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Solar Geoengineering: History, Methods, Governance, Prospects

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Abstract

Solar geoengineering, also called sunlight reflection or solar radiation modification (SRM), is a potential climate response that would cool the Earth's surface and reduce many other climate changes by scattering on order 1% of incoming sunlight back to space. SRM can only imperfectly correct for elevated greenhouse gases, but it might complement other climate responses to reduce risks, while also bringing new risks and new challenges to global governance. As climate alarm and calls for effective near-term action mount, SRM is attracting sharply increased attention and controversy, with many calls for expanded research and governance consultations along with ongoing concerns about risks, misuse, or overreliance. We review SRM's history, methods, potential uses and impacts, and governance needs, prioritizing the approach that is most prominent and promising, stratospheric aerosol injection. We identify several policy-relevant characteristics of SRM interventions and identify four narratives that capture current arguments over how SRM might be developed or used in sociopolitical context to either beneficial or destructive effect, with implications for near-term research, assessment, and governance activity.

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1. INTRODUCTION: SOLAR GEOENGINEERING AND ITS RISING PROMINENCE

Action and debate on climate change are in a period of upheaval. Rapid climate changes and impacts are raising alarm and spurring calls for stronger responses. Efforts to decarbonize the energy system have surged, with 1.7% of global economic output now being spent on clean energy (1), making it likely that world emissions will peak within a decade, but emissions cuts still fall far short of pledged targets (2–4). In this context, solar geoengineering, also known as sunlight reflection or solar radiation modification (SRM), is seeing increased interest as a potential climate response. SRM would actively intervene in the climate to partially offset effects of CO_2 and other greenhouse gases by changing the Earth's energy balance (5, 6). Most SRM approaches would increase the Earth's albedo, scattering perhaps a percent of incoming sunlight. SRM cannot fully offset the effects of greenhouse gases but might complement other responses to reduce risks in ways not otherwise possible. SRM also brings new uncertainties and risks, including novel governance challenges. Concerns about potential misuse or overreliance have thus far hindered SRM research and debate. Research has progressed despite limited funding but has lacked the scale, coordination, or linkage to assessment needed to realistically probe SRM's promise or risks. Many bodies are now calling for expanded research and consultation on SRM's potential use and governance needs. Growing urgent demand for effective near-term climate response is likely to bring continuing sharp increases in attention to SRM.

SRM: solar radiation modification; synonym for solar geoengineering, also called sunlight reflection methods

SRM is one form of geoengineering, intentional environmental alteration at large (continental to global) scale (7, 8). Geoengineering was long viewed as comprising two main intervention methods, SRM and carbon dioxide removal (CDR) (9, 10), but these diverged in the past decade as CDR became central to climate response projections (11). We consider only SRM, prioritizing methods that are more prominent in current research and more promising in near-term feasibility, particularly stratospheric aerosol injection (SAI). We review SRM's historical emergence and current debate (Section 2), relevant international treaties and institutions (Section 3), the major proposed SRM methods and their feasibility (Section 4), and high-level results of SRM research and grounds for confidence in these (Section 5). Section 6 discusses SRM as a sociopolitical and governance challenge, while Section 7 discusses proposed near-term steps to advance knowledge and decision capacity on SRM and its potential role in climate response.

CDR: carbon dioxide removal

SAI: stratospheric aerosol injection

2. EMERGENCE AND DEVELOPMENT OF SRM: CURRENT DEBATE

The prospect of changing the Earth's albedo to reduce CO_2-driven warming has been recognized since the 1960s, based on cooling observed from volcanic eruptions and burning sulfur-bearing fuels. In the first scientific report to a US president on climate change, in 1965, albedo modification was the only response considered. Placing reflective aerosols in the stratosphere, where long residence times reduce the mass of material required, was proposed in the early 1970s (12). The idea received brief mention in early climate reports by National Academy of Sciences committees, then deeper consideration including preliminary engineering cost estimates in a 1992 report (13–15). By this time there was already concern that discussing SRM might weaken other climate responses (16)—concerns seemingly validated by a 1996 paper that suggested SRM could largely replace emissions cuts (17). The first SRM climate-model experiment (18) and first review article (8) both appeared in 2000.

Despite SRM's prior scientific history, when climate appeared on policy agendas in the late 1980s, the only response considered was cutting emissions (19, 20). Over time, growing recognition that emissions cuts alone could not eliminate climate risks led to consideration of other responses, adaptation from the mid-1990s and CDR from the early 2010s. While each added response strengthened risk management, each faced opposition based on both its own limitations and concerns that it might weaken emissions cuts. Consideration of SRM now raises similar issues: Adding it to climate response might allow risk reductions not otherwise possible but also brings new uncertainties and risks, including potential overreliance and weakening of other responses. These concerns became salient in 2006, when a prominent essay by Nobel laureate Paul Crutzen argued that SRM should be researched despite its environmental risks, because it might be needed if other responses fall short—in particular, to offset increased heating from cutting sulfur pollution in the lower atmosphere (21). Although some scientists opposed publication of Crutzen's essay based on anticipated public reaction (22–24), it gained wide prominence and spurred several assessments and conferences over the next few years (6, 25–27). These expressed a careful dual message: warning against developing or relying on SRM but recommending expanded research.

Proposals to expand research soon attracted opposition from some scientists and nongovernmental organizations. Opponents proposed restrictions on some or all SRM research, arguing that research cannot be clearly distinguished from deployment, or could lock in expansion toward deployment even if unwarranted (28, 29). Proposals for outdoor field experiments, even minimal-impact experiments millions- to billions-fold too small for discernible climate impact, attracted particularly strong opposition (30–32). Others argued that research should proceed only after establishment of international governance meeting ambitious conditions of global engagement, precaution, and legal force (33). Opposition culminated in a 2022 call for a "nonuse agreement"

(NUA) that proposed, in addition to barring SRM deployment, rejecting public research funding, intellectual property rights, outdoor experiments of any size, and discussions in international institutions (34). Research proponents responded that deep uncertainties require SRM research and governance to coevolve (35, 36) and that demanding such underdefined and aspirational governance preconditions for research, based on conjectured harms that cannot be investigated because doing so is presumed to trigger the harms, relies on axiomatic, non-falsifiable reasoning and is a proxy for prohibition (37, 38). SRM-related research proceeded while these debates stalled, but was marginalized and under-resourced.

NUA: nonuse agreement

OF: ocean fertilization

Growing recognition of the severity of climate risks and the potential contributions of SRM is now raising support for expanded research and governance consultations, with pragmatic controls aiming to limit identified risks. Beyond a general rise in press and policy attention, there have been new organizations established (39, 40), modestly expanded research funding (41, 42), an international scientific assessment of stratospheric effects of SAI (43), open letters identifying the need for research and opposing the NUA's expansive bans (44, 45), and calls for research and consultation by governments and international bodies (2, 46–54).

This shift does not imply endorsement of SRM deployment, which is widely judged premature absent more knowledge. Nor does it imply the concerns about SRM research have been authoritatively refuted, although it does in practice reject their most expansive forms. These concerns have not been refuted, because they are posed in terms that resemble a legal burden-shifting exercise and so cannot be refuted by empirical evidence. The possibility that they may have some validity warrants careful management of SRM research, adaptive assessment and coevolution of research and governance, and vigilance against a potential slide to unwarranted deployment, but it does not warrant blocking research, either explicitly or by proxy via procedural preconditions. An irony of the debate thus far is that opposition to discussing SRM in any terms other than categorical rejection, by hindering research, assessment, and practical governance, may have increased risks—including risk of uninformed, unilateral, or hasty use (37, 38).

3. THE CURRENT GOVERNANCE LANDSCAPE RELEVANT TO SRM

While SRM's potential future governance needs are expansive, the present governance landscape is thin. Many international regimes have relevant mandates, including those on climate change, the ozone layer, long-range air pollution, the law of the sea, and the Antarctic. Other regimes, notably in security and technology cooperation, may offer relevant insights for SRM governance. But none of these bodies has a mandate that would include control of SRM, or the capacity to control it effectively. Several principles of customary international law are also relevant but provide no concrete guidance for potential SRM use (55, 56). In particular, none takes account of the dual effects of SRM, which would reduce climate risks but also introduce new risks (37, 38).

The international actions to date most relevant to SRM are decisions under two environmental treaties. In a 2010 decision (57), the Convention on Biological Diversity "Invite(d) Parties. . .to consider the guidance below. . .(w) Ensure, . . .in the absence of science based, global, transparent and effective control and regulatory mechanisms. . .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. . . ." Although sometimes claimed to represent a moratorium (real or "de facto"), this text's advisory language and multiple qualifications mean it neither creates any legal obligations nor makes a clear declaration of intentions. It is best understood as a nonbinding statement of concern.

Parties to the London Convention and Protocol, which regulate ocean dumping, have also taken actions of potential relevance to SRM, based on prior concern with ocean fertilization (OF), a potential CDR method. Following OF resolutions in 2008 and 2010 (52, 58, 59), parties adopted a 2013 amendment barring "placement of matter into the sea. . .for marine geoengineering activities." Although a 2022 statement suggested the aim that "marine geoengineering" include marine cloud brightening (MCB) and one other SRM method (60), the amendment explicitly names only OF and is not yet in force, so its implications for SRM remain hypothetical.

ENMOD: 1976 Convention on Environmental Modification

UNESCO: United Nations Educational, Scientific, and Cultural Organization

UNEP: United Nations Environment Programme

CCT: cirrus cloud thinning

The 1976 Convention on Environmental Modification (ENMOD) is a treaty often proposed as relevant to SRM. Adopted after US use of defoliants and cloud seeding in the Vietnam War, ENMOD prohibits military or other hostile use of environmental modification "having widespread, long-lasting, or severe effects" (61, Article I). While ENMOD's definition of environmental modification would clearly include SRM, its prohibition only covers ". . .military and other hostile use. . .as the means of destruction, damage or injury to any other State Party" (61, Article I). The treaty explicitly exempts modification for peaceful aims, indeed charges parties to cooperate in ". . .preservation, improvement, and peaceful utilization of the environment. . ." (61, Article III)—text that could be read to affirmatively support international research programs on SRM.

Several international bodies are starting to address SRM. From 2017 to 2023, the Carnegie Climate Governance Initiative (C2G) briefed national and international officials on CDR and SRM (62). The 2023 report of the Climate Overshoot Commission, an independent high-level body on the risk of exceeding the Paris targets, recommended SRM research and governance consultations, paired with a moratorium on large-scale interventions (2). Discussion papers on SRM were issued by the United Nations Educational, Scientific, and Cultural Organization (UNESCO) and commissioned by the Human Rights Advisory Council in 2023 (49, 52). At the United Nations Environment Programme (UNEP), a February 2023 expert panel called for international SRM assessment and research governance, while resolutions supporting an ongoing SRM assessment role were proposed at the 2019 and 2024 UN Environment Assemblies but not adopted (48, 63). The World Climate Research Programme adopted climate intervention as a new research initiative in October 2023 (50). These steps signal organizations' interest in joining expected SRM debates and decisions, but none yet engages SRM's governance challenges with specific diagnoses or proposals.

4. PROPOSED SRM METHODS AND TECHNOLOGICAL FEASIBILITY

Here and in the next section, we consider specific proposed SRM methods, their technical feasibility, and the state of research on their effectiveness and impacts. We treat feasibility as plausible ability to achieve global, climatically meaningful effects over the next few decades, based on technological readiness, industrial capacity, anticipated side effects, and cost. All proposed SRM methods but one would reduce the solar energy absorbed by increasing the Earth's albedo, the fraction of incoming sunlight reflected back to space. The exception, cirrus cloud thinning (CCT), would increase the atmosphere's transmission of thermal infrared radiation, thus directly offsetting the reduced infrared transmission due to elevated greenhouse gases. We devote more attention to methods that are more prominent in the scientific literature and policy debates, and closer to feasibility by our criteria, especially SAI.

4.1. Stratospheric Aerosol Injection

Stratospheric aerosol injection (SAI) would aim to replicate the cooling effect of current aerosol pollution in the lower atmosphere but avoid the immense harm that pollution causes to human health and the environment by injecting aerosols in the stratosphere, where atmospheric lifetimes are much longer: more than 1.5 years around 20 km altitude, versus a few days for aerosols injected at the surface, rising to perhaps 10 days in the upper troposphere. Because aerosol light-scattering effectiveness varies little with altitude, this 100-fold longer atmospheric lifetime means the same radiative forcing can be achieved with 100-times smaller aerosol injections and impacts, relative to current inadvertent tropospheric injection.

MCB: marine cloud brightening

CCN: cloud condensation nuclei

Analysis of SAI has focused on sulfuric acid aerosols for several reasons: they are the dominant natural aerosol in the stratosphere, volcanic eruptions provide a natural analog, and they offer the clearest technology paths to making aerosols with the required size distribution in the stratosphere. Most analyses assume, as in volcanic eruptions, that sulfur would be injected as SO_2 gas, which oxidizes over about a month to SO_3 and then quickly joins with water to form sulfuric acid aerosols. Other sulfur compounds with less mass per unit sulfuric acid formed may be preferred for deployment. Compared with SO_2, H_2S would reduce mass by almost half but be more toxic, while CS_2 would cut mass by 40% and be less toxic. Elemental sulfur would be both lightest and safest but would require in situ combustion to produce SO_2.

Various solid aerosols have been proposed as alternatives to sulfuric acid, including calcium carbonate, diamond, and alumina. Advantages of solid aerosols would include reduced heating of the lower stratosphere because they absorb less sunlight, less impact on ozone chemistry, and less visual and ecological impact from diffuse downward scattering of light. Calcite and alumina powders of the right size are commercially available at low cost, and models suggest that solid aerosols can be effective for SAI once dispersed. But the technical feasibility of dispersing solid aerosols in the stratosphere without rapid coagulation is unknown.

Various methods have been studied to transport SAI materials to the stratosphere. Rockets, artillery shells, and balloons appear to be costly and risky, leaving aircraft the most promising choice (64). The difficulty of lifting materials increases with altitude. Most SAI analyses have considered altitudes from 15 to 25 km: 15 km is high enough to reach the stratosphere at mid-latitudes, as is 20 km in the tropics, but slightly higher altitudes offer the advantage of longer aerosol lifetimes. Currently, some high-performance business jets can operate at 15.5 km, while existing aircraft that can operate above 20 km have payloads of only a few tons and are thus unsuitable for deployment. Existing engine and airframe technology give high confidence that aircraft could be developed for deployment around 20 km at a cost of a few thousand dollars per ton. While aircraft capable of deployment up to about 25 km could also be developed with high confidence, this would require new engine designs with considerably longer development time and higher cost (64, 65).

4.2. Marine Cloud Brightening

Marine cloud brightening (MCB) would add cloud condensation nuclei (CCN) to low-elevation clouds to increase their albedo or lifetime. Proposals focus on the marine stratocumulus clouds that form at the eastern edges of ocean basins where upwelling cools the ocean surface, using sea salt crystals as CCN. MCB would mimic a natural process that is a major contributor to marine CCN, the popping of wave-generated bubbles that releases submicron water droplets, which evaporate to leave the salt aerosol (66).

For a fixed water content, increasing CCN predictably increases cloud albedo. Complexities arise, however, because changing CCN can change cloud water content by changing rain rate or the radiative cooling that maintains the stratocumulus. MCB's net effect can thus vary strongly with local meteorology: It will increase albedo in many conditions but may have little effect or even reduce albedo in others (67).

Understanding MCB is intertwined with basic climate-system uncertainties about aerosol-cloud interactions. A recent analysis of ship tracks—a close analog to MCB—found that aerosols from global shipping had a radiative forcing of $-0.1\ W\ m^{-2}$, substantially larger than prior estimates (68). Other analyses suggest aerosols may have less effect on cloud radiative forcing than this estimate would suggest (69, 70).

Many technologies can generate sprays of the 0.1–0.5 μm size required for MCB. Neukermans and colleagues (71) have experimented with electro-spray, two-phase gas/liquid effervescent atomization, and spraying a supercritical brine through a high-pressure nozzle. A deployed ship or buoy-mounted spray system would need to make $\sim 10^{16}$ CCN per second, with at least 10^4 such systems required to achieve 1 W m^{-2} of global radiative forcing (66). The best systems presently demonstrated in the laboratory achieve at best 10^{13} CCN per second from one nozzle and would require more than 1 MW of power to reach 10^{16} CCN s^{-1} with multiple nozzles (71–73). Building MCB systems is physically possible, and several promising spray technologies have recently seen expanded research, but demonstrated performance is a few orders of magnitude below that required for deployment with significant climate impact at reasonable cost.

4.3. Cirrus Cloud Thinning

All clouds alter both solar and infrared fluxes, but negative radiative forcing from albedo changes dominates for low clouds, while positive radiative forcing can dominate for high clouds. Cirrus cloud thinning (CCT) would distribute ice nucleating particles such as bismuth triiodide to increase production of large ice crystals and thus thin clouds by gravitational settling. CCT is only relevant where cirrus clouds are heterogeneously nucleated, and even there the effect on radiative forcing can either heat or cool, depending on local meteorological conditions (74).

Aircraft contrails are a form of artificial cirrus, making it appropriate to consider contrail management along with CCT (74, 75). Proposals to modify aircraft tracks to reduce cirrus formation are advancing quickly—proposals that, if implemented, would be the first large-scale deliberate modification of radiative forcing to limit climate change.

Comparing CCT to MCB, CCT is less mature in assessment of deployment technology but may exhibit much larger sensitivity of radiative forcing to additional cloud nuclei. It is thus plausible that large-scale deployment may be more technologically feasible for CCT, but only if strategies can be developed to produce consistent and significant reduction in radiative forcing.

4.4. Space

Space-based solar geoengineering would scatter or absorb sunlight before it reaches the Earth. A space-based system could operate near the L1 Lagrange point, about 1% of the distance from the Earth to the Sun. Designs for space geoengineering systems fall broadly into two types. Low-mass systems would use highly engineered structures lifted from the Earth's surface with high cost per unit mass, while high-mass systems would use in situ resources such as asteroids to generate less sophisticated scatterers with much lower cost per unit mass (76, 77).

There is no reasonable prospect of building space-based systems at climate-altering scales in the next quarter-century. We nevertheless include them here because SRM deployments in models of optimal climate policy continue one to two centuries (78), over which time ongoing decreases in launch costs, along with in-space manufacture and resource utilization, may make space systems relevant despite a continuing cost disadvantage relative to other methods. Feasibility of space SRM is tied to the prospects of a substantial off-world economy, so development of space-based SRM might complement other commercial or prestige-seeking aims to drive large flows of capital despite high costs (77).

4.5. Surface

A wide variety of methods could be used to alter albedo at the Earth's surface. Small-scale modifications such as white roofs may be locally beneficial, but their global effect on radiative forcing is negligible. To achieve a given radiative forcing, surface albedo modification will generally require much larger amounts of material than other methods, so its environmental impact per unit of radiative forcing may be large. Generating long-lived microbubbles to whiten ocean surfaces initially appeared to have low material inputs per unit radiative forcing and thus higher leverage, but there is very little evidence that bubble lifetimes could be long enough to make the approach effective at reasonable cost. Some methods, particularly modification of agricultural crops and practices, may usefully be compared with human transformation of land surface that has significantly altered surface albedo. Glass microspheres can increase local ice albedo, but their large-scale effectiveness is uncertain (79).

4.6. Technological Feasibility

Research on SRM generally presumes that the intervention method studied can feasibly make a globally significant perturbation of radiative forcing soon enough to be relevant for climate response decisions. Such practical feasibility is not just a matter of physical possibility. Many potential interventions are physically possible, yet irrelevant over the next few decades because technology to implement them at scale is too costly or uncertain. For example, contrary to frequent statements that SRM cannot compensate both the temperature and precipitation effects of elevated greenhouse gases, it is physically possible to develop spectrally selective scatterers that would achieve both these goals (80). Yet SRM research sensibly ignores this possibility because there is currently no plausible way to manufacture and deploy such scatterers.

Analyses of technological feasibility often focus too much on the existence of demonstration hardware, an approach influenced by the widespread use of technology readiness levels. While these are useful in many contexts, they were developed for early space programs and so prioritize performance characteristics of technologies with little regard for the ability to produce them cost-effectively at scale. In assessing SRM approaches that would have to be implemented at large scale and sustained many years to have a meaningful climate effect, we suggest this approach may be misleading. Rather, we propose a functional approach to assessing feasibility of SRM methods, which integrates performance characteristics of technologies with judgments of the ability to deploy them at a specified scale with targets for development time and cost. Concretely, our proposed approach would consider the ability of credible industrial suppliers to bid for contracts to supply technologies to meet these targets, with performance guarantees.

To illustrate this approach, we propose a benchmark of achieving 0.2 W m^{-2} global forcing by 2040, at a maximum cost of US$15 billion per year. This would reduce heating through 2040 by about half, at a cost somewhat below 1% of current world spending on clean energy. These values are arbitrary, chosen mainly to illustrate how linked factors of performance, development time, and cost underpin feasibility judgments. We suggest that with such a benchmark, one could work with technology suppliers to concretely assess the feasibility of alternative SRM methods. In our judgment, this exercise would assign high feasibility to sulfur SAI, in that multiple suppliers could provide confident performance estimates based on multiple independent combinations of aircraft and sulfur delivery methods. On the same metric, we are confident that space-based SRM would presently be judged infeasible, and we expect that the feasibility of MCB, CCT, and surface methods would be low, since none now has a clear pathway for engineering development that would meet this benchmark.

In these judgments, the distinction between research and development is crucial—a point on which the case of MCB is especially informative. Given presently demonstrated laboratory performance, there is not a technology pathway to a deployable MCB system meeting this performance benchmark through routine engineering development. It is, of course, possible that research now underway will yield a viable MCB sprayer design this year, which could then be developed to a deployable system. But while engineering development of a system based on demonstrated technologies is relatively predictable—even if the system does some novel task, such as dispersing SO_2 gas at 20-km altitude for SAI—progress in research prior to demonstrated technology performance is much more difficult to predict. The multiple lines of research now underway into sprayer technologies, while promising, thus do not refute our judgments of the present relative feasibility of alternative SRM methods.

We do not put high confidence in the specific judgments of current technical feasibility that emerge from this thought experiment. Rather, we present the exercise to support and illustrate two claims: first, that implicit assumptions about technological feasibility underlie decisions about what interventions to research or model, which in turn shape debate about SRM technologies, and second, that refining such feasibility judgments to explicitly distinguish research-related from development-related uncertainties could more effectively focus policy-relevant SRM research and support more useful assessments.

5. SCIENTIFIC RESEARCH ON SRM EFFICACY AND RISKS

In this section, we review the major policy-relevant highlights from scientific research to date relevant to the efficacy and risks of SRM. We also characterize the diverse bodies of research that underlie these broad conclusions, to provide a basis for assessing their reliability.

5.1. Policy-Relevant Conclusions from SRM-Relevant Research: Highlights

More comprehensive surveys of the large body of scientific research relevant to the climatic and other environmental effects of SRM are available elsewhere (81, 82). Here we briefly review the high-level conclusions that can be drawn from this research, focusing on the impacts of potential SRM deployment of greatest relevance to policy and decisions.

SRM presents two fundamental policy-relevant scientific questions. How effectively could it reduce climate risks? And what additional harms or risks, of what severity, would it introduce? Answers to these questions about SRM's effects rely partly on knowledge derived from scientific research, but they also depend on assumptions about how SRM is used, under what background conditions of greenhouse gases emissions and climate change. The three principal dimensions of choice in how SRM is used are how much global-average cooling or radiative forcing is pursued, how changes in radiative forcing are distributed around the world, and what SRM method is used.

Typical assumptions of how SRM is used have changed markedly over the quarter-century since the first model study of SRM (18). Many early simulations aimed to explore climate system behavior and test models by assuming large greenhouse gas increases offset by extreme SRM deployment, e.g., doubling or quadrupling preindustrial CO_2 and fully restoring global-average temperature with SRM. These extreme scenarios were not intended to be relevant for decisions, nor even to represent realistic uses of SRM. These studies can be used to inform policy-relevant questions with appropriate linearization and scaling but are prone to misinterpretation absent such scaling. More recent studies have used more plausible and more directly policy-relevant scenarios, in which SRM complements emissions cuts to limit climate impacts (83). Several recent studies use mid-range climate projections [such as the IPCC's Representative Concentration Pathway (RCP) 4.5], offset by half or less with SAI, with balanced cooling in the Northern and Southern Hemispheres. These studies yield the following broad results:

- Such use of SAI could reduce many important climate hazards, including not just annual-average temperatures but also extreme heat, extreme precipitation, changes in water availability (including droughts and floods), tropical storms, and sea level rise (84–86).
- Even such partial and uniform use of SAI would likely produce some instances of climate change being exacerbated, i.e., climate variables moved further from their preindustrial state.

But this is projected to occur on less than 0.5% of the Earth's surface area for average and extreme temperature and precipitation, and less than 2% for water availability (87, 88).

- Such use of SAI would increase tropospheric air pollution and ozone loss and would have non-climate side effects such as small changes in the visual appearance of the sky (89–91).
- Additional risks introduced by such use of SRM may be small relative to benefits. Comparing aggregate benefits and costs in terms of their effects on human mortality, research suggests that decreases in heat-related mortality are roughly 100 times larger than increases in mortality from increased air pollution and UV exposure due to ozone loss (92).

These results are uncertain and depend strongly on the assumed partial, gradual, and balanced SRM deployment. Hemispherically unbalanced deployment would move the intertropical convergence zone of high rainfall near the equator, causing large climate disruptions. For any given average cooling, spatially uneven changes to radiative forcing, either by strong north–south imbalance of SAI or by patchy use of MCB or CCT, would likely exacerbate climate changes over larger areas than an even distribution with the same average cooling.

5.2. Reliability of SRM Research

How robust are research results like those we summarize above? This is a central question for policymakers. In making decisions based on research results, including allocating attention and resources across issues, policymakers must consider the possibility that results are wrong. A particular risk is a potential bias to overconfidence when researchers assess the importance of natural processes or the impacts of innovations identified by their own research community. The concern is not just that predictions about SRM are uncertain. All climate predictions are uncertain. Rather, the concern is errors so large that decisions based on them may fail to achieve their aim or do harm. For example, suppose some future policymaker favored a specific implementation of SRM based on research showing it would reduce drought frequency in Africa by 30%. If the true effect was a 20% or 40% reduction, that would probably not represent a policy-relevant error. But if the true effect was a 30% increase in drought frequency, that would present a grave risk of harm from decisions based on the erroneous projection.

We cannot confidently judge whether the reliability of the broad points from SRM research we summarize above makes them more like the first or the second case in this example. Yet there are some factors about the history and context of SRM research, and its relationship to other areas of geoscience research, that give a basis for confidence in the reliability of these results.

In general, we propose that the reliability of a body of research increases with the duration of research, the total volume of research, and the intellectual diversity of the research community. This is because the opportunity to identify and correct errors grows with time, attention, and critical scrutiny from diverse perspectives. We also expect reliability to be lower when commercial or other nonscientific incentives drive the research. We think of the depth of research, and thus its reliability, as reflecting the combined effect of these factors: duration, volume, diversity, and freedom from commercial interests.

In these terms, several factors can suggest that scientific research on SRM is shallow. Most explicit SRM research has been done in the past decade, and the scale of funding is small. Horton et al. (41) estimated cumulative global SRM funding from 2008 to 2021 as US$95 million. Even within this total, a significant fraction was for assessment and policy engagement, so scientific research funding for SRM is well under 0.1% of total climate research. Moreover, while other fields typically have organized research programs with explicit objectives, periodic reviews, and some degree of coordination between diverse funding streams, SRM lacks any such organized research program.

There are also countervailing factors that suggest scientific research on SRM is surprisingly deep. First, much SRM research is not captured in that US$95 million estimate because it is done by researchers working without explicitly targeted SRM funding. Second, although a large fraction of research is recent, this reflects rapid recent expansion, while some SRM research goes back about as far as modern research on climate change. The first SRM study dates to the 1960s, while the topic got serious attention in a 1992 National Academies report (15) and the first model simulation was published in 2000 (18). This long duration of research, albeit at small scale and with little funding, represents substantial time to find serious flaws, particularly given the skeptical stance of much of the climate science community toward SRM research and the resultant motivation to root out errors and biases.

A third indication that SRM research is deep is its tight connection to research in other areas of environmental geoscience. If SRM research relied on new methods to study novel atmospheric processes, then the factors suggesting research is shallow would be compelling. But SRM is better understood as an application of related research domains than as an independent field. The major results of SRM research that we summarize above rest on four distinct bodies of long-standing atmospheric and climate research.

NOAA: US National Oceanic and Atmospheric Administration

Stratospheric Aerosol Processes, Budget, and Radiative Effects (SABRE): a NOAA scientific mission to observe stratospheric aerosols and related processes

E-PEACE: Eastern Pacific Emitted Aerosol Cloud Experiment

5.2.1. Study of analogs. All proposed SRM methods are analogous to some other natural or anthropogenic perturbation, so SRM understanding benefits from research on these analogs. Sulfur SAI is an application of research on stratospheric aerosols, on which more than 2,500 scientific papers have been published starting in 1961. This research includes extensive studies of response to volcanic eruptions but extends beyond volcanos and beyond sulfur. For example, recent proposals to use alumina aerosols for SAI draw on a significant body of research on alumina injected into the stratosphere by the space shuttle program.

5.2.2. Laboratory studies. Estimates of SRM effects build on a long history of relevant laboratory research of several types. Examples include the extensive history of experimentally measured chemical rate constants that provide the foundation for all estimates of chemical impacts of SAI, augmented as needed by new SAI-specific measurements under stratospheric conditions (93); the long history of cloud chamber experiments that informs understanding of the effects of CCT and MCB; and experiments used to test deployment technologies such as MCB spray systems.

5.2.3. Field missions or experiments. Field experiments related to SRM include limited-duration observational studies such as the US National Oceanic and Atmospheric Administration (NOAA) Stratospheric Aerosol Processes, Budget, and Radiative Effects (SABRE) mission (42), as well as experiments that introduce SRM-relevant perturbations such as the Eastern Pacific Emitted Aerosol Cloud Experiment (E-PEACE) (94) or MCB experiments on the Great Barrier Reef (95). These experiments rely on a network of instruments, analysis techniques, aircraft, and institutions that have developed over decades. The boundary between SRM and non-SRM field experiments is inherently fuzzy, because experiments rarely illuminate just one topic. Many experiments not explicitly about SRM are important to its understanding, just as SRM field experiments will likely produce results of use outside SRM.

5.2.4. Explicit simulation of SRM interventions. Much of the current SRM literature is based on explicit simulation of SRM interventions using Earth system models. These models embody and integrate a deep body of research in atmospheric science conducted over more than a century. They have been extensively tested by studying their response to perturbations that are close analogs to SRM methods, including sea spray, pollution aerosols, mineral dust, and volcanic eruptions. Model intercomparison exercises such as the Geoengineering Model Intercomparison

Project (GeoMIP), which compares responses of a set of Earth system models to consistent SRM scenarios (83), use methods previously developed for intercomparison of climate predictions.

GeoMIP: Geoengineering Model Intercomparison Project

In summary, while there are plausible grounds to judge scientific knowledge of SRM either shallow or deep, these reflect different ways of defining the scope of research relevant to SRM. On balance, we find the strong linkages with several deep bodies of climate research, the relatively long history of explicit SRM studies, and the incentive of the climate science community to identify weaknesses and biases in SRM research—and the absence thus far of commercial interests that would favor overclaiming—to be the stronger case. We thus find grounds for cautious confidence in the reliability of broad results from current research.

6. SRM IN SOCIETAL CONTEXT, GOVERNANCE CHALLENGES

6.1. Policy-Relevant Knowledge about SRM Uses and Impacts

The effects of SRM on people and ecosystems will depend not just on characteristics of the technologies and the climate system but also on the social and political context in which SRM is researched, developed, and possibly used. If SRM is ever used, its effects will depend on the specific way it is used. The research summarized above projects the effects of specific deployment strategies on specific biophysical and socioeconomic outcomes to inform assessment of benefits and costs and support decisions made on that basis. This research shows the possibility that SRM, if appropriately deployed, can reduce near-term climate risks and bring large, widely distributed net benefits for people and the environment. But the possibility of such benefits provides no guarantee they will be realized, since decisions will be made not by a global welfare-maximizer but by real political actors. Impacts will depend on actual decisions about SRM use or nonuse—which research-based analysis can inform but not determine—and also on related perceptions, reactions, attributions, strategic interactions, and links to other climate responses and other issues.

These conditions of future use and impacts present multiple linked scientific, technological, and socioeconomic uncertainties. Yet despite deep uncertainty, these are not matters of complete ignorance. Two types of knowledge relevant to understanding SRM's potential uses and impacts are available: characteristics of the technologies that influence what can be done with them, and the identities, interests, and behaviors of actors who would be involved in decisions about development and use. We review these here and in Section 6.2, respectively.

SRM exhibits several characteristics that are likely to be persistent and policy relevant. They are persistent, in that they reflect properties of the technology or the environment that are likely robust to near-term advances in knowledge and capability. And they are policy relevant, in that they influence what SRM can and cannot do, and thus how it might be beneficially used and how various actors might want to use it. These characteristics influence SRM's uses, impacts, and governance needs. This is not a claim of technological determinism, but a more modest claim of relevance and influence. Technologies partly shape social and political outcomes but do not fully determine them. We identify six prominent policy-relevant characteristics of SRM interventions and briefly note each one's implications for use, impacts, and governance.

SRM deployment necessarily entails multiple dimensions of choice.

- Although the decision to use SRM is often portrayed as binary, any actual use would entail multiple dimensions of choice. The three most important choices are the trajectory of global-average cooling over time, the spatial distribution of radiative forcing, and the method used, e.g., SAI, MCB, CCT, or combinations.
- These choices will affect the magnitude, form, and distribution of impacts. Any claim about SRM benefits or harms depends on assumptions about these choices, whether in interpreting a model simulation or contemplating a real intervention.

- Implications: Every nation, and many nonstate actors, will be concerned about these choices and have a claim to knowledge about and influence over them.

All proposed SRM methods except sulfuric acid SAI are uncertain in near-term feasibility.

- Except sulfur SAI, every SRM method lacks a clear technology development pathway to global climate impact over the next few decades, due to specific identified barriers.
- These barriers differ for each method. For SAI with solid aerosols, barriers are related to particle dispersal and production; for MCB, performance of spray technologies; for CCT, uncertainty in radiative-forcing effect; for space SRM, cost and technology readiness; and for surface albedo, environmental impact and cost of climatically significant deployment.
- Implications: The current focus of SRM governance debates on sulfur SAI is appropriate. While large research advances on other methods could change this judgment, current modeling and speculation about other methods achieving significant global impact presume capabilities well beyond presently demonstrated development trajectories.

SAI could be deployed well before mid-century.

- In contrast to other methods, there are no identified scientific or technical barriers to achieving significant global cooling with sulfur SAI.
- The required duration of development effort prior to deployment depends on the scale of contemplated deployment. An incremental cooling of ∼0.1°C could plausibly be done within a decade, but cooling of ∼1°C would require an aircraft development program of at least one to two decades (96).
- Deployment aimed at global-average cooling broadly aligned with promising current model results could be achieved from two locations, in north and south tropical latitudes.
- If global emissions follow a moderately low scenario (e.g., scenario RCP 4.5), estimated deployment cost to stop further heating after 2030 would start at a few billion US dollars per year and grow to ∼$10 billion in 2050, less than 0.1% of world economic output.
- Implications: Deployment would be feasible well before mid-century, by some uncertain number of major states or coalitions. The set of unilaterally capable actors will be more strongly constrained by geopolitics and specific technological capabilities than by cost.

SRM's effects cannot be confined to a region.

- No SRM method can make sustained, significant changes to a regional climate without distant effects.
- SAI deployment strategy can adjust changes to radiative forcing along a north–south axis, but only by broad latitude bands (97). Non-SAI methods could make region-specific changes to radiative forcing, but dynamic linkages may extend resultant climate changes over larger areas. If non-SAI methods become feasible at synoptic scales (∼1,000-km radius), the strongest effects outside the perturbed region may be similar to those within.
- Implications: Every nation and world region will have a legitimate claim to participate in deployment decisions, for SAI and possibly for other methods. The intensity of those claims will depend on the extent, controllability, and spatial scale of regional impacts.

SRM cannot fully reverse the effects of elevated greenhouse gases.

- No currently identified SRM method can reverse the effect of greenhouse gases on all global and regional climate variables. Even simulations that show SRM moving climate toward prior, less perturbed states almost everywhere also show some climate variables moving further away from preindustrial values for 0.5% to 2% of the Earth's surface. Whether or not SRM is used, any increase in net emissions will increase risk.

- All SRM methods have their own environmental impacts, depending on the method used.
- Implications: SRM may delay but cannot eliminate the need to bring net emissions to zero to stabilize global climate.

Uncertainty about the effects of SRM is unavoidable.

- While research can reduce uncertainty, the impacts of any SRM deployment will be uncertain. After deployment, some uncertainties (some chemical and physical side effects) will decrease quickly. Others, such as regional climate impacts and their attribution, will not.
- Even if SRM is deployed at large scale, it will take many decades to detect and attribute climate responses at regional scales (98).
- Implications: Any intervention will be subject to continued contestation over attribution of effects, particularly for any observed regional extremes.

6.2. Relevant Actors and Interests

Decisions about SRM, and associated impacts, perceptions, attributions, and governance responses, are likely to be most salient at the international level, with nation-states as major actors. States' interests in SRM will reflect some combination of elite policymaker views, interest-group politics, and citizen preferences. On citizen preferences, the first global (30-nation) public opinion survey finds significant divergence between the Global North and South. Global South citizens were more concerned about climate change and more favorable toward SRM and enabling policies. They were also more concerned about identified SRM risks such as undermining emissions cuts or unequal benefits. The study authors conjecture that these differences reflect younger populations in the Global South, because they become insignificant with control for differences in national median age (99).

Absent clear evidence on other determinants of national interests, conjectures on states' SRM-relevant interests have taken three approaches. SRM can be treated purely as a climate response, so states' interests would be determined by projected effects of climate change—seeking an optimal climate (100) or minimizing departure from past climate (101, 102)—or by effects of climate responses. This view of state interests would suggest strong SRM support from two strange bedfellows—climate-vulnerable states and fossil-dependent states aiming to delay emissions cuts—or coalitions aligned on one or both of these axes.

Alternatively, states could view SRM in terms of national security (103–105). Despite SRM's unsuitability as a weapon (106), this view might be salient if domestic authority over SRM is captured by security institutions. This view would promote perceiving interests as opposed rather than shared; viewing others' SRM capabilities as diffuse threats and thus promoting secrecy, mutual suspicion, and escalation; and forming coalitions aligned with current alliances and rivalries. Finally, states could view SRM in symbolic terms—perhaps as a prestige technology (41), or one for which participating in control or experiencing cross-border impacts is perceived to bolster or insult sovereign dignity, independent of any material effects.

Some nonstate actors are also likely to have strong interests in SRM and may seek to influence decisions about its use and governance. Transnational civil-society organizations have been active in shaping current debates and may pursue central roles in shaping future decisions about research, development, and potential deployment. Private as well as public actors with strong interests in fossil fuel production may promote SRM to delay emissions cuts. Though not yet observed, this remains plausible when emissions cuts start to significantly threaten fossil fuel production. Actors facing large financial risk from climate change, such as property, finance, and insurance firms, might view climate risks in more straightforward risk-management terms than states and may promote SRM deployment to limit their risk exposure. Private actors may, as a few recently have, promote SRM for commercial reasons, either to directly monetize it or to benefit other business lines (107–109). Any deployment program will involve multiple firms, labor unions, and other private actors with interests in influencing the terms of deployment.

IAMs: integrated assessment models

6.3. Prevailing Narratives of SRM Use and Governance

These two bodies of relevant information—characteristics of SRM interventions and relevant actors' interests—provide the raw material for conjectures and arguments about how SRM might be used, in what context, and with what effects. These are often organized into lists of broad SRM governance challenges, with proposals for some mix of research, exploratory analysis, and consultation to develop responses. We take a different approach, presenting four narratives that capture prominent recurring themes in the SRM debate. The narratives range from aspirational, sketching how adding SRM to climate responses could broadly benefit human welfare and the environment, to cautionary, sketching how SRM might exacerbate climate change, drive geopolitical destabilization or conflict, undermine emissions cuts, concentrate power, or worsen global inequity.

These narratives involve too many linked assumptions to be understood as predictions or testable hypotheses. They are basically scenarios, which organize the main hopes and concerns expressed in current debate to support exploration of alternative pathways, causal mechanisms, and potential interventions. We outline the essential elements of each narrative and identify underlying assumptions and implications for research, assessment, or policy.

6.3.1. Planned temporary deployment with good enough governance. A repeatedly proposed model for beneficial use of SRM involves temporary deployment to supplement emissions cuts and removals, providing a stopgap to reduce near-term climate impacts while these other responses scale. From one early form sketched on a napkin by the 2009 Royal Society assessment Chair, variants of this narrative have been widely circulated, analyzed in integrated assessment models (IAMs), and repeated in subsequent assessments (48, 78, 110–112).

While varying widely in detail, presentations of this narrative involve a few key common elements: a relatively early start to SRM deployment; a gradual build-up of cuts and removals that continues through the period of SRM deployment, and possibly after; a trajectory of SRM use that increases to a maximum when atmospheric carbon concentrations peak and net emissions go negative, then decreases and phases out; and eventual return, after a century or more, to a stable global temperature with net anthropogenic emissions of zero. Within this broad picture, specific presentations vary in how early and strongly SRM is begun; the level of SRM deployment and associated temperature trajectory during deployment; how fast cuts and removals scale up, which determines how much SRM is needed for how long to achieve that temperature trajectory; and the temperature endpoint, which depends on the cumulative balance of emissions and removals.

Of the four narratives, this one best fits a utilitarian optimizing perspective. It aims to minimize the size and duration of temperature overshoot, subject to constraints on the speed of scaling cuts and removals, the maximum strength of SRM deployment, and its rates of increase and decrease. The narrative is generally stated simply as response trajectories with no discussion of how, or by whom, these are achieved—i.e., with no policy or politics. It has been criticized for presuming a benevolent global dictator or legitimate world government, although it might not require such extreme and unlikely conditions. The narrative clearly requires coordinated action to start, sustain, and eventually stop SRM deployment. It also requires other nations' acquiescence to this deployment trajectory, which in turn presumes the deployment is bringing sufficiently clear and widespread benefits to deter states or others who might be able to obstruct it from doing so. Finally, the narrative presumes that emissions cuts and removals, however motivated and controlled, grow enough to stabilize climate in a widely accepted state after SRM is phased out.

These governance presumptions are demanding, but not as much as sometimes suggested. They could reflect ideal global governance that is competent, precautionary, and just, based on climate change being prioritized and framed as a non-rival, shared peril. But the minimum governance requirement is lower: enough competency and prudence in managing SRM, enough support or acquiescence by others, and strong enough emissions cuts and CDR to achieve the needed transition. Whether such adequate governance could be achieved by collaborative action working through existing international institutions is an open question, but it is not clear a priori that it could not. Indeed, the minimal geopolitical and institutional conditions for climate coordination that includes SRM may well be no more demanding, perhaps less, than those needed to achieve the same stable climate endpoint through emissions cuts and CDR alone, because those alternative paths without SRM would have to be sustained through more extreme realized climate changes and would probably present more unequal distributions of costs and benefits and stronger zero-sum interests.

6.3.2. Unilateral or unauthorized use. A second prominent narrative draws on the often-voiced concern that one or a few states might act alone to deploy SRM, either in the absence of international governance or in defiance of some governance regime that does exist. States' motives for acting unilaterally are generally assumed to be climate-dominated: some combination of severe climate impacts and judgments that other responses, national or international, are unavailable, ineffective, or too slow. Other plausible motives would include seeking to prompt international SRM action, dramatize the state's plight to seek aid, or spur new coalitions organized by climate risk.

States generally identified as likely to act unilaterally are defined by climate vulnerability, technological capability, and geopolitical positioning. Speculation often settles on India, perhaps in a coalition of climate-vulnerable low- and middle-income states (113–115). This speculation gains support from projections that hot, low-latitude countries would benefit most from SRM (100), yet it may still reflect a narrow or biased view of climate vulnerability. Growing recognition of widespread climate vulnerabilities and weakening global institutions suggests the plausibility of unilateral actions by industrialized countries, or by novel coalitions that combine technical capability with climatic and geopolitical positioning.

This narrative, and in particular who might lead in pursuing unilateral SRM deployment, varies strongly with precisely what is assumed to be done unilaterally. Early speculation considered deploying sulfur SAI at a scale to achieve significant global cooling, ~1 Mt per year, but this appears infeasible even for great powers without a decade or more of prior development. The provocative initial step would thus not be immediate large-scale deployment, but starting this development process. Because this would be observable, other states could object; if they do not, this would suggest some degree of tacit support.

Provocative unilateral action could also take the form of a deployment much smaller than the one in this full-scale scenario, placing on order one-tenth as much sulfur or less. Such subscale deployment, using current technology, would be within reach of many more actors and could be started within a few years. Such a deployment might aim to develop capabilities, to demonstrate possibilities, or to force the SRM issue onto the agenda. The change in climate achievable in this way would not be detectable above natural variability at national scale, so deployers could argue that this was consistent with avoiding trans-boundary harm under customary international law (96).

Non-SAI methods—MCB, CCT, or surface albedo change—might be deployed unilaterally over limited areas to reduce regional impacts. Research suggests that using these at synoptic meteorological scales ($\geq 10^6$ km^2) may have distant effects (116–118), but as we note above, interventions at this scale may be infeasible over the next few decades. Using these methods at a smaller scale ($\sim 10^4$ km^2) would be more feasible and present less risk of distant climate effects. It could thus more readily be asserted to lie within sovereign discretion.

The main threat from unilateral intervention is the provocation it presents to other states and the resultant risks of destabilization or conflict. Other states will surely object, for various reasons and with varying intensity, ranging from pro forma objection to firm determination to resist. The severity of geopolitical threat from this narrative will mainly depend on these responses by other states, especially major powers.

One recourse for other states would be to invoke international law. In general, the scale of environmental effect that requires international engagement is indeterminate. The duty to avoid trans-boundary harm is well established, but the record lacks precedents relevant to the novel case of SRM. At one extreme, even a synoptic-scale MCB intervention could be deemed a domestic matter if there are not material distant effects clearly attributable to the intervention. At the other, tiny symbolic activities with negligible material impact could spur calls for international response, which international institutions might be compelled to address.

Beyond legal objection, states would have three possible responses. They could use sanctions to induce the instigator to stop or change, including the threat of force if their relative power is sufficient. They could conduct or threaten offsetting interventions, if the balance of efficacy and risks makes these credible (119). Or they could bid to tame the disruptive action and bring it under shared control. Limited information relevant to these responses is available, mostly from scenario exercises that simulated international reactions to unilateral interventions (114, 120). These have favored the third response, taming the provocation and seeking shared control rather than trying to stop it—a result sufficiently consistent to suggest that escalation threat from unilateral SRM provocations might be less severe than thought. If other states exercise restraint, their reactions and subsequent events could even help build a response that fulfills the good enough governance needs sketched in the narrative above. The main difference between the two narratives would then reduce to whether governance is built in advance of a provocation, or in reaction to one that has occurred. Given the difficulty of creating new institutions except in response to a crisis, starting with a unilateral provocation might even represent the more plausible pathway toward acceptable governance.

6.3.3. Selfish, rivalrous, or hostile use. A third prominent narrative in current debate and concern, related to but distinct from unilateral use, is that some actors may seek SRM deployment that aims to selectively benefit their region, with less regard—or in the extreme, with hostility—for others' interests. In extreme form, these narratives presume—contrary to current evidence—that SRM can be weaponized (105, 106), analogizing to Cold War speculation on weaponizing weather modification and its hostile use by the United States in the Vietnam War (8, 121, 122).

One requirement for this narrative to be plausible is the ability to differentially control significant regional effects of SRM. SAI targets global changes at interannual or longer timescales, and results thus far suggest limited ability to tune effects by broad latitude band, and no ability to tune effects by longitude or finer-scale region.

Within this generally limited capacity for regional control, however, one significant pattern of regional disruption has been identified. Asymmetric intervention between the Northern and Southern Hemispheres would disrupt climate in the tropics by moving the intertropical convergence zone away from the more strongly cooled hemisphere (123). While this asymmetry is typically seen as a deployment failure to be avoided, it is plausible that arid subtropical countries may regard the increase in precipitation from such asymmetric intervention as a benefit. This would represent the first plausible identification of a specific regionally rivalrous use of SRM, albeit one requiring an intervention in the opposite hemisphere from the countries seeking to benefit. It also represents the first plausibly attractive use of counter-geoengineering, since the instigator's aim and resultant disruptions could be counteracted by an equal SAI deployment in the other hemisphere, producing a hemispherically symmetric deployment similar to the broadly beneficial ones discussed in the first narrative.

In addition to technical plausibility, assessing the risk of selfish or hostile use requires specifying the geopolitical scenario by which it would come about. States reacting to any unilateral deployment are virtually certain to express suspicion of selfish or hostile intent. But the issues discussed above—time-lags to build toward meaningful global-scale deployment, the visibility of such preparations to other states, and the greater dependence of outcomes on others' response than on the initial provocation—would all apply in this case and limit the associated threat.

A subtler case would be selfish or hostile use that is not unilateral, but instead operates through an international governance system. In this case, the instigator would have to subvert the system to their advantage. If governance is broadly shared, this would require clandestine knowledge or control over implementation details, which seems implausible for any sustained, nontrivial intervention. If effective control is more limited—e.g., if a few mid-latitude countries are dominant and have identified strategies that benefit mid relative to low latitudes—the concern becomes somewhat more plausible, although still with several grounds for skepticism. Model results suggest the largest benefits go to low-latitude, climate-vulnerable regions. Even the new case we identify above, hemispheric asymmetry benefiting arid subtropical countries in one hemisphere, would require an obviously distorted intervention with well-known effects. Given the real-time observability and one-year controllability of interventions, even some subtle new tactic for regional benefit would be limited by the trade-off that sustained regional benefits big enough to be worth pursuing would also be big enough to detect and attribute. Those harmed by, or not gaining fair benefit from, such an intervention would know soon enough and be able to respond.

The SRM methods conducted in the troposphere, MCB and CCT, present different issues for selfish or hostile use. The strongest known impacts of these are regional, with the smaller, more feasible scales of deployment only weakly distinguished from weather modification. Even weather modification can have trans-boundary effects when conducted near borders, but such bilateral conflicts do not present novel global governance challenges. If use of these methods at larger scales is found to be more feasible than we suggest, and evidence of distant effects persists, then the case for global engagement would be stronger—rebutting our conjecture above that states could credibly claim their use of these methods is a purely sovereign matter.

In our tentative judgment, pursuit of selfish SRM interventions is unlikely to present serious geopolitical risks. As noted above, there is little evidence of regional tunability of SAI impacts. Even our novel example of regional benefits from hemispheric asymmetry may be geopolitically implausible. Yet there will surely be claims of both harmful impacts and rivalrous intent, and these may be disruptive even if their scientific support is weak. This suggests the importance of broad global participation and control in any SAI governance—broad but not necessarily universal, since similarly situated states may choose collective representation. Irreducible uncertainty in attributing regional effects to any intervention—certainty of continued uncertainty—will require governance mechanisms to address alleged harms from interventions, even without persuasive attribution. This may be the case for MCB and CCT as well as SAI, if these are deployed at large enough scale. Nations will have to consider the possibility of persistent disagreements, with those making deployments claiming these are purely sovereign matters while others allege significant distant impacts, and no clear scientific basis to resolve the disputes. This suggests the possibility that one high-stakes, SRM-related governance decision may be required early, well before serious consideration or development of globally significant deployment: deciding which methods and scales of deployment will be treated as a purely sovereign or bilateral border matter just like old-fashioned weather modification.

6.3.4. SRM impairing emissions cuts. Our final narrative reflects long-standing concern about how the presence of SRM on the climate agenda—its use, development, research, or mere identification and awareness—might influence other climate responses. Many such interactions are possible and merit examination: SRM may shift the scale or mix of adaptation, emissions cuts, and removals and thus the distribution of costs and benefits over places, people, and time. But in this narrative we follow the most prominent concern—often called "moral hazard" (8), or more precisely (and with different valence) "mitigation displacement"—that SRM may weaken emissions cuts (124).

The concern is that some SRM-related knowledge or action may trigger a behavioral adjustment mechanism, typically involving SRM being incorrectly perceived or relied on as a complete climate response. The mechanism could operate at an individual or political level: (*a*) a widespread bias to overvalue near-term benefits of SRM relative to longer-term benefits of emissions cuts, or (*b*) a capture of decision processes by fossil fuel or other interests threatened by emissions cuts (125). The opposite effect has also been proposed, that considering SRM may credibly signal climate alarm and so galvanize support for all responses, including mitigation.

Two lines of research have examined this interaction, which both call into question strong concerns about mitigation displacement. In empirical studies of individual decision-making, people express concern about mitigation displacement, but learning about SRM either increases their support for cuts or has no significant effect (126, 127). One study found an intriguing perverse consequence of this disparity between people's worries and actions: Subjects placed in policymaker roles declined to take clearly beneficial SRM actions because they thought other participants would respond by weakening their mitigation efforts, even though they themselves did not (128). Game-theoretic studies of strategic interactions in states' climate decisions found a parallel result, that the threat of SRM under some conditions can induce stronger, even excessive emissions cuts (129, 130). Both lines of research suggest mitigation displacement might not be as harmful as this narrative presumes, although neither targets the precise concern: that real political decisions under interest-group mobilization will cut emissions too little in the presence of SRM. In particular, neither addresses the policy influence of fossil fuel interests, which have thus far been silent on SRM but could plausibly mobilize, when proposed cuts begin to seriously threaten their interests, to falsely portray the availability of SRM as obviating the need for emissions cuts.

Beyond these empirical questions, there is a conceptual ambiguity in the concern underlying the narrative, including basic ambiguity in the term "mitigation displacement"—displacement relative to what, and is this always bad? In any normative analysis of climate change that considers alternative responses and trade-offs between them, different response types exhibit some degree of substitutability in pursuit of the goal. In such analyses, the availability of SRM delays the trajectory of preferred emissions cuts on the route to climate stabilization, just as does the availability of adaptation or CDR. This result is best known from IAM studies of optimal climate-response trajectories using either a benefit–cost or cost-effectiveness framework, where mitigation displacement increases societal welfare because the shift from earlier emissions cuts to later cuts with SRM brings more benefits than costs (78). The result is not limited to such a utilitarian framework, however. Displacement would also occur under any alternative normative framework, such as rights-based or capabilities approaches, so long as different responses exhibit substitution in pursuing the normative aim.

The concern motivating this narrative agrees with these analyses that including SRM in potential responses delays emissions cuts, but it judges this displacement a harm, not a benefit. Two possible lines of reasoning could support this conclusion. The first would reject assessing climate responses by benefits and costs, or by any other normative framework that would allow response substitution to weaken emissions cuts. This line of reasoning would assign moral priority to emissions cuts themselves, treating them as ends rather than means that supplant any other end that can be advanced by cuts or other responses. But by this reasoning, how much emission cutting, how fast, holds such normative priority? In view of compelling needs in health, education, development, and other societal priorities—including other environmental values—it appears implausible that the answer is to direct all societal resources to cutting greenhouse gas emissions. But this line of reasoning gives no basis for defining the right level of mitigation effort anywhere short of that implausible endpoint.

The second line of reasoning would accept the normative framework but argue that emissions cuts are too weak relative to that framework, either because the analysis gets the relevant benefits and costs wrong or because the processes that determine policy outcomes ignore them. This is in principle an empirical claim, but it cannot be resolved by observation because the weakening occurs relative to a counterfactual trajectory of mitigation effort that is unobservable. The question can thus only be resolved by proxy methods such as modeling or research, including observation of the historical trajectories of mitigation effort and knowledge of SRM. While there is wide agreement that mitigation has been inadequate, it is not clear that SRM is responsible, since weak mitigation long predates the emergence of SRM in debate. Moreover, given that past shortfalls cannot be changed, it is not clear by how much current mitigation effort—for which clean energy investment, currently 1.7% of world economic output and rising, provides a reasonable albeit incomplete measure—remains suboptimal.

While the prospect that attention to SRM may have weakened mitigation is not observable, it is clear that concern about such displacement has driven opposition to discussing SRM since the early 1980s, with strikingly little advance in debate since then (131; F. Press & W.S. Broecker, personal communication; K. Hasselman & W.S. Broecker, personal communication; B. Bolin & W.S. Broecker, personal communication; J.D. Mahlman & W.S. Broecker, personal communication).[1] It appears likely that the narrative that SRM may weaken mitigation will remain prominent, but that the reality and scale of harmful mitigation displacement will remain uncertain—a serious concern that warrants practical efforts to lessen but is unresolvable. There are proposals to address the concern through norm building and institutional setting—locating decisions about emissions and SRM together, so joint action and trade-offs can be explicitly debated—or by linking decision agendas to make mitigation and SRM mutually reinforcing, by requiring strong cuts as a condition for states to participate in SRM decisions or gain related benefits (132, 133). Evaluation of these preliminary proposals is also hindered by the weak evidence and underspecified causal mechanisms of the moral hazard narrative. More research and policy innovation are needed, both for managing SRM–mitigation interaction in the context of continued saliency of the moral hazard narrative, and for the broader challenge of coherently integrating the four elements of climate response—mitigation, adaptation, CDR, and SG—over multiple decades.

7. PROPOSED NEAR-TERM ACTIONS/INITIATIVES

A few near-term initiatives have been proposed that could provide urgently needed advances in arguments about and understanding of SRM's potential role in climate response. This section outlines these, with brief notes on likely prominent issues and controversies.

[1]We thank Alan Robock for bringing this early correspondence on mitigation displacement to our attention.

7.1. SRM Research, Research Governance, and Assessment

Support for SRM research is expanding sharply, with government and philanthropically funded programs announced or in development in several countries. Further work is needed to define near-term research agendas, but several recent reports have laid the groundwork with proposed agendas that combine lab studies, climate-model simulations, environmental observations, and field experiments.

A significant gap in recent research has been engineering studies to assess feasibility and barriers for specific methods and scales of deployment. Understanding SRM impacts requires judgments of what types and scales of intervention are feasible. These, in turn, require engineering analyses of performance and cost, which may show either feasibility or infeasibility. We conjecture that the present gap may reflect researchers' reluctance to be seen as supporting deployment, but the gap may paradoxically have encouraged an undisciplined debate, marked by speculation about methods and scales of use that are unlikely to present significant promise or threat on a policy-relevant timescale. Correcting this gap could support a more focused and practical debate about plausible options.

Recent research proposals acknowledge concerns about SRM and calls for SRM-specific research governance. It is unclear how to address these, however, as they pertain not to direct controllable harms caused by research activity itself but rather to indirect risks of research, typically from misuse of the resultant knowledge. There are few precedents for controlling research by subject matter based on such indirect threats, all in weapons-related research areas of limited relevance to SRM. The likelihood of multiple independent programs will further complicate research governance. Collaborative programs like the World Climate Research Programme's 10-year Lighthouse Activity can support research coordination and priority-setting (50). There is also broad support for principles of responsible research such as transparency, avoiding conflict of interest, and global collaboration that prioritizes engagement and capacity-building in lower- and middle-income nations, but translating these principles into concrete practices has been challenging and may remain so given multiple programs with no single governance authority.

Assessment of SRM—synthesizing research results and gaps to inform policy-relevant questions and communicating these effectively with international nonscientific stakeholders—is a distinct need from research coordination, usually done by a separate body. Effective assessment bodies sit between science and policy, requiring strong and trusted connections to both. There is no present body well positioned to perform this function for SRM. UNEP would seem an obvious candidate, given its strong global credibility, particularly in the Global South, and its recent support for a strong ad hoc expert-group assessment. Its governing body has twice rejected proposals to put SRM assessment on stronger institutional footing, however, most recently in March 2024. The urgent issue of identifying a feasible institutional home for international SRM assessment thus remains unresolved.

7.2. A Moratorium on Large-Scale Interventions

The Climate Overshoot Commission recently proposed a moratorium on SRM deployment (2). A moratorium is a temporary or conditional prohibition, adopted to provide time to assess and control a shared risk or to negotiate sharing and management of a contested resource (134). The Commission's moratorium would cover any SRM intervention large enough to risk significant trans-boundary harm, aligned with the "no harm" principle of customary international law.

The Commission paired the moratorium with support for SRM research and governance consultations, aiming to calm concerns that these activities might improperly expand to large-scale intervention by explicitly barring the large-scale activities. Other proposed SRM moratoria have been more restrictive and lacked this balancing character, defeating the purpose of safely building knowledge and governance capacity by blocking small-scale activities that would contribute to these. While any moratorium should stop short of barring small-scale research and other activities to build knowledge and governance capacity, the Commission's proposal might usefully be expanded to include recently identified subscale interventions that, by building a path to global deployment, may present near-term risks of geopolitical disruption.

The target actors for a moratorium are the states potentially capable of conducting the restricted activities—a small set of major powers under the Commission's original proposal, or a somewhat larger set if the moratorium also aims to include subscale deployment. The Commission proposed that states adopt the moratorium individually or in informal coordination, but no state has yet done so. We conjecture that major powers facing domestic controversy over SRM might manage that controversy by adopting a moratorium in parallel with establishing SRM research programs and tightening mitigation.

7.3. Building Toward Future SRM Governance

The prospect of future SRM deployment, of any form by any actor, will present governance challenges that are novel, potentially severe, and deeply uncertain. There may be substantial benefit in exploring these governance issues early, but there has been little effort thus far, with no significant engagement of governments—and few concrete proposals on how to start.

Governance issues can be informed by research, including studies of perceptions of SRM and policy implications of technology characteristics as we discuss above. Governance capacity may grow organically as a spillover effect of research coordination, assessment, or debates over moratoria. But these activities alone are unlikely to advance understanding on key high-stakes questions about governance needs for future deployment-related challenges: For example, what advance preparations might minimize risks of a unilateral SRM-related provocation? Who must participate in decisions on SRM interventions and governance? By what criteria would such decisions be made? What is the necessary scope of authority for an SRM governing process? How would such authority relate to existing governance processes?

These questions urgently need exploration, but they are not ripe for near-term decisions or posed sharply enough for research. Exploration of these questions will need to draw on relevant expert knowledge and experience, political judgments, speculation about future climate and geopolitical conditions, and normative visions. It will require open-ended exploratory and integrative methods, adapted from long-range visioning and strategic planning exercises, scenario and simulation methods, and war games. The aims of these explorations would include stimulating new insights based on wise and expert political judgments, building understanding and norms, disseminating knowledge, and civic education. Given this range of aims, there is value in multiple independent activities, with diverse methods; national and international settings with particular attention to engagement in the Global South; and participants including experts in multiple areas, officials, educators and students, journalists and artists, activists and critics. Because it can be difficult or risky for governments or international organizations to convene or endorse such speculative and exploratory activities, early-stage convening may best lie with unofficial bodies—research, public-service, or other civil-society organizations, or novel ad hoc convenings—provided these can attract the needed resources and participation.

8. CONCLUSIONS

Consideration of SRM and its potential role in climate response is at a crux. After a decade of narrow debate, interest is rising, and increases in research effort, policy attention, and controversy are likely. This shift will bring significant new challenges and responsibilities. As SRM becomes prominent, interests may emerge that seek to capture it for their benefit, so it is critical to steer its development to align with broad human and environmental welfare.

Research and assessment need to urgently advance the knowledge base for reasoned consideration of SRM without provoking either uncritical overreliance or backlash. This will require robust international consultation and a trusted process to assess the implications of advancing science and technology. It will also require stronger integration of SRM research into mainstream climate science and building links in several directions: to engineering assessments of feasibility, to studies of relevant attitudes and values, and to assessment of practical interventions to limit risks.

Progress on governance may pose even greater challenges. The range of plausible governance needs for SRM is vast: It might be manageable by adjusting present international law and institutions, or it might require unprecedented new global governance authority. The new authorities that are required will not necessarily follow current issue boundaries but may instead require new linkages to other climate responses; other environmental issues; or development, security, or other issues beyond the environment. Governance challenges may be manageable if shared interests in reducing climate risks dominate rival ones. Progress may come from pragmatic accommodations to meet immediate needs as they arise within adaptive frameworks. But neither of these easy pathways is assured.

SRM is a prominent landmark in the transition to the Anthropocene, dramatizing the responsibilities that flow from having control, even imperfect, of global conditions formerly beyond human agency. This profound transformation has been coming for more than a century, but SRM will make it undeniable. By dramatizing the reality of shared control and responsibility for the atmosphere, SRM implicates issues of global development, solidarity, and justice, even more sharply than climate change already has. The potential consequences—political, cultural, psychological, and moral—are profound.

SUMMARY POINTS

1. After a long slow start, solar radiation modification (SRM) is seeing a rapid increase in research, attention, involvement of private and public organizations, and controversy.
2. Stratospheric aerosol injection (SAI) with sulfuric acid is the only SRM method with a clear technology development path to deployment within two decades, and thus the only one likely to present significant climate-response opportunity or geopolitical threat over that period.
3. The benefits and harms of SRM depend strongly on specific assumptions of how it would be used, particularly what method is used, how strongly, and with what spatial distribution.
4. If sulfur SAI is used to offset only a fraction of total warming and deployment is hemispherically balanced, it can reduce many aspects of climate change over most of world, with risks and harms that appear small compared with its benefits.
5. International disruptions could come soon, from unilateral pursuit of a development path toward SAI deployment or from related challenges, but the resultant geopolitical threat will mainly depend on other states' reactions and may be less severe than previously suggested.

6. New global governance capacity will be needed to manage deployment-related challenges but may more likely arise in reaction to a triggering event than be developed prospectively.
7. Mitigation displacement (or moral hazard) is a significant concern that warrants vigilance against SRM weakening overall climate response, but understanding of its severity has not progressed in decades and may be unachievable, so the concern does not warrant continued marginalization of SRM in mainstream climate policy debate.

FUTURE ISSUES

1. SRM research is likely to increase rapidly, including expanded stratospheric observations and small field experiments.
2. A moratorium on large-scale interventions may be a prudent near-term step, provided its scope is drawn to enable, not suppress, research. Such a moratorium might be adopted by major powers in conjunction with expansion of research and significant strengthening of mitigation action.
3. Alleged deployments, such as recent claims from tiny startup firms, are likely to continue and expand. These have no material climate impact but still carry substantial potential for confusion and political disruption.
4. Linkage of popular commentary on SRM with conspiracy theories is already present and may expand and merge with broad anti-science and anti-technology conspiracy movements.
5. SRM's future governance needs are novel, potentially severe, and deeply uncertain. There is an urgent need to start exploring these, with diverse methods and broad participation, including government and international officials in settings that encourage candid speculative exploration of scenarios and options.

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AUTHOR CONTRIBUTIONS

The coauthors participated equally in developing the framing, scope, and major arguments and conclusions of the review. D.W.K. led the drafting of Sections 4 and 5; E.A.P. led the drafting of sections 1, 2, 3, and 7. The coauthors participated equally in drafting Section 6 and in revising, editing, integrating, and writing of conclusions, summary points, and future issues.

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