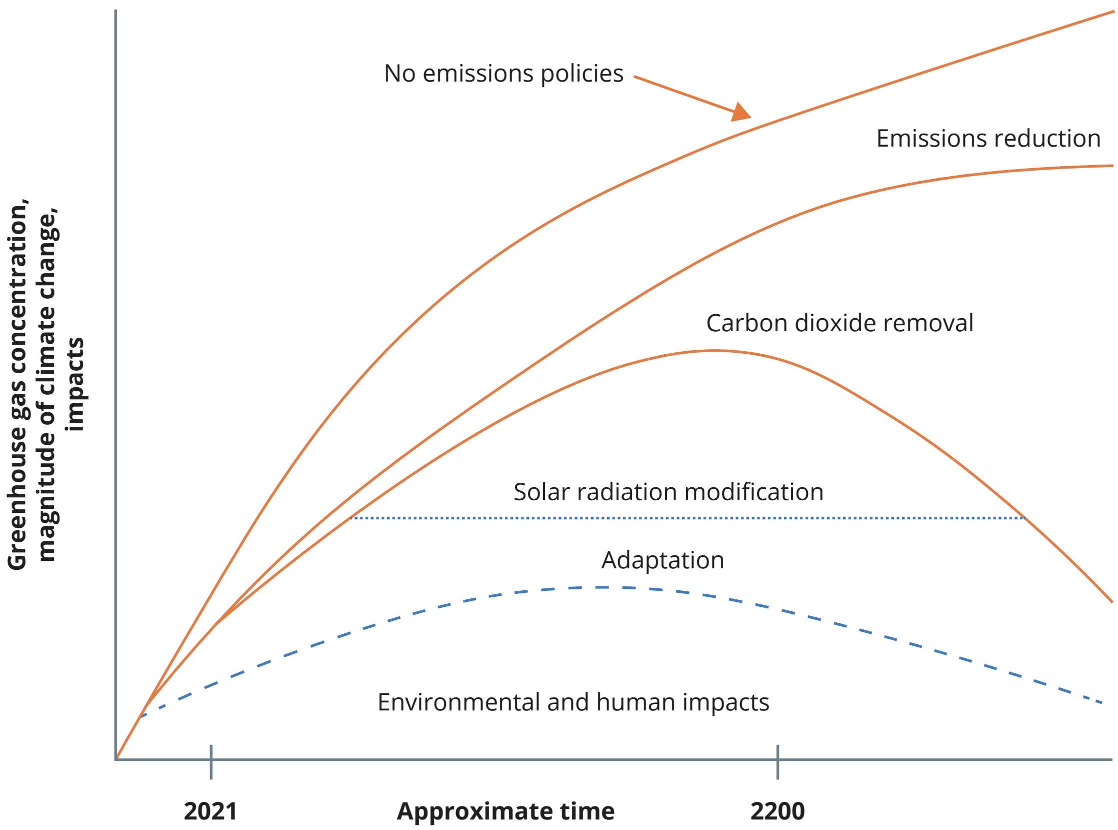
SRM would also counteract for GHG-induced changes in temperature and precipitation differently. Elevated atmospheric GHG concentrations warm the planet. They are projected to also change precipitation patterns, increasing precipitation in some areas and decreasing it in others, yielding a slight net global increase (IPCC, 2021: Ch. 4 86). SRM seems able to offset changes in both, but not in the same way. For one thing, it would more efficiently compensate for warming than for precipitation changes (IPCC, 2021: Ch. 4 86). Thus, if SRM were used to fully counteract human-caused global warming, it would overcorrect precipitation changes (Krishnamohan and Bala, 2022). For this reason, scientists are increasingly modelling the effects of using SRM to reduce, but not eliminate, global warming. For another thing, SRM's reduction of warming could be relatively precise (IPCC, 2021: Ch. 4 187–188), especially if its parameters were optimized (Visioni et al., 2020), while that of precipitation changes is projected to be less so (IPCC, 2021: Ch. 4 187–188).

Models consistently indicate that SRM's climatic effects would manifest relatively rapidly and could be reversed. In other words, if it were begun, increased or decreased in intensity, or ended, a new climatic equilibrium would be reached within a year or so (Kashimura et al., 2017; at the same time, its speed and reversibility create a 'termination risk', described below). SRM's speed and reversibility could give it a distinct role in helping manage climate change risks. If the impacts of climate change turn out to be worse than expected, then SRM could reduce short-term impacts while emissions reduction, CDR, and adaptation—all of which are relatively slow—scale up (Figure 1) (Long and Shepherd, 2014; Reynolds, 2019b: 25–26). Such worse-than-expected impacts could arise through several paths:

- Net GHG emissions could continue to be high.
- Climate change per unit increase in atmospheric GHG concentrations could be greater than expected.
- The impacts on human and natural systems per degree warming could be worse than expected.
- Climate change could manifest suddenly due to 'tipping points'.

In other words, SRM may be the only approach to reduce some climate change risks in the short-term (Shepherd et al., 2009: x).

Figure 1. Proposed complementary roles of approaches to reduce climate change and its impacts. SRM could complement emissions reduction, CDR, and adaptation to form an optimal risk management strategy. The vertical Y axis represents three different but roughly proportional metrics. The years are only suggestive, not specific (based on Long and Shepherd, 2014; in Reynolds, 2019a).



While SRM would probably have global climate effects, some desired regional variation might be possible (IPCC, 2021: Ch. 4 84; Moore et al., 2020). Stratospheric aerosols would rapidly mix along east-west lines and gradually migrate poleward (Tilmes et al., 2017). SAI could thus be implemented at a greater intensity toward the poles, which—given that SAI is less efficacious there—would more evenly counteract climate change or even cool the poles more than the low latitudes (Kravitz et al., 2019; Lee et al., 2021). MCB might be able to be used regionally, but only where dark low-lying marine clouds are present. For example, it is currently being researched as a potential approach to temporarily cool the waters of the Great Barrier Reef to prevent heat-induced bleaching events (Tollefson, 2021). CCT's capacity for achieving desired regional variation is less clear, in part due to its earlier stage of research. In all cases, heat and thus climatic effects would be transmitted through the atmosphere beyond the location of the SRM intervention. Thus, any substantial regional SRM would have important secondary effects, including in locations other than the targeted one.

To reiterate, SRM's effects are still somewhat uncertain. Research is at an early stage, mostly being conducted since about 2010 (Oldham et al., 2014). It receives an exceedingly small portion of total climate change research investment, about a few per cent of one per cent (Necheles et al., 2018). Almost all evidence is from models (albeit the same ones that scientists utilize to understand and project human-caused climate change) (IPCC, 2021: Ch. 4 85). Evidence from natural analogues, such as volcanic eruptions, is of limited applicability to SRM (IPCC, 2021: Ch. 4 87). Some findings, such as the quotation from the IPCC that opened this subsection, can be stated with high confidence. Others—for instance, CCT's expected effects—can be stated with much less (IPCC, 2021: Ch. 4 89). Large knowledge gaps and scientific uncertainties remain regarding SRM's effects, capabilities, associated physical and chemical processes, optimal characteristics and behaviour of injected material, and delivery and monitoring requirements (IPCC, 2021: Ch. 4 84–89; MacMartin and Kravitz, 2019). Importantly, the preceding paragraphs' description of what SRM could do often assumed SRM's moderate and careful use, which may not be the case.

Environmental risks

Although SRM appears to have the potential to reduce harmful climate change, it could also pose serious environmental risks, which would strongly depend on the details of how it would be implemented. As with SRM's climatic effects, substantial uncertainty persists regarding the character and magnitude of its environmental risks. Although SRM used moderately (that is, significantly less than fully counteracting global warming) and carefully (that is, relatively consistently across space and time) would, according to current evidence, reduce climate change (IPCC, 2021: Ch. 4 90), it otherwise would be dangerous. One such way is if SRM were used at excessive intensity. As described above, this would overcompensate some metrics of climate change—especially precipitation—in some places at some times (Kravitz et al., 20214). Increasingly excessive intensity would overcompensate more climate metrics at more places at more times. A second way that SRM could be used imprudently is if it were highly inconsistent across space. Changes in atmospheric circulation, precipitation patterns, and other climatic phenomena would arise (Jones et al., 2017; Nalam et al., 2017). This is a particular concern with MCB and CCT, which require specific cloud types and would therefore necessarily be 'spotty' (IPCC, 2021: Ch. 4 89). A third way would be if SRM, after being used for a substantial time and at a significant intensity, were suddenly stopped and not resumed. This ***'termination risk'***, if manifested, would cause the previously suppressed climate change to manifest rapidly and dangerously (IPCC, 2021: Ch. 4 90).

A few of SRM's environmental risks could arise even with if used moderately and carefully. The leading candidate material for SAI is sulphates. However, they could accelerate the destruction of stratospheric ozone, which blocks the sun's harmful ultraviolet radiation, and thus slow the recovery of this protective layer (IPCC, 2021: Ch. 4 88). For this reason, other materials—some of which may be able to help repair stratospheric ozone—are under consideration (Keith et al., 2016). Another concern regarding SRM is that it would not directly reduce the elevated atmospheric CO_2 concentration, which is acidifying the oceans (IPCC, 2018: 351). This is not a direct risk of SRM per se, but if the development and use of SRM led to countries, firms, and people emitting more CO_2 (see 'Governance during indoor research', below), then one could assert that the SRM led to greater ocean acidification (IPCC, 2021: 5 10). At the same time, the combination of SRM and a greater CO_2 concentration increases the terrestrial uptake of CO_2, reducing ocean acidification (IPCC, 2021: Ch. 5 111–115; Keith et al., 2017).

Wider effects on sustainable development

The primary motivation to reduce climate change is to avoid expected negative impacts on human and natural systems (UNFCCC: Article 2). These and other objectives are captured in the SDGs. As a first approximation, to the extent that SRM would reduce climate change, it would also facilitate progress toward climate-sensitive SDGs. Likewise, to the extent that SRM posed climatic and other risks, it could inhibit progress (Honegger et al., 2021). Yet the relationships among climate change, SRM, and the SDGs are complicated by intervening and confounding variables and by the current limited state of knowledge. It is therefore more helpful to compare a world of elevated GHG concentrations and SRM with one of GHG-induced climate change, not with one without such climate change. This is because SRM is being considered only as an approach to reduce climate change and its impacts. Four salient climate-sensitive SDGs are discussed here.

First, SDG-2 is to 'end hunger, achieve food security and improve [..] nutrition and promote sustainable agriculture' (United Nations General Assembly, 2015). SRM could change crop yields, but whether and to what extent remains uncertain. One recent modelling study found that SRM under conditions of elevated GHG concentrations increased global yields of six crops relative to both elevated and preindustrial GHG concentrations (Fan et al., 2021). Yet a previous study, drawing from evidence of volcanic eruptions, concluded that SAI's benefits to agriculture would be negligible because they would be cancelled out by the scattering of incoming sunlight (Proctor et al., 2018).

Second, SDG-10 is to 'reduce inequalities within and among countries' (United Nations General Assembly, 2015). Climate change is projected to disproportionately harm developing countries, potentially increasing inequality among countries (IPCC, 2014a: 20). SRM appears able to reduce international inequality relative to a world with GHG-induced climate change (Harding et al., 2020). If this is indeed the case, SRM would further this SDG.

Thirdly, SDG-11 seeks to 'make cities… safe, resilient, and sustainable' (United Nations General Assembly, 2015). However, climate change is expected to raise sea levels, increasing the frequency and severity of flooding of low-lying areas where many cities are (IPCC, 2021: SPM 33). SRM could reduce the rates of global warming and the consequent polar ice melting that causes sea-level rise (IPCC, 2021: Ch. 4 86). This effect, though, would be attenuated. Globally uniform SRM would be less efficacious near the poles (Ridley and Blockley, 2018), so a greater intensity may be needed there to slow or halt polar-ice melting. Stabilizing the global surface air temperature via SRM might not end polar ice melting due to possibly accelerated ocean currents (Fasullo et al., 2018).

Finally, SDG-15 includes protecting terrestrial ecosystems and halting biodiversity loss. A recent review and prospectus concluded that impacts on primary productivity, ecosystem composition, and more will differ between SAI and emissions cuts because of their distinct climatic effects (Zarnetske et al., 2021).

Together, this evidence suggests that SRM could, in the case of climate change, help advance climate-sensitive SDGs, but its contribution would have some limitations, present other risks and remain scientifically highly uncertain.

3. Governance dimensions and challenges

SRM seems potentially able to reduce climate change and its impacts but could pose its own serious risks to human and natural systems, especially if it were not used moderately and carefully. SRM could advance or hinder progress toward widely supported goals, and could be consistent with or contrary to commonly endorsed principles. In other words, SRM presents a high-stakes risk-risk trade-off under uncertainty (Harrison et al., 2021). Decision-making in such conditions is difficult. As such, governance—the full range of means for deciding, managing, implementing and monitoring policies and measures—of SRM's research, evaluation, and any use is important.

One key intertemporal challenge pervades the governance of SRM. Governance may be more effective if it anticipates later dimensions and challenges (Guston, 2014). But in the case of emerging technologies, what governance could and should do often cannot be known until substantial research and evidence-informed dialogues have taken place, creating a dilemma (Collingridge, 1982). Although it may be impossible to overcome entirely, a few policies—developing SRM governance in parallel with its research, undertaking broad upstream assessments, maintaining flexibility in governance, and adapting to changing knowledge and conditions—can help mitigate the dilemma's impacts.

This section describes plausible functions of the governance of SRM and, in some cases, associated difficulties. This assessment is based on commonly agreed-upon principles and objectives, among which are the prevention and minimisation of harm, including transboundary harm; cooperation; intra- and intergenerational equity; common but differentiated responsibilities and respective capabilities; basing decisions on the best available scientific knowledge; the SDGs; and peaceful and stable international relations. These governance dimensions and challenges are organised into those that may arise before and during the stages of indoor and of outdoor research, leading up to a potential decision whether to deploy SRM, and—if such a decision were affirmatively taken—afterwards. The boundaries among these stages are not sharp.

Governance during indoor research

Research of SRM's expected impacts, techniques, and more is currently almost entirely indoors. Here, activities in the natural sciences consist largely of modelling and laboratory work of its climatic and other impacts. Social sciences and humanities research is also occurring (Aldy et al., 2021). Inter- and transdisciplinary research is often put forth as an objective (Convention on Biological Diversity, 2016; National Academies of Sciences, Engineering, and Medicine, 2021).

The first, foundational governance issue is to *whether SRM should be researched* at all. Until the mid to late 2000s, the topic was largely taboo (Crutzen, 2006). A consensus may be emerging that SRM research should proceed, as evidenced in diverse endorsements from intergovernmental, state, and nonstate actors (American Geophysical Union Council, 2018; American Meteorological

Society Council, 2009; Conference of the Parties to the Convention on Biological Diversity, 2016; Deutsche Forschungsgemeinschaft, 2012; National Academies of Sciences, Engineering, and Medicine, 2021; Reekie and Howard, 2012; Schütte, 2014; Shepherd et al., 2009; US Global Change Research Program, 2017). Nevertheless, some academics and activists call for an end to SRM research (Biermann, 2021 and 2022; Geoengineering Monitor, 2018). This paper henceforth assumes that SRM research will proceed.

If SRM is indeed to be investigated, then governance may need to *enable research* (Long and Parson, 2019; Reynolds, 2020: 100–101). This includes funding. To date, states have not been especially supportive in this way, with global public funding remaining about USD $10 million annually (Necheles et al., 2018). Calls by national academies of sciences for increasing SRM research funding, including to specific amounts, have not been fulfilled (National Academies of Sciences, Engineering, and Medicine, 2021; Shepherd et al., 2009). Private funders have partially filled this gap, largely in the US (Necheles et al., 2018). Focused national programmes may also be necessary to enable research (Bipartisan Policy Center's Task Force on Climate Remediation Research, 2013; Bodansky and Wanser, 2021; National Academies of Sciences, Engineering, and Medicine, 2021). Priorities could be set, nationally and perhaps internationally, and might be driven by explicit missions, not simply investigators' curiosity (MacMartin and Kravitz, 2019). Among possible research priorities are reducing key uncertainties regarding SRM techniques' effectiveness, capability, costs, speed, reversibility, and limitations; identifying critical risks, maybe through dedicated 'red teams'; improving understanding of potential decision-making, monitoring, and attribution; technology development; and social and governance dimensions (Bipartisan Policy Center's Task Force on Climate Remediation Research, 2013: 24; National Academies of Sciences, Engineering, and Medicine, 2021: 15). The coordination of funding and activities, including data sharing and standardisation, may increase the efficiency of research in progress toward these priorities (Reynolds et al., 2017).

Furthermore, governance could *ensure the quality and reliability of research outputs* (Long and Parson, 2019). Many norms and processes that advance this are already common across scientific endeavours, especially those that are mission-oriented: ex ante project and programmatic design, competitive calls for funding, pre-registration of hypotheses and methods, independent peer review, publication of both positive and negative results, and evaluation of progress toward research priorities and goals. Regular in-depth authoritative reviews, assessments, and syntheses of the latest scientific evidence of SRM are also essential but are lacking at the international level (Reynolds, 2020).

Governance may be able to *help legitimize research*. At the least, research's means and ends should be consistent with widely held norms and principles as well as the general public interest (National Academies of Sciences, Engineering, and Medicine, 2021: 6). This could be furthered by regularly communicating the results to and engaging with the public, thought leaders, and decision-makers in ways that are fair and representative (Carr et al., 2013). The purpose here is *not* to change opinions to back research but instead to help align research's goals, approaches, and activities with these groups' values and priorities. Some observers assert that stakeholders should have roles in decision-making (Rayner et al., 2013). Funding by public bodies (Morgan et al., 2013) as well as transparency of research's justifications, plans, methods, results, conclusions, and implications could also enhance perceived legitimacy (Chhetri et al., 2018: xiv; Shepherd et al., 2009: xii). International research cooperation and capacity building, particularly with scientists in and from developing countries, is a final means to facilitate legitimacy (National Academies of Sciences, Engineering, and Medicine, 2021: 8, 11; Rahman et al., 2018). Such cooperation could also improve research's quality and to increase international trust.

Two particular widespread concerns may warrant being addressed through governance. One is that *early research and evaluation activities will unduly bias future decisions in favour of SRM's further development and use* (IPCC, 2018: 349), informally called a '***slippery slope***' (Bellamy and Healey, 2018). This prospect is sometimes characterised as 'lock-in', in which systems, institutions, and processes become entrenched in ways that make certain future choices difficult or impossible (Lin, 2020). Other descriptions emphasize ideas, in which current actions shape future values, norms, and expectations (Callies, 2019). Four governance mechanisms might be able to help manage this. First, diverse methods and techniques could be researched, perhaps giving extra weight to those that might hold less promise. Secondly, given the potential for 'groupthink', the identification of serious limitations, risks, and feasible failure modes could be prioritised and maybe undertaken by dedicated 'red teams' (Bipartisan Policy Center's Task Force on Climate Remediation Research, 2013: 24). Third is rules that could stop future activities. These could be moratoria, in which the path to more research and development is closed at some point unless some positive criteria are met (Parson and Herzog, 2016); stage-gates, which are agreements to go forward for now, coupled with an explicit later decision concerning whether to continue; and/or breakpoints or exit ramps, in which the path is open unless some negative criteria are met (National Academies of Sciences, Engineering, and Medicine, 2021). Notably, those criteria can be substantive (e.g., that the results are favourable or unfavourable) or socio-political (e.g., that there is or is not a social licence to operate). Fourth would be to regulate actors whose deep involvement in SRM could cause problems, actual or perceived. For example, the role of for-profit firms could be partially controlled through novel intellectual property policies such as patent pledges, patent pools, defensive patenting, or prohibitions on SRM patents (IPCC, 2018: 349; Reynolds et al., 2017). Likewise, limiting militaries' roles in SRM might reduce their undue influence and foster international trust.

The other widespread concern—indeed, the most influential one—is that *SRM's research, development, and evaluation would lessen emissions reduction* (IPCC, 2018: 349). This potential effect is variously called moral hazard, risk compensation, or ***mitigation deterrence,*** obstruction, or displacement. Scholars have suggested various means to avoid or lessen this unwanted outcome (Banerjee, 2011; Halstead, 2018; Lin, 2013; McLaren, 2016; Morrow, 2014; Reynolds, 2020, 2021), among which are encouraging diverse SRM avenues and methods of inquiry; limiting research to low-risk techniques or to governance matters; subjecting research to breakpoints, stage gates and/or moratoria; communicating carefully, perhaps emphasizing SRM's limitations and risks; engaging proactively with the public and decision-makers; and internationally linking mitigation and SRM policies. At the same time, there is an argument and some empirical evidence that introducing consideration of SRM could increase motivations to reduce GHG emissions (Reynolds, 2019b: 37–40).

Governance during outdoor research

Only a few modest outdoor SRM research activities have taken place, with negligible environmental impact (Izrael et al., 2009; Russell et al., 2013; Tollefson, 2021). These might increase in number, scale, and magnitude of intervention in the near future. One can imagine overlapping stages such as equipment testing and development; studies of relevant physical, chemical and radiative processes; active tests to validate models; and climate response tests, blurring the boundary with SRM's deployment (Keith et al., 2014). If research moves outdoors and expands, SRM's governance dimensions and challenges would expand for three primary reasons.

First, some activists and academics oppose outdoor SRM research, which indicates that it might turn out to be socially and politically unacceptable (Geoengineering Monitor, 2018; IPCC, 2014b; 488–489; Schafer et al., 2013). They do so usually for second-order reasons, that is, not in opposition to outdoor research itself but in order to slow the process so that governance can be strengthened or entire SRM endeavour might be halted (Sandahl et al., 2021). Regardless, as with research in general, a foundational governance issue is *whether outdoor SRM research should take place*.

The second—and related—reason is that the *demands for legitimacy seem more stringent* in the case of outdoor SRM research. The few outdoor SRM tests were notably low-profile and largely MCB (Izrael et al., 2009; Russell et al., 2013; Tollefson, 2021). Meanwhile, the two high-profile

SAI equipment tests were cancelled or indefinitely delayed due, at least in part, to opposition by activists, despite the fact that both would have had negligible environmental impacts (Goering, 2021; Watson, 2012). Political contestation appears more likely for high-profile outdoor SAI activities. Furthermore, in some countries, conspiracies about secret chemical spraying of the sky are modestly popular (Tingley and Wagner, 2017). Public education and engagement could help prevent misinformed backlash and better understand informed concerns (Carr et al., 2013). Greater involvement of state actors, such as funders, relative to private ones may also enhance legitimacy as well as accountability.

The third way in which governance dimensions and challenges would expand is that outdoor SRM tests and experiments could pose *physical and environmental risks*. Some risks will be typical of outdoor activities. For example, equipment could fail and harm people or property. At larger scales and magnitudes, the climatic intervention might have significant environmental risks, maybe quite at distance from the experiment site. Those affected may ask for compensation for perceived or actual harm caused by outdoor SRM activities, but demonstrating causation would likely be difficult (Reynolds, 2019b: 178–195). This becomes more complex if impacts cross national borders or are in areas beyond national jurisdiction, such as the high seas. International accusations of blame—even unfounded ones—are possible. Because outdoor tests and experiments would vary widely in their scale, magnitude of perturbation, and associated risks, governance could be tiered (Solar Radiation Management Governance Initiative, 2011).

In addition, some further governance dimensions would arise in the case of multiple large-scale outdoor SRM experiments. Greater *coordination* could prevent the experiments interfering with each other. And *costs* may be high enough that international cost-sharing agreements may be helpful (Ghosh, 2018).

Governance prior to potential use

The question of whether to ever use SRM, and how such a decision could be legitimately made, have received much attention. Although this has focused on controlling unwanted SRM (discussed below), states—which would in all likelihood be the decision-makers of whether and how to implement SRM (Keohane, 2015: 23; Parson, 2014; Rabitz, 2016; Reynolds, 2019b, 165–167)—may be able take steps in the nearer term in order to reduce the chance future conflict. For example, early international consultations could yield a sense as to *what norms and objectives should guide SRM decision-making* (Nye, 2019; Victor, 2008), a process that could take years. One means to do this would be diverse esteemed experts operating as an independent and multi-stakeholder roundtable, such as a 'World Commission on Climate Engineering' (Parson, 2017). Rejection of using SRM, including on nonmaterial grounds, could be an option.

Preventing and controlling unwanted SRM deployment may be its greatest governance challenge. SRM's capacity for widespread environmental effects, technological simplicity, and relatively low direct financial costs of deployment give it—and especially SAI—high leverage. One or a few countries—including those other than superpowers—could begin SRM before and/or contrary to any international consensus (IPCC, 2018: 347). This could be seen as problematic even if SRM were widely expected to be beneficial. Uni- or minilateral SRM might be domestically motivated by severe and sudden climate impacts, consequent popular unrest, and/or a desire to provoke the rest of the world to reduce emissions more aggressively and internationally finance adaptation (Barrett, 2014; Morton, 2015: 347–359; Rabitz, 2016). Either way, threats or actions in this area could precipitate international tension and conflict (IPCC, 2014a: 776–777).

States, intergovernmental organisations, and other actors could take various steps in *anticipation of possible SRM contrary to international consensus*. This would become salient as soon as some actors have the requisite technical and financial capabilities, and arguably the motivation as well, to implement. The concerned states and others may develop and cooperate in monitoring for indications of clandestine SRM and consult regarding how they would respond to any positive signals or announcements of active SRM (Philippe, 2019). They could also try to limit the number of countries that have SRM capabilities through, for example, some sort of non-proliferation mechanism (Reynolds, 2019b: 58, 211–214).

Inexorably related to the previous issue is *legitimately enabling operational SRM if and when international consensus is sufficient*. The norms, objectives, and process on which such decision-making could be established, as well as which—if any—existing institutions could offer a governance site (Biniaz and Bodansky, 2020) are currently uncertain and may become sharply contested.

Governance during potential use

Finally, different and additional governance dimensions would be salient if and when SRM were used. Specifically, the *ongoing SRM would need to be managed*, about which few experts have written (Bunn, 2019; MacMartin et al., 2019; Reynolds, 2019b: 216–220). Ongoing dialogues, perhaps including relevant nonstate stakeholders, on the implementation's objectives may reduce the likelihood and magnitude of any conflicts. Monitoring and assessment of the SRM's impacts and subsequent refinement of its parameters through feedback would further progress toward its objectives. Transparently collecting, integrating, sharing, and validating information concerning use and impacts could facilitate cooperation, trust, and effective risk management. This would also be consistent with the call for 'public access to information and cooperation' and the transparency framework found in the Paris Agreement (preamble, recital 14; Articles 12–13). Integrating SRM decision-making with other responses to climate change—emissions reduction, CDR, and adaptation—as well as related issues such as economic development and biodiversity conservation could increase complementarity toward achieving overall goals (Reynolds, 2020: 105).

Climate change is, and SRM would be, a matter of international politics. As described above, to the extent that SRM reduces climate change, it could help lessen and prevent challenging influences on international relations but could also cause tension and conflict, even independent of climate change (IPCC, 2014a: 776–777). Specifically, because a number of identifiable actors, probably states, would be responsible for implementing SRM, they could be blamed for extreme weather events or highly asymmetrical perceived effects. There may thus be *claims of unfair impacts* (Lawrence et al., 2018: 4). Victims—in absolute or relative terms, real or merely purported—might demand cessation and/or reparations, or threaten countermeasures. Either way, a dispute resolution forum as well as some form of compensation may be justified on legal and/or political grounds (Horton et al., 2015; IPCC, 2018: 349; Reynolds, 2019b: 178–195).

At least in principle, *SRM could be unduly used for political ends*. For example, some observers have suggested that SRM could be securitized, in which it becomes encompassed by the politics and logic of national security, which would run the risks of escalating international tensions and suboptimal climatic outcomes (Corry, 2017). Claims of SRM's capacity for weaponization are sometimes made but disputed (Smith and Henly, 2021: 4–5). Regardless, governance could aim to prevent both prospects.

SRM would have costs and other burdens. Although SRM's direct costs of deployment seem low in terms of climate change economics, they could nevertheless be substantial, especially when other expenses—including monitoring and potential compensation—are included (Reynolds et al., 2016: 564–565). SRM could also impose other non-financial burdens, for instance receiving less climatic benefits or even net environmental harms. Governance could *equitably share costs and burdens* (IPCC, 2018: 349).

Finally, if SRM were used at a sufficiently great intensity and length of time, stopped, and not resumed, the climate would then change rapidly and dangerously. *The sudden and sustained termination of SRM could be prevented*. This might be possible by ensuring that the systems, equipment, supplies, relationships, and knowledge to undertake SRM are redundant and secure (Parker and Irvine, 2018). Likewise, if and when atmospheric GHG concentration returns closer to its preindustrial value, SRM could be gradually phased out.

4. Existing governance

SRM presents a governance conundrum. Its apparent capabilities, risks, and uncertainties generate demand for governance of its research, evaluation, and potential use. However, addressing some of these dimensions may require further SRM research, without which policymakers might not have sufficient knowledge on which to act. Thus, balancing governance's prohibitive, permissive, and other characteristics must, to some degree, be anticipatory and in advance of specific scenarios of future SRM. Furthermore, some of SRM's benefits and downsides may be unknown, unknowable, and contested (Gupta and Möller, 2019).

So far, climatic risks, the inherently unclear future, and social challenges have been central themes surrounding SRM governance. There are several scenarios of how SRM research and implementation could be conducted, among which are privately funded research, publicly funded research within a country, several countries participating in a research network, a powerful country acting unilaterally, or one or more extremely climate-vulnerable countries giving others access to their territory to conduct large-scale SRM experiments (Ghosh, 2011; Victor, 2019). It is clear that no single instrument or form of governance would suffice in all cases.

The current governance landscape for SRM—such as in terms of research and development, risk assessment, accountability, and responsibility for impacts—is limited but far from vacant. Currently, there are no international agreements imposing any legally binding obligations that are specific to SRM. At the same time, there are norms, instruments, and institutions that could govern SRM. Given SRM's complex, transboundary, and uncertain nature, governance may emerge in a polycentric manner (Reynolds, 2018). Three top-level categories of governance can be identified: non-state, national, and international.

Non-state governance

Although countries play a crucial role in planning and funding research on climate change, environmental risks, and more, their involvement in SRM research and evaluation has been limited. In such an absence of state leadership, non-state governance can play an important role in managing SRM, especially indoor and smaller-scale outdoor research (Armeni, 2015; National Academies of Sciences, Engineering, and Medicine, 2021: 159). Non-state actors can explore governance options and help lay a foundation for further, possibly national and international governance as well as publicly-funded programmes. Moreover, non-state actors also can exert substantial transboundary influence through international partnerships and tools among which are rules, market incentives, social norms, statements of principles, codes of conduct, and knowledge sharing (Heyvaert, 2018). This has the advantage of flexibility and speed but can raise questions about accountability and, in the case of self-regulation, real or perceived conflicts of interest. Reynolds and Parson (2020) identify six groups of non-state actors in terms of their capacity, knowledge, and interest to govern SRM: scientists, universities and other research institutions, funders, professional societies, academic publishers, and non-government advocacy organisations.

Thus far, scholars and others have advanced several sets of explicit non-binding principles, often for ***'geoengineering'***, which consists of SRM and large-scale CDR and is called 'climate-altering techniques' by the Carnegie Climate Governance Initiative. The most influential set, known as the 'Oxford Principles', were envisioned as 'laying down the basic parameters for decision-making', to be operationalised as 'part of a flexible architecture… to shape a culture of responsibility among researchers', inform bottom-up self-regulation, and contribute subsequently to more strongly legalised governance mechanisms (Rayner et al., 2013). The five Oxford Principles are, in brief:

1. Geoengineering to be regulated as a public good;
2. Public participation in geoengineering decision-making;
3. Disclosure of geoengineering research and open publication of results;
4. Independent assessment of impacts; and
5. Governance before deployment.

Some observers have called for a more detailed code of conduct for SRM research (Shepherd et al., 2009: xii; National Academies of Sciences, Engineering, and Medicine, 2021: 13). Morgan et al (2013) put forth three objectives that such a code should satisfy: transparency of SRM research results, delineation of outdoor activities that could result in adverse impacts, and a moratorium on outdoor activities that could have adverse impacts until national and international governance frameworks are in place. The Geoengineering Research Development Project, a joint initiative between the University of Calgary, the Institute for Advanced Sustainability Studies, and the University of Oxford created the *Code of Conduct for Responsible Geoengineering Research* (Hubert, 2021). This Code is based on existing international law to promote the near-term research governance and guide responsible decision-making across a full spectrum of state, intergovernmental, and non-state actors. It adopted a precautionary approach and put forth a moratorium in which 'no geoengineering activities should take place, until there is an adequate scientific basis on which to justify such activities and appropriate consideration of environmental and other effects' (Hubert, 2017: 6).

These and other sets of principles for SRM (and often CDR) have much in common (see Appendix). The commonalities include the research and governance of SRM for the wider public good, a role for the public in decision-making, transparency, cooperation, independent monitoring and assessment, governance before deployment, and the primacy of emissions reduction. Given this notable overlap, a possible next step could be more formal codification of these shared principles.

In some contrast are the Tollgate Principles, which were formulated as a critique of the Oxford Principles' instrumentality, procedural emphasis, and ambiguity (Gardiner and Fragnière, 2018). These are grounded in a more diverse and stringent set of foundational norms, including ecological ones. For instance, the Tollgate Principles call for decision-making—including the authorisation of research programmes, large-scale field trials, and deployment—to be done by bodies acting on 'behalf of the global, intergenerational and ecological public, with appropriate authority and in accordance with suitably strong ethical norms (e.g. justice, political legitimacy)' (Gardiner and Fragnière, 2018: 152).

There are also many nongovernmental organisations advancing SRM governance discourse at national and intergovernmental levels. These include the Carnegie Climate Governance Initiative (which commissioned this paper) and SilverLining. Some environmental groups, such as Environmental Defense Fund, Natural Resources Defense Council, and the Union of Concerned Scientists, have engaged this issue, as have professional bodies: the American Geophysical Union, the Institution of Mechanical Engineers, the American Meteorological Society, and the International Commission on Clouds and Precipitation. A Global Commission on Governing Risks from Climate Overshoot, consisting of diverse independent leaders, is being formed that will recommend strategies to reduce climate change risks through SRM, CDR, and adaptation (Paris Peace Forum, 2021).[3]

3 One of the authors of this paper (Reynolds) began managing this Global Commission from January 2022.

The DEGREES Initiative ('Developing country Governance, REsearch, and Evaluation of SRM', formerly the SRM Governance Initiative) is a nongovernmental organisation that steers SRM in a unique way. It builds capacity for developing countries to make informed decisions by funding scientists in developing countries to conduct SRM research and hosting engagement workshops. As one example, it funded an examination of SRM's potential effects on rainfall in sub-Saharan Africa (Abiodun et al., 2021). Associated scholars have also made the case for greater inclusion of developing countries in SRM research (Rahman et al., 2018).

There is arguably another dimension to governance: 'voice', in which advocacy organisations and other stakeholders express their desires, concerns, and suggestions. If one adopted an expansive understanding of 'governance' to include efforts to influence governance—perhaps understood as 'second-order governance'—then such advocacy could be considered as non-state governance. This is procedurally and normatively salient given the uncertainty of SRM's effects and risks. In this respect, there has been regular questioning of and opposition to SRM from activist organisations for almost 15 years. In 2018, the Hands Off Mother Earth Manifesto was signed and is now supported by 195 organisations from 45 countries across five continents, calling for a halt to testing and political consideration of SRM (Geoengineering Monitor, 2018). More recently, in July 2021, indigenous people and others urged Harvard University to abandon their outdoor SRM equipment test and experiment (Geoengineering Monitor, 2019), stating that SRM 'goes against the respect' that Saami are taught to treat nature (Doyle, 2021).

National governance

A second top-level category is national governance, which is often relatively formal and legal. As domestic exercises of state sovereignty, this can be legally binding and rely on neither international cooperation nor the enforcement of international agreements, both of which can be difficult. Instead, national governance (here including the European Union and subnational jurisdictions) relies on established mechanisms, whether through executive and administrative agencies, legislative oversight, and/or judicial rulings, and has the power of enforcement through, for example, fines, and withdrawal of public funding.

This subsection summarizes some illustrative cases of salient national governance, because describing the full scope of the world's countries would be excessive. These examples are those states that have been most active in SRM. The cases point toward national governance's important limitations. Some countries apparently recognise uncertainties regarding SRM and its impacts and acknowledge that more international research is warranted. At the same time, they have been, for the most part, cautious about overly restrictive regulations that could unduly stymie research.

When and if SRM activities move outdoors and increase in scale and magnitude of intervention, they may begin to pose environmental risks. Most industrialized and many developing countries have fairly robust domestic environmental and liability laws that would regulate these. The operation of this regulation and liability differs between common law and civil law systems, in terms of structure, enforcement strategies, and institutional organisation (Germani, 2007). Common law systems are inclined towards criminal liability for breach of environmental rules. For instance, in the US, the National Environmental Policy Act requires the federal government to assess and consider the environmental impacts of projects that it undertakes, funds, or approves, while the Clean Air Act regulates some substances injected into the atmosphere as air pollutants (see Lin, 2018). Furthermore, the common law of torts, particularly the principles of nuisance and strict liability, could hold those who undertake outdoor SRM activities liable for harm to others. In contrast civil law jurisdictions maintain a broad focus on civil liability. The effectiveness of national environmental governance mechanisms across the world is challenged by gaps in enforcement and prevention. While existing regulatory landscapes could address liability for illegal SRM experiments, meaningful action may require executive and judicial awareness about the potentials and risks of SRM.

Three industrialized countries have begun to address some governance issues relating to SRM, in part, through a combination of (quasi)national assessments and public funding. First, the United States has led in assessing SRM, with its national academies issuing a chapter on 'geoengineering' as early as 1992 and full reports on SRM in 2015 and 2021 (Institute of Medicine et al., 1992: 433–464; National Research Council, 2015; National Academies of Sciences, Engineering, and Medicine, 2021). The recent one recommends a national transdisciplinary research programme, in coordination with other countries (National Academies of Sciences, Engineering, and Medicine, 2021: 8). According to the committee of authors, such a programme should cover three areas: the context and goals of SRM research, impacts and technical dimensions, and the social dimensions (National Academies of Sciences, Engineering, and Medicine, 2021: 13–14). For governing SRM activities, the National Academies' report asserts that research should comply with a code of conduct, be catalogued in a public registry, be subject to regular programme assessment and review, and allow for wide public engagement. Moreover, the report suggested that outdoor experiments that involve the release of substances should be limited to those that could provide additional critical insights that indoor work cannot (National Academies of Sciences, Engineering, and Medicine, 2021: 16). Public funding of SRM research has been annually earmarked, most recently at USD $9 million for fiscal year 2021 (National Oceanic and Atmospheric Administration, n.d.).

Secondly, the approach towards SRM in the United Kingdom has been guided by a combination of assessments by academic bodies, deliberations in parliament, and decisions by the executive. The House of Commons Science and Technology Committee considered the issue in 2009 and 2010. On the first occasion, it (then called the Innovation, Universities, Science and Skills Committee) put forward SRM as a potential 'Plan B' and urged the government to evaluate SRM as part of a portfolio of responses, proactively communicate to avoid misperceptions, support socio-economic research, lead the debate on ethical implications, and engage in international discussions (UK House of Commons, 2009). On the second, it proposed that the government push SRM higher up the international agenda and that regulatory systems be designed and implemented for techniques that fall outside existing international regimes (UK House of Commons, 2010). Overall, the Committee endorsed a top-down approach to SRM regulation to ensure legitimacy, appropriate scientific standards, effective oversight, and the management of environmental risks. The Committee also backed small-scale outdoor experiments as long as they complied with an international regulatory framework and set of principles, including the Oxford Principles; had negligible or predictable environmental impact; had no transboundary effects; and involved international scientists, including from more climate-vulnerable developing countries. The UK Government responded that it was 'too early to be able to establish appropriate regulatory frameworks for geoengineering research or deployment… without a clear view of what needs to be regulated and how. [It is] premature for inter-governmental action on regulatory arrangements' (Great Britain Department of Energy and Climate Change, 2010: 4, 10). In the time between these two House of Commons reports, the Royal Society published a seminal report on geoengineering, recommending among other things a ten-year research programme at £10 million annually (USD $13.5 million; Shepherd et al., 2009: xii). Three state-funded research projects started in 2010 and ended in 2015, totalling about USD $6.9 million (Necheles et al., 2018). However, since then the UK government has seemed more conservative. For example, by 2019, it stated that it is too premature to determine international SRM regulatory arrangements without prior consensus on which principles could drive research, adopting a wait-and-watch approach (UK Department for Business, Energy & Industrial Strategy, 2019). In 2019, the government responded to parliamentary queries by stating that further research has not been commissioned because it was awaiting results from the World Climate Research Programme's Geoengineering Model Intercomparison Project (UK Parliament, 2019).

Thirdly, in the case of Germany, various government departments published assessments of SRM in 2011 and 2012 (Ginzky et al., 2011; Planungsamt der Bundeswehr, 2012; Rickels et al., 2011). Each considered the physical science as well as ethical, social, and political aspects of SRM research and deployment. Acknowledging heterogeneous social attitudes towards SRM, these reports' advice has been consistently of exercising caution and not lessening emissions reduction efforts. At the same time, the German parliament notably did not implement the proposal of its Federal Environment Agency of a moratorium on the employment of SRM measures (Ginzky et al., 2011: 4) and, in fact, explicitly rejected a moratorium on SRM research (Deutscher Bundestag, 2012: 11–12). On the funding front, a Priority Programme of the German Research Foundation invested USD $3.5 million to improve understanding of SRM's ecological, social, and political risks and of associated challenges and opportunities (Necheles et al., 2018; Priority Programme 1689 of the German Research Foundation, n.d.).

A couple of countries with emerging and developing economies have also publicly funded SRM research. First, China backed an approximately USD $2.4 million programme from 2015 to 2020 to examine whether SRM could reduce climate change impacts as well as explore policy and governance issues (Temple, 2017; Zhang, 2020). This has focused on how SRM might affect agricultural, economic and health outcomes. Second, India has supported SRM-related climate modelling since 2014 and, since 2017, invested in studies that examine the impact of sulphate aerosols on tropical rainfall and climate extremes. It has also consulted with physical and social scientists on the need for a cohesive national SRM strategy (Bala and Gupta, 2019).

Finally, across Africa and Asia, academic and scientific networks have commented on the potential impact of SRM to address climate change. This includes research modelling efforts at the University of Cape Town to review potential impacts of SRM to address the Day Zero drought in South Africa (Odoulami et al., 2020). Simulations were also conducted on the potential impact of SRM on temperature and rainfall means and extremes in sub-Saharan Africa (Pinto et al., 2020).

International governance

The third and final category of governance is international, either directly applying or adapting existing international instruments. The advantage of international governance is the increased legitimacy, via broader representation of countries, in processes of deliberation and decision-making. An alternative to existing instruments would be to negotiate new international agreements to govern SRM. One concern with both applying existing instruments and especially developing a new one is the required time and attention in a context of overburdened intergovernmental organisations and national representatives. Regarding a possible new legal agreement, legal scholar Catherine Redgwell wrote that 'a multilateral geoengineering treaty is… unlikely because the appetite for law-making, particularly in the climate change context… is low. It appears inconceivable that the political will would be generated for law-making on this scale and where such a degree of controversy exists' (Redgwell, 2011: 188). Another issue with using existing international mechanisms and adapting treaties to govern SRM is the challenge of enforcement and dispute resolution. Whereas legal persons (including corporations and nongovernmental organisations) can domestically be bound by national law backed by the implicit threat of force, sovereign states are not subject to similar kinds of enforcement. As a result, while international law derives from mutually agreed treaties, long-standing customary behaviour, and general principles or rulings of tribunals, its enforcement rests on reciprocal behaviour, retaliation, reputational costs, and renegotiation of treaties (Guzman, 2008). To be clear, international governance instruments include binding treaties as well as nonbinding agreements, which can serve several important functions. For example, they can help establish and explicate shared norms and objectives while remaining adaptive in a changing context. Such 'soft law' can also lay a foundation for subsequent legally binding agreements (Abbott et al., 2000).

Directly applicable international governance

The Conference of Parties to the **Convention on Biological Diversity (CBD)** was the first intergovernmental body to address SRM, making three non-binding decisions concerning 'climate-related geo-engineering'. In 2010, grounded in precaution, Parties offered the guidance 'that no climate-related geo-engineering activities that may affect biodiversity take place, until there is an adequate scientific basis on which to justify such activities and appropriate consideration of the associated risks' (Convention on Biological Diversity, Conference of the Parties, 2010). At the same time, this 'non-binding normative framework' (Convention on Biological Diversity, Secretariat, 2012: 106) explicitly makes some exception for small-scale experiments in controlled settings within national jurisdiction that are justifiable by the need to gather specific scientific information. The 2012 and 2016 decisions reaffirmed the previous one while, in the latter, calling for more transdisciplinary research to improve understanding of potential impacts on biodiversity (Convention on Biological Diversity, Conference of the Parties, 2012; Convention on Biological Diversity, Conference of the Parties, 2016).

In 2021, the **International Law Commission** produced draft guidelines on protection of the atmosphere that aim to codify and further develop international law. Guideline 7 states that 'activities aimed at intentional large-scale modification of the atmosphere should only be conducted with prudence and caution, and subject to any applicable rules of international law, including those relating to environmental impact assessment' (International Law Commission, 2021).

At the fourth session of the **UN Environment Assembly (UNEA)**, the governing body of the UN Environment Programme (UNEP), countries considered but did not agree on a resolution on 'geoengineering and its governance'. In light of the substantial knowledge gaps, capacities, and risks, Switzerland—supported by 10 other countries (Burkina Faso, Federated States of Micronesia, Georgia, Liechtenstein, Mali, Mexico, Montenegro, Niger, Republic of Korea and Senegal)—proposed a resolution on 'Geoengineering and its governance' in 2019 for an assessment on SRM and CDR (Switzerland, 2019). The Swiss were motivated by a 'belief in the strength of multilateralism', to 'prevent unilateral action to the detriment of all', pointing to 'significant environmental and geopolitical risks', as well as 'ethical and social questions' associated with SRM and CDR approaches (Jinnah and Nicholson, 2019: 878, citing Switzerland, 2018). The resolution would have formed an ad hoc group to assess, among other things:

- criteria to define SRM and CDR technologies;
- the current state of science surrounding such technologies, including research gaps;
- the actors and activities with regard to research and deployment;
- current knowledge of potential impacts, including risks, benefits, and uncertainties with regard to each geoengineering technology; and
- conclusions on potential global governance frameworks for each geoengineering technology (Switzerland, 2019).

The proposal received mixed reactions. Some participants, such as the European Union and Bolivia, were concerned that it would weaken existing international efforts to govern the techniques under the CBD (Jinnah and Nicholson, 2019). Saudi Arabia and the US criticised the proposal for insufficiently differentiating between SRM and CDR, insisting that UNEP should wait for the IPCC's Sixth Assessment Report and that UNEP is not sufficiently 'scientific and neutral' to make such a non-partisan assessment (Perrez, 2020: 11). The role of precaution was a particular point of disagreement. Some scholars also suggested that it might be more appropriate for the IPCC or UNFCCC, with their specific climate change expertise, to carry out this sort of assessment (Forum for Climate Engineering Assessment, 2019). Given all this, this proposal was withdrawn and not adopted by UNEA, although several countries indicate that efforts should continue to better understand the implications (Perrez, 2020).

Adaptable international governance

Despite the limited scope of explicit international governance thus far, there are several international legal treaties which could, in principle, apply to at least certain aspects of SRM.

The **United Nations Framework Convention on Climate Change (UNFCCC)** is relevant but offers little guidance. None of the agreements directly address SRM, but perhaps could through their wide interpretation. Although SRM would not directly help stabilize atmospheric GHG concentrations—the objective of the UNFCCC—it is expected to do so indirectly by increasing CO_2 terrestrial uptake, among other mechanisms (IPCC, 2021: Ch. 5 111–115; Keith et al., 2017). Furthermore, SRM could possibly be viewed as a form of adaptation. And SRM could fit into the Paris Agreement's objective to limit temperature rise, and parties do not seem to be prevented from including SRM activities in their nationally determined contributions (Craik and Burns, 2016; National Academies of Sciences, Engineering, and Medicine, 2021: 98–99). Either way, the agreements and their principles, including that of common but differentiated responsibilities and respective capabilities, would need to be taken in consideration (Jayaram, 2021). Finally, the UNFCCC institutions, with universal participation and expectations of consensus, which tends to empower relatively less influential countries, might be able to aid in the establishment of an equitable governance mechanism.

The **Convention on the Prohibition of Military or Any Other Hostile Use of Environmental Modification Techniques (ENMOD)** regulates and prohibits military or hostile use of environmental modification techniques, which are defined such that SRM would fall within this scope and be governed by the associated provisions (Reynolds, 2019b: 131–132). A central feature of ENMOD is a prohibition on environmental modification techniques that have 'widespread, long-lasting or severe effects' on other states or carried out for a 'military or other hostile purpose' (Article I.1). It explicitly does not hinder environmental modification techniques for peaceful purposes (Article III) and, in its preamble, notes that they 'could improve the interrelationship of man and nature and contribute to the preservation and improvement of the environment for the benefit of present and future generations (preamble, recital 5). There are mixed views on ENMOD's capacity for SRM governance. For one thing, the treaty would not regulate SRM activities conducted for peaceful purposes. Furthermore, the Convention has only 78 ratified parties (C2G, 2019). ENMOD established limited institutional support and its parties have held only two meetings since it came into effect in 1977 (Reynolds, 2019b: 131–132). In contrast, McGee et al (2020) argue that ENMOD's potential role in SRM governance has not received sufficient attention.

The **Vienna Convention on the Protection of the Ozone layer** and its **Montreal Protocol** aim to end and reduce impacts from the depletion of the protective stratospheric ozone layer. The former treaty obligates parties to undertake research on physical and chemical processes and human activities that may affect the ozone layer. Given this, the parties could investigate such possible effects of SAI and, consequently, human health. The latter restricts the production and consumption of specifically listed ozone-depleting substances. Although the Montreal Protocol could, in principle, govern SAI using sulphate aerosols, at present the risk of ozone damage from SAI is unclear (C2G, 2019). Regardless, in order to regulate the substances used in SAI, the Montreal Protocol parties would need to add these substances to the list of regulated substances. Some work under the Montreal Protocol began in 2018, when the Federated States of Micronesia, Mali, Morocco and Nigeria submitted a proposal requesting a report on SRM by the Protocol's Scientific Assessment Panel (Earth Negotiations Bulletin, 2018; Perrez, 2020). But due to time constraints, the proposal was withdrawn. SRM was briefly mentioned in the 2018 Quadrennial Assessment of the Montreal Protocol's Scientific Assessment Panel (WMO, 2018) and will be considered in more depth in the next one (due to be published in 2022). This may offer an important additional means to inform international decision-makers regarding SRM (Biniaz and Bodansky, 2020).

The **Convention on Long-range Transboundary Air Pollution (CLRTAP)** is a regional agreement, supplemented by several protocols, that addresses long-range transboundary air pollutants, particularly those responsible for acid rain. Its membership is restricted to European countries, Canada, and the US, which is a limitation to CLRTAP serving as a basis for global governance. Specifically, it does not include emerging economies like Brazil, China, and India, which are now major sources of long-range air pollution. Nevertheless, the regime could be salient to the regional governance of SRM, particularly SAI using sulphates (Blackstock and Ghosh, 2011). It obligates parties to research on and report the substances at hand, similar to the Vienna Convention. Furthermore, three of CLRTAP's protocols address sulphur emissions:

- The 1985 Helsinki Protocol calls on Parties to reduce annual sulphur emissions by 30 per cent;
- the 1994 Oslo Protocol establishes limits on sulphur emissions; and
- the 1999 Gothenburg Protocol adjusts sulphur emissions caps in relation to their social and environmental effects in generating acidification, eutrophication, and ground-level ozone.

According to Blackstock and Ghosh (2011), since the CLRTAP and its protocols mainly focus on industrial emissions, they are more likely to regulate activities in the lower rather than the upper atmosphere. This distinction, however, is not explicitly stated.

The **UN Convention on the Law of the Sea (UNCLOS)** governs the ocean. One set of applicable provisions regard protection and preservation of the marine environment (C2G, 2019). It should be noted that, under UNCLOS, 'marine environment' is generally interpreted to include the atmosphere above the oceans, in which case these could govern even terrestrial SRM activities that substantially affect the marine atmosphere. For instance, parties 'shall take… all measures… necessary to prevent, reduce and control pollution of the marine environment from any source', including pollution 'from land-based sources', 'from or through the atmosphere', and that 'resulting from the use of technologies under their jurisdiction or control' (Articles 194, 196, 207, 212).

A second set of UNCLOS's provisions of interest concern scientific research. Here, parties 'have the right to conduct marine scientific research subject to the rights and duties of other States [and] promote and facilitate' such research (Article 238, 239). The Convention further emphasises that marine scientific research is to 'be conducted exclusively for peaceful purposes… with appropriate scientific methods and means', and in a manner consistent with parties' other rights and obligations concerning the ocean (Article 240). And countries would be responsible and liable for damage caused by marine scientific research conducted by them or on their behalf (Article 263).

The three previous international legal regimes—those of the Vienna Convention and Montreal Protocol for stratospheric ozone, CLRTAP and its protocols for transboundary air pollution, and UNCLOS for the seas—each may present something of a tension with respect to SRM. They define the 'pollution' or 'adverse effects' that they aim to reduce in a way that could include both GHG-induced global warming (or the GHGs themselves; Sands and Peel, 2018: 261) and SRM. For example, in CLRTAP pollution is 'the introduction by man, directly or indirectly, of substances or energy into the air resulting in deleterious effects of such a nature as to endanger human health, harm living resources and ecosystems and material property and impair or interfere with amenities and other legitimate uses of the environment' (Article 1(a)). Global warming is expected to result in such deleterious effects, and SRM might. The ultimate implications of these agreements' provisions are thus unclear.

With some suggestions for SRM to focus on the poles, the **Antarctic Treaty System** also holds relevance as it seeks to both protect the environment and to foster scientific research (Reynolds, 2019b: 126–128). The Antarctic Treaty encourages research among its 53 members, and its Madrid Protocol on Environmental Protection designates 'Antarctica as a natural reserve, devoted to peace and science' (Article 2). If SRM could protect the Antarctic environment and avoid adverse consequences, such activities might be considered permissible—but not otherwise. In planning their activities, states have to avoid adverse impacts on the climate, weather patterns, air, or water quality; changes in atmospheric, terrestrial, glacial or marine environment; changes to populations of plants and animals; and endangering other species. All Antarctic research programmes are subject to prior environmental impact assessment. The risk-risk approach is critical, since climate change is reshaping the Antarctic in material ways in the Anthropocene (McGee, 2019).

5. Governance gaps

Below, we describe the most salient gaps in the governance of SRM and, where possible, identify potential means and institutional sites for addressing them. These gaps are the governance dimensions and challenges that existing instruments and institutions neither currently address nor seem likely to do so within sufficient time. For example, extant national and, in some situations, international law appears able to adequately regulate the physical and environmental risks of outdoor SRM research and to resolve associated intranational disputes. Furthermore, some of the governance needs during any use of SRM are less certain to arise, temporally distant, readily surmountable, and/or able to be governed by instruments, institutions, and processes that appear likely to develop somewhat organically out of pre-deployment governance. These include managing ongoing SRM, sharing costs and burdens equitably, and preventing sudden and sustained termination.[4] We then group the remaining governance needs and challenges into six coherent areas.

Facilitate responsible research

If research of SRM's expected impacts, techniques, and more is to proceed, then governance could facilitate it and ensure responsibility in multiple ways. At the least, this could be advanced through the funding of scientific and other scholarly investigations. This is traditionally the domain of national governments, although private actors could contribute.

Other means to facilitate responsible SRM research may call for some degree of international action. For one thing, an authoritative international scientific assessment could establish and help solidify a shared body of evidence-based knowledge. The IPCC seems an obvious candidate for this (Rahman et al., 2018: 24), although it has dedicated relatively little attention to SRM thus far. For example, its latest report—the contribution of Working Group I to the Sixth Assessment Report—allocated only about ten pages out of four thousand to SRM and did not include it as part of any of its illustrative scenarios (IPCC, 2021: TS 69–70, Ch. 4 83–91, Ch. 5 111–115). The IPCC could produce a special report on SRM before its seventh assessment report. Alternative sites for authoritative international scientific assessment include UNEP, an ad hoc UN process, and a coalition of multiple national academies of science (Reynolds, 2020: 105).

Secondly, international cooperation could facilitate responsible SRM research in multiple ways: to improve knowledge production; to help prevent international suspicions, tensions, and disputes; and to bring developing countries—which have relatively little scientific capacity—more into the fold of evaluation and governance consultations (National Academies of Sciences, Engineering, and Medicine, 2021: 8, 11; Rahman et al., 2018).

4 Although the prospect of sudden and sustained termination is an important concern regarding SRM, it both is temporally distant and seems surmountable. The former is the case because dangerous termination would require SRM's use at a substantial intensity, sustained long enough to reach a new planetary equilibrium, and then ended for another length of time—totalling decades from now. The risk of such termination seems surmountable through, during implementation, backup physical and knowledge systems distributed among a small number of countries (Parker and Irvine, 2018) and, at its cessation, though a gradual phase-out of SRM combined with aggressive mitigation (IPCC, 2021: Ch. 4–90).

Thirdly, SRM research, if it proceeds, should arguably be legitimized (Long and Parson, 2019). Greater involvement of states and, where appropriate, intergovernmental institutions in regulating environmental risks, funding scientific investigation, contributing to authoritative international scientific assessments, and cooperating internationally would go far in this regard. (Public engagement, which can contribute to legitimacy, is important enough to warrant particular attention in the following subsection.)

Finally, if and when the SRM research endeavour is of great enough scale, then major funding and scientific bodies could coordinate in order to set shared priorities; to ensure that all relevant questions, methods and lines of inquiry are pursued; to decrease redundancy among research programmes; and to share costs equitably (Ghosh, 2018). Multilateral processes and existing bodies such as the UNFCCC Conferences of Parties, the International Science Council, the World Meteorological Organization, and the World Climate Research Programme appear positioned to contribute to these responsibilities of international cooperation, legitimization, and coordination (Reynolds, 2019b: 174, 207–218).

Guide outdoor experiments and engage with the global public

Many scientists assert that outdoor SRM tests and experiments would generate useful knowledge to advance understanding of its capabilities, limitations, expected impacts, risks, techniques, and more (Keith et al., 2014). However, proposals for such activities have been contentious, especially in the case of SAI. Indeed, a mere test of equipment, with no release of materials, was recently postponed—perhaps indefinitely—due to accusations of insufficient engagement with the local public (Henriksen et al., 2021; Keutsch Group at Harvard University, 2021; Sandahl et al., 2021). Yet in this case, the protestors opposed all SRM research and offered no criteria for acceptable public engagement. The result is a stalemate in which opponents may be able to prevent outdoor SRM activities by repeatedly demanding further public engagement. A constellation of authoritative nonstate actors and quasi-state ones (for example, national academies of science) could help break this by developing guidelines for responsible outdoor SRM research that address public engagement, among other things (Reynolds and Parson, 2020).

A specific challenge here is whose voice is heard and who might remain under-represented. There is, for instance, a lack of indigenous voices in the SRM scientific and policy discourses (Whyte, 2018). Similarly, although vibrant civil society groups can be found across the developing world, the efforts to draft principles and codes of conduct on SRM have not been in consultation with them. Moreover, some activists and academics in industrialized countries aim to sway or claim to speak on behalf of developing countries, a process which may be 'paternalistic' and 'colonial' (Rahman et al., 2018: 24; Táíwò and Talati, 2021: 1). Consequently, relying only on ad hoc principles and codes in limited geographies, regardless of good intentions, may face backlash from groups and communities which feel left out.

This situation concerning outdoor SRM tests and experiments is a manifestation of a larger conundrum. As a wider enterprise, SRM raises multiple serious concerns. Many observers assert that, in order for research to move forward responsibly and legitimately, the public should be engaged (Carr et al., 2013). And because SRM is a global issue, some engagement should arguably likewise be international, with particular attention to populations that are traditionally underrepresented and that have the most at stake with climate change and SRM. This governance gap causes individual outdoor tests and experiments to be treated by critics and some others as political quasi-referendums on whether any SRM research should proceed (Henriksen et al., 2021; Sandahl et al., 2021). Not only does such a situation cause the scientists to bear a disproportionate burden, but they are also not trained to carry out public engagement. Thus, one or more authoritative international institutions could engage the global public, although it is unclear which ones should, could, and would do so. A UN-affiliated body would presumably confer legitimacy but might be slow to act relative to multinational and nonstate processes. An alternative is, as above, a constellation of authoritative nonstate and quasi-state actors.

Integrate with other climate responses

Arguably the most widespread and influential concern regarding SRM is that it would undermine efforts to reduce GHG emissions (Reynolds, 2019a: 12–13). Another common one is that SRM's early research and evaluation would cause its subsequent development and use to be unduly likely. These two concerns—sometimes called 'mitigation obstruction' and 'slippery slope' respectively—both seem to arise out of a widely-held desire to prevent SRM from becoming the primary approach to manage climate change risks. They are also perhaps the most difficult governance issues to address because the prospect would be the result of numerous decisions by many different actors who may not even be aware of what has influenced their thinking, much less publicly reveal those influences. Thus, observing whether mitigation obstruction or slippery slopes have manifested is challenging, and developing and implementing governance mechanisms, processes, and institutions to prevent them appear even more so. Of course, these phenomena could be prevented with certainty by ending all discussion, research, and evaluation of SRM (e.g., Biermann, 2021 and 2022). However, this could increase net climate risks, which would be borne disproportionately by those in developing countries and low-lying island states.

This suggests that these concerns may be reframed as one of maintaining SRM's proper position in climate-related decision-making amid difficult risk-risk trade-offs. To do so, SRM could be integrated with other approaches to climate change: GHG emissions reduction, CDR, and adaptation (Aldy and Zeckhauser, 2020; Reynolds, 2020). This could occur at international, national, and non-state governance sites that substantially engage with SRM as a potential approach to climate change risks. Governance activities could improve connections among decision-making forums and processes and help these actors 'get in front of' the issue by identifying how SRM fits within the institutions' mandates, inventorying and assessing their salient governance capacities, fostering institutional knowledge, strengthening engagement, and locating and describing challenges. Here, the Conference of Parties, the Subsidiary Body for Scientific and Technological Advice, the Technology Executive Committee and the Climate Technology Centre and Network, and other UNFCCC institutions could play key roles, even if SRM itself is, strictly speaking, outside the objectives of the UNFCCC and perhaps of the Paris Agreement. Two other means to integrate SRM with other responses would be for major public and private funders, first, to ensure 'red team' research, in which some projects are dedicated to identifying feasible relevant failure modes (Bipartisan Policy Center's Task Force on Climate Remediation Research, 2013: 24), and second, to implement breakpoints (commitments to stop under specified circumstances), stage gates (agreements to go forward for now, coupled with a planned later decision whether to continue), and moratoria (temporary bans that could be ended under certain conditions) (Reynolds, 2020). These functions may require coordination across intergovernmental, national, and other institutions.

Balance commercial interests and governance concerns

For-profit firms offer opportunities and challenges in a contested technological domain such as SRM. On the one hand, if SRM is researched at large-scale or used, then commercial actors could provide goods and services, probably for state actors on a procurement basis. The prospect of private profit creates an incentive for requisite innovation. On the other hand, commercial interests could become powerful enough to unduly influence decision-making (Reynolds et al., 2017). They might even be able to drive deployment (Victor, 2019).

This suggests that the governance of SRM research, both before and during any potential deployment, could strike a balance between offering incentives for private actors to innovate while avoiding their inappropriate influence. One means to do so would be an innovative intellectual property policy. This could draw on precedence from other international research endeavours such as the multi-country European Organization for Nuclear Research (CERN, a major particle physics laboratory). These either hold the intellectual property themselves or permit joint ownership for commercial and free access to the intellectual property. Moreover, revenues from commercialisation are divided among those who developed the technology and used to replenish a fund set aside for technology transfer (Ghosh, 2018).

At the same time, top-down regulations on SRM-related patents could take much time to establish and enforce via widespread coordinated national legislative changes (Reynolds et al., 2017). One bottom-up alternative would be a 'research commons' centred on a patent pledge (National Academies of Sciences, Engineering, and Medicine, 2021: 177). Another option is patent pools that allow holders of interrelated patents to use each other's innovations in SRM technologies (Chavez, 2015). There is precedence for this, for instance under ITER, an international nuclear energy research project (Ghosh, 2018). The challenge with this approach, however, is that since SRM technologies are not well proven, it is difficult to know which set of patents to pool. So, a final prospect is defensive patenting and publication in order to prevent commercial entities from capturing the technology. This also brings limitations, and there is a chance that commercial interests could secure relevant patents in future.

Prepare to make high-stakes decisions

The matter of who would decide whether to implement SRM has received great attention. States will almost certainly be responsible for this, as they would presumably have little tolerance for SRM by private actors (Parson, 2014). Countries are likely to address this matter eventually, as an absence of action would imply a permissive setting for singleton or small coalitions to undertake SRM.

What form might a mechanism to prevent unwanted SRM while enabling any widely supported implementation take? A high threshold for legitimacy for a decision of this import would require that many (or all) countries be represented. Indeed, some observers suggest a binding multilateral legal agreement, with as broad participation as possible, that prohibits SRM in the absence of international authorisation via a specified deliberative process (Scott, 2013). However, wider participation, especially in a setting that expects consensus, could give too many members veto power, enabling them to act as spoilers. Furthermore, treaties are legally binding only by parties' consent; those states that would be most interested in undertaking SRM would be the least likely to ratify an agreement that would limit their lawful authority to do so (Barrett, 2014). There thus seems to be a trade-off between a governing mechanism's explicitness, specificity, and obligatory nature with its breadth of participation. A highly legalized agreement, as just described, might lie at one end of the spectrum. Unwritten norms, such as that against the first use of nuclear weapons (Schelling, 2005), and written ones are at the other end. Between them could be an institution that promulgates explicit norms, requires notification and consultation of any intended SRM, prohibits military or hostile use, facilitates cooperation and information exchange, and mediates disputes (Armeni and Redgwell, 2015; Reynolds, 2019b: 214–220). Such an institution and any associated agreement may be able to attract the participation of all countries with the interest and capacity to engage in SRM while also having sufficiently explicit and specific provisions.

In addition, when and if a decision to use SRM is made, governance would need also to enable SRM to be carried out to achieve agreed-upon goals without undue political interference. This may require entirely new institutions. A model here could be how many nations manage monetary policy, in which traditional leaders set general objectives and a more politically isolated body determines the specific parameters to try to achieve those (Reynolds, 2019b: 62, 217–218).

Although these operative decisions are arguably not yet urgent, much could be done soon to lay a constructive foundation so that future, highly consequential decisions would be more legitimate, more effective, and potentially less conflictual. These governance processes could take place at diverse sites: intergovernmental bodies with wide or narrow representation, ad hoc multinational forums, bilateral consultations, informal dialogues, and low-profile 'Track II' diplomatic channels.

One topic that states and other relevant actors could discuss relatively soon is which norms and objectives should guide future SRM decision-making (Nye, 2019; Victor, 2008). For example, how should widespread participation for the sake of legitimacy be balanced with a desire for effective and dynamic decision-making? To what extent should SRM aim to reduce all human-caused climate change, slow the rate of climate change, minimize harm to people or biodiversity, and act as an 'insurance policy' that is held in reserve and used only in the case of severe climate impacts?

Another potential step in the shorter term would be for countries to cooperate to prevent large-scale or global SRM that is contrary to any international consensus. Activities here might include cooperation in monitoring and perhaps efforts to limit the number of countries that have the capability to globally deploy SRM.

The ways in which these anticipatory dimensions of governance could be addressed would depend, in part, on states' perceptions of other states' intentions. If a sense of cooperation dominated, then general norms and procedures might suffice. On the other hand, if states suspected that others might use SRM for relative advantage, then more formal, precise, and obligatory governance mechanisms may be warranted (Ghosh, 2011).

Resolve international disputes

If SRM is ever used, countries may disagree on some aspects of it: the decision-making process, the original or revised purpose, the deployment parameters, the cause of and responsibility for the impacts, and more. A traditional means to prevent and resolve high stakes disputes is international law, but this has difficulties in making individual states responsible for complex environmental impacts. Specifically, there are limited means to obtain advance provisional measures to stop activities that may breach international obligations. The analysis of the norms applicable to SRM activities requires identifying appropriate decision-making authority and procedures, enforcement capacity and mechanisms, and a degree of legitimacy (Bodle, 2010). But as with almost all international law, countries can choose whether to participate or to abide by adjudicated decisions.

Some regimes provide for dispute resolution frameworks, varying in design and effectiveness. UNCLOS, for instance, provides compulsory dispute resolution mechanisms. The UNFCCC and the Paris Agreement, by contrast, have rules for conciliation but these are in the form of non-binding recommendations. The Vienna Convention for the Protection of the Ozone Layer prescribes a similar structure with the alternative final option of a conciliation commission that can give a final, recommendatory award. Notably, ENMOD provides for dispute resolution through a complaint procedure to the Security Council of the UN. One of these could serve for SRM, or a new one may be justified. At the same time, introducing the issue of SRM into these forums could expose tensions between different governance imperatives, for example mitigating climate change or governing the oceans, and how SRM-related disputes would be considered as a result (Doelle, 2014).

The decision on which forum to choose to resolve SRM-related disputes, in turn, depends on the nature of the dispute. How would the mechanism respond if a country violates an emerging or extant international consensus governing SRM activities? In the absence of a national law, would the activities of private actors be attributed to states? What provisions could be used to compensate for asymmetric and adverse impacts of SRM activities? What if the activities were intentionally undertaken to benefit one region over another?

Whereas the first two questions—those of violating consensus and attributing acts to states—could be potentially addressed in one of the aforementioned forums, the absence of a mechanism to secure compensation for adverse impacts is a hurdle for potential large-scale outdoor SRM research. There is precedence of explicit liability clauses in international research programmes. For instance, CERN insures members of collaborating institutions (to a limited extent) from third party liabilities incurred at CERN during an experiment (European Organization for Nuclear Research, 2020). Such provisions indicate the kind of liability rules that may be necessary for a SRM research programme. However, because SRM is being developed and, if used, would hopefully be for beneficent purposes, liability may be an inappropriate framework because it would disincentivise countries from undertaking activities that could be widely beneficial. Instead, other means such as international funds and/or parametric insurance might be able to compensate demonstrated harm (Horton and Keith, 2019; Reynolds, 2019b: 188–195).

6. Conclusion

Human-caused climate change threatens progress toward and achievement of the SDGs. SRM may be able to complement GHG emissions reduction, CDR, and adaptation and appears able to reduce risks to human and natural systems, especially those that are already vulnerable. At the same time, substantial uncertainty remains regarding SRM's efficacy, limitations, and potential impacts.

SRM brings with it multiple diverse governance dimensions, some of which are challenging. Existing national, international, and nonstate governance instruments, institutions, processes, and norms can manage some of these to varying extents, while others can be adapted to contribute to this. But they are insufficient in their current form and function, and important governance gaps remain. Consultation and action—especially at the international level—could address some of these and help prepare for others.

We highlight three particular challenges that pervade discussions of SRM and its governance. First, the relationship between further research and the development of governance is complex, with each requiring the other, at least to some degree. This suggests that these processes could occur in parallel and inform each other. Second, climate change presents risks of increasing severity. SRM seems able to reduce these but poses risks of its own. Risk-risk trade-offs are thus central to SRM and its governance. Focusing on only one side of the risk 'ledger' will likely hinder decision-making. Third, there is a strong case for international collaboration and inclusivity in any SRM research and development of governance. An expectation for legitimacy may require that these processes reflect many voices, including those that have been historically underrepresented and are especially vulnerable to the climatic impacts both in a world with SRM and that with dangerous climate change.

Appendix: Nonstate governance principles

Table 1. Nonstate governance principles. These are ordered from the most to least common principles among six proposed sets. The texts are direct quotations or paraphrases. These groupings are, and can only be, an approximation. There are no definitive means to group or split within a column, or to match or distinguish across a row. We do not include the Tollgate Principles here because they are more distinct (Gardiner and Fragnière, 2018).

Oxford Principles (Rayner et al., 2013)	Asilomar Principles (Asilomar Scientific Organizing Committee, 2010)	SRMGI (Solar Radiation Management Governance Initiative, 2011)	Bipartisan Policy Center (Bipartisan Policy Center's Task Force on Climate Remediation Research, 2013)	Geoengineering Research Development Project (Hubert, 2017)	US National Academies (National Academies of Sciences, Engineering, and Medicine, 2021)
disclosure of research and open publication of results	open and cooperative research	research transparency	transparency	cooperation; access to information	make research activities, funding sources, and results public
independent assessment of impacts	iterative evaluation and assessment	monitoring, compliance, and verification	direction of research should be based on advice from a range of experts	ex ante assessment and post-project monitoring of outdoor experiments	assess, monitor, and minimize potential adverse effects from research
public participation in decision-making	public involvement and consent	public engagement; participation and legitimacy		public participation	provide for suitable levels of public and stakeholder participation and engagement
regulated as a public good	promoting collective benefit		purpose should be to protect the public and the environment from climate change and climate remediation technologies		

governance before deployment			field deployment of SRM systems would be inappropriate at this stage		avoid atmospheric experiments with detectable climate or other environmental effects
	establishing responsibility and liability	liability and compensation			
				geoengineering should not be promoted or used as a substitute for mitigation and adaptation	accept research funding only from entities that prioritize mitigation and adaptation
				the best scientific methods and means that are reasonably available	protect the scientific quality of proposed research
			adaptive management		
				accordance with all applicable laws and regulations	
				due diligence obligation to prevent and minimize environmental harm from outdoor experiments	
				incremental, proportional 'step-by-step' approach to the design of outdoor experiments	
					identify and limit and, when necessary, avoid conflicts of interest
					actively support and advance the goals of racial, gender, geographic, and economic equity in research

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