Solar Geoengineering Landscape Analysis

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Executive Summary

Solar geoengineering (also referred to as solar radiation management, solar radiation modification, or solar climate intervention) is a set of proposed technologies that would reduce the amount of solar energy received by the Earth to partly offset global warming and climate change. The leading proposal for solar geoengineering is stratospheric aerosol injection (SAI), which would involve dispersing aerosols in the upper atmosphere to reflect a small fraction of incoming sunlight back to space and lower global temperatures. Marine cloud brightening (MCB) is a less studied proposal to whiten marine clouds by spraying sea salt, also to reflect sunlight and reduce temperatures. In both cases, since the introduced particles would eventually fall out of the atmosphere, they would need to be replenished on a continual basis. This analysis is focused on SAI, and the terms "solar geoengineering" and "SAI" are used interchangeably unless otherwise noted.

Solar geoengineering would be *fast*, producing climate effects within a year; *cheap*, with direct costs in the tens of billions of dollars; and *imperfect*, because reflecting sunlight is not a substitute for cutting greenhouse gas emissions. Solar geoengineering could not restore the climate to historical conditions; instead, a geoengineered climate would have some novel features, such as altered patterns of regional precipitation compared to preindustrial times. A geoengineered climate, however, may well be safer for people and nature than a warmer climate without solar geoengineering. Decisions about solar geoengineering, in other words, will involve difficult risk-risk trade-offs. Importantly, modeling results consistently show that moderate amounts of solar geoengineering reduce climate risks compared to simulations without solar geoengineering.

Solar geoengineering would entail a number of additional risks. Its low cost and relative technical simplicity might allow for unilateral deployment by a single country, leading to international instability and potentially conflict. Diverse national interests will likely complicate reaching international agreement on whether and how to implement the technology; disagreements may center on the global distribution of benefits, costs, and risks anticipated to result from deployment. Talking about, researching, and/or implementing solar geoengineering might pose a moral hazard by undermining efforts to decarbonize. Failure to continually replenish aerosols could result in a "termination shock" of rapid, destructive warming. These and other risks pose serious governance challenges; however, the severity of these challenges is unclear, and effective governance solutions may be available. And these risks must be weighed against the risks of not pursuing the potentially huge benefits associated with the technology.

Contemporary global governance of solar geoengineering is inadequate. The United Nations Framework Convention on Climate Change and its Paris Agreement do not address solar geoengineering. The Convention on Biological Diversity (CBD) adopted a moratorium on geoengineering activities that could negatively impact biodiversity in 2010, but it carved out an exception for small-scale research, is not legally binding, and has had little substantive impact.

A small number of civil society groups have attempted to influence how the issue is perceived and governed. So far, the most consequential of them is the Action Group on Erosion, Technology, and Concentration, better known as the ETC Group, an activist group opposed to emerging technologies that helped orchestrate the CBD moratorium.

Although there is no longer a taboo on researching solar geoengineering, research has proceeded very slowly due to concerns about the risks and challenges posed by the technology. Leading research efforts include Harvard's Solar Geoengineering Research Program (SGRP) and the National Oceanic and Atmospheric Administration's Earth's Radiation Budget (ERB) initiative, as well as Australian research on MCB that is part of an initiative to protect the Great Barrier Reef. Virtually no outdoor field experiments have taken place, and no country has established a national research program.

Global funding for solar geoengineering research from 2008 to 2021 totaled approximately $95 million; this accounts for a tiny fraction of overall spending on climate change research. Limited funding has impeded research. Most of what has been provided has gone toward interdisciplinary research. Governments and philanthropies have provided roughly comparable amounts, but public funders have tended to support research marked by skeptical views, while private funders have tended to support more ambitious research. The US dominates research funding, with Australia a distant second.

The politics of solar geoengineering is still emerging, but for now it has coalesced around the question, *should research on the technology be expanded?* Support for research generally declines in proportion to the scale of physical intervention proposed: indoor research is relatively uncontroversial, but support drops for small-scale outdoor experiments, and large-scale experiments are widely opposed. Policymakers and civil society groups who back limited field tests tend to support a restrictive regulatory approach that would attach relatively strict conditions to proposed experiments, as opposed to a more permissive approach. Other stakeholders oppose outdoor experiments at any scale. Disagreement over whether small-scale field trials should be tightly regulated or prohibited altogether divides the US environmental community, which wields uncommon influence on the future of research in the US and therefore throughout the world.

This analysis leads to the following recommendations:

Recommendation 1: Convene a collaborative process that includes pragmatic environmental groups, regulatory experts, and scientists with the goal of reaching consensus on a model of research governance for solar geoengineering applicable to small-scale outdoor experiments.

Recommendation 2: Facilitate or coordinate the formation of an international solar geoengineering research consortium involving scientists from around the world, including from the US and China.

Recommendation 3: Organize or sponsor a research project to assess anticipated national preferences regarding desirable amounts of planetary cooling, covering a representative set of countries and employing multiple methods.

Recommendation 4: Cultivate or seed an advocacy group dedicated to pushing for expanded research on solar geoengineering.

Solar Geoengineering Landscape Analysis

Introduction

This study provides an overview of the science, governance, and emerging politics of solar geoengineering, for the purpose of offering recommendations for strategic interventions in this space by the Rockefeller Foundation. Solar geoengineering is a set of proposed technologies that would reduce the amount of solar energy received by the Earth to partly offset climate change. Solar geoengineering has the potential to deliver significant global benefits by limiting the impacts of climate change, but it also involves significant risks and uncertainties that pose serious governance challenges. Improving our understanding of these benefits, risks, and uncertainties requires research, yet concerns about the technology have constrained research funding and limited scientific investigation. Contemporary policy debates about solar geoengineering revolve around the desirability of expanded research and how such research should be regulated. Serious political discussions about the technology have barely taken place.

To characterize the solar geoengineering landscape, this report proceeds as follows. First, the basic science of solar geoengineering will be reviewed at a high level and in nontechnical language, and its key risks and limitations considered. This will be followed by a discussion of the governance challenges posed by these risks, a review of current global governance arrangements, and a survey of civil society engagement on the issue. The current state of research and research funding will then be summarized, followed by a discussion of nascent debates about expanding research and research governance. Finally, four specific recommendations informed by this landscape analysis will be made. They include:

Recommendation 1: Convene a collaborative process that includes pragmatic environmental groups, regulatory experts, and scientists with the goal of reaching consensus on a model of research governance for solar geoengineering applicable to small-scale outdoor experiments.

Recommendation 2: Facilitate or coordinate the formation of an international solar geoengineering research consortium involving scientists from around the world, including from the US and China.

Recommendation 3: Organize or sponsor a research project to assess anticipated national preferences regarding desirable amounts of planetary cooling, covering a representative set of countries and employing multiple methods.

Recommendation 4: Cultivate or seed an advocacy group dedicated to pushing for expanded research on solar geoengineering.

The Basic Science of Solar Geoengineering

Solar geoengineering (also referred to as solar radiation management or solar radiation modification–SRM–as well as solar climate intervention) is a set of proposed technologies that would reduce the amount of solar energy received by the Earth to partly offset global warming and other impacts of climate change.[1][2] The type of solar geoengineering most seriously considered up to now would use aerosols in the upper atmosphere (stratosphere) to reflect a small fraction of incoming sunlight back to space. Stratospheric aerosol injection (SAI), the most studied and arguably most plausible form of solar geoengineering, would involve using aircraft to disperse aerosols in the stratosphere to scatter sunlight. SAI is inspired by the observed effects of large volcanic eruptions such as Mt. Pinatubo in the Philippines in 1991, which cooled global temperatures by approximately 0.5 °C in the year that followed.

Aerosols dispersed by SAI would quickly circulate around the hemisphere in which they were injected and then move toward the poles (they would not cross the equator). Furthermore, injecting aerosols in one hemisphere but not the other—for example, in the northern but not the southern hemisphere—would push the Intertropical Convergence Zone (an equatorial band of clouds encircling the planet) away from the hemisphere in which aerosols were released, disrupting tropical precipitation in the opposite hemisphere with likely harmful consequences. Consequently, responsible implementation of SAI would require dispersing aerosols in both hemispheres. In practical terms, this means that using SAI would generate either global effects, or regional effects at both poles. Given that climate risks are concentrated in tropical and subtropical areas, SAI has been investigated primarily as a potential global intervention.

A second form of sunlight reflection, marine cloud brightening (MCB), would entail spraying seawater from ships into marine clouds in the lower atmosphere (troposphere); sea salt from the spray would act as cloud condensation nuclei, whitening the clouds and increasing their reflectivity. Brighter clouds would cool underlying ocean waters in the same way that ship tracks reduce temperatures in their wake. MCB thus has the potential to cool small patches of the ocean; those areas with the best conditions for cloud whitening are off the western coasts of North and South America and Africa. MCB would have local effects, i.e., cooling would be limited to within tens of kilometers of the spray site. While local applications could be aggregated to produce regional and possibly global effects, such effects would necessarily be patchy and might make some climate impacts worse. Figure 1 illustrates both SAI and MCB.

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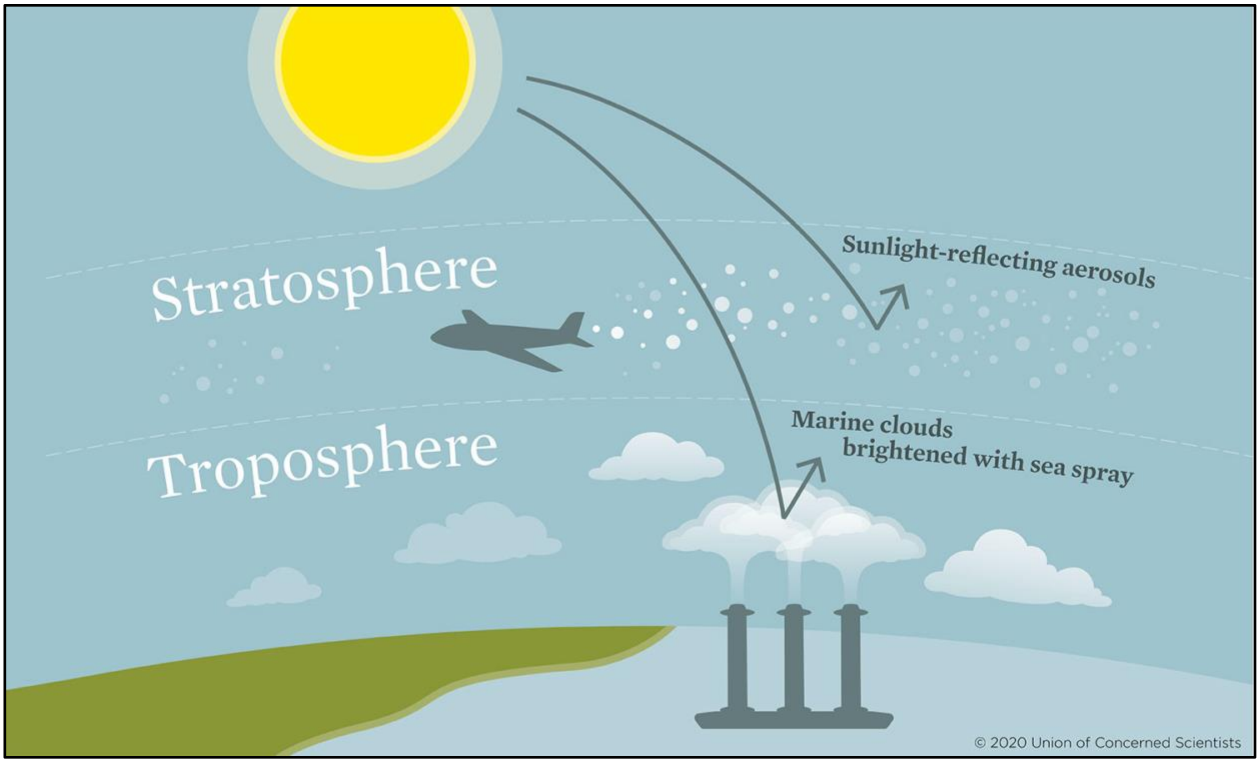
[1] For an up-to-date comprehensive discussion of the science of solar geoengineering, see NASEM 2021.

[2] Cirrus cloud thinning (CCT) is a proposed geoengineering technique related to but different from solar geoengineering. CCT would involve seeding high-altitude clouds above the poles to facilitate heat flow out of the atmosphere. Unlike solar geoengineering, which would reflect sunlight (or "shortwave radiation"), CCT would increase the amount of heat (or "longwave radiation") transferred from the Earth's surface back to space. Because very little research has been conducted on CCT, this method will not be covered in this landscape analysis.

Figure 1: SAI and MCB Solar Geoengineering



Source: UCS 2020.

The key difference between SAI and MCB thus relates to the scale of their effects, with the former being global and the latter local in nature. Some researchers have raised the possibility of "cocktail geoengineering" in which different techniques might be mixed to increase net climate benefits (Cao et al. 2017). By contrast, a key, policy-relevant similarity between SAI and MCB is the fact that particles dispersed by either technique would fall out of the atmosphere, within a couple of years for SAI (due to the high altitudes involved) and in less than a day for MCB (due to the low altitude at which it would operate); in both cases, particles would need to be replenished on a continual basis if enhanced reflectivity were to be maintained. Because most natural and social scientific research on solar geoengineering to date has focused on SAI, due to its perceived greater feasibility relative to MCB, I will treat solar geoengineering and SAI as synonymous throughout the remainder of this study unless otherwise noted.[3]

Compared to conventional emissions reductions, solar geoengineering appears to be fast, cheap, and imperfect. It is *fast* insofar as the effects of solar geoengineering on the climate would manifest within a year. It is *cheap* in that the direct costs of deployment are estimated to be between $15 billion and $70 billion per year, a small fraction of the cost of decarbonizing

[3] A third proposed sunlight reflection technology is space-based solar geoengineering, for example, using reflectors positioned at a stable point between the Earth and the sun. However, the implementation of space-based systems appears infeasible in the coming decades due to extremely high cost estimates and deep uncertainties. This landscape analysis will therefore not cover space-based solar geoengineering.

the world economy (Robock 2020). And it is *imperfect* in the sense that reflecting sunlight cannot perfectly compensate for the warming caused by excessive greenhouse gas (GHG) concentrations, since they involve different physical mechanisms. More specifically, high GHG concentrations amplify the natural greenhouse effect, trapping additional heat that would otherwise radiate out to space ("longwave radiation") and thereby warming the planet. By contrast, solar geoengineering would reduce the source of this heat—incoming sunlight—by reflecting sunlight ("shortwave" or "solar radiation") back to space before it reaches the Earth's surface.[4] (The balance between shortwave and longwave radiation determines global temperatures and is referred to as "radiative forcing"). Reflecting sunlight *directly* alters radiative forcing by reducing shortwave radiation, while cutting emissions *indirectly* affects radiative forcing by altering atmospheric concentrations of GHGs and thus the intensity of the greenhouse effect, and thereby changing the amount of longwave radiation retained by the Earth.

These differences mean that solar geoengineering and emissions reductions are not perfect substitutes. An important consequence of this is that solar geoengineering is not capable of returning global temperature and precipitation to preindustrial conditions simultaneously. (It is also incapable of addressing ocean acidification, which is caused by emissions of carbon dioxide.) Thus, a geoengineered climate would not be equivalent to a restored climate, but instead would constitute a novel climate featuring, for example, altered patterns of regional precipitation compared to preindustrial conditions. Critically, however, a world with climate change and solar geoengineering may be safer–perhaps much safer–than a world with climate change but without solar geoengineering.

The extent to which a geoengineered climate differs from historically observed conditions, and the extent to which it reduces risks relative to a non-engineered, high-GHG climate, would depend on how solar geoengineering was deployed, in particular, on how much solar geoengineering was implemented, and how quickly. Objectives might include returning the Earth to preindustrial global mean temperatures, maintaining global mean temperature at 1.5 °C or 2 °C above preindustrial levels, or reducing the rate of warming; each goal could be pursued more or less gradually or abruptly. Some observers have suggested that moderate use of SAI—for example, to reduce the rate of global warming by half—could be used to "shave the peak" off the dangerous multidecadal warming likely to result from exceeding the Paris Agreement temperature targets. In addition, any given strategy could be designed in multiple ways depending on choices regarding the hemisphere, latitude, and season of injection; different combinations of these "knob" settings would result in different distributions of impacts, which would allow decision-makers some scope for moderating the novel features of a geoengineered world (Zhang et al. 2022).

[4] This is the origin of the (interchangeable) terms solar radiation management and solar radiation modification.

Risks and Limitations

Any solar geoengineering intervention would entail risks. As mentioned, regional precipitation patterns would change compared to both historical patterns and the patterns that would obtain in a non-engineered high-GHG climate. These and other imperfect climate responses to solar geoengineering could result in harms attributable to the technology. Operational aspects of implementation might produce significant side effects. For example, depending on the type of aerosol used, the recovery of the ozone layer could be delayed because some candidate aerosols, for example, sulfate, promote ozone depletion. (Sulfate is the aerosol most proposed for use in solar geoengineering because its release into the stratosphere during large volcanic eruptions is known to reduce temperatures, and its climate and environmental effects have been observed repeatedly.) Other candidate aerosols like calcite or diamond dust, however, might have more benign or even positive side effects. Another potential side effect is that skies might appear slightly whiter to observers on the ground (although such whitening may be barely perceptible). These physical risks are some of the "known unknowns" associated with solar geoengineering, but there are likely to be "unknown unknowns" as well. In general, a significant degree of uncertainty would accompany any deployment of solar geoengineering.

The physical risks and uncertainty associated with solar geoengineering, however, must ultimately be weighed against the physical risks and uncertainty present in a world experiencing climate change without solar geoengineering. Decisions about solar geoengineering, in other words, will involve difficult risk-risk trade-offs. Modeling results consistently show that moderate amounts of solar geoengineering—for instance, engineered cooling sufficient to reduce the rate of global warming by half—reduce climate risks compared to simulations without solar geoengineering. One prominent study, for example, demonstrated that halving the warming induced by a doubling of atmospheric carbon dioxide using solar geoengineering would generally reduce climate impacts across the globe—lowering average and maximum temperatures, increasing water availability, moderating heat waves and tropical cyclones—without making any region worse off (Irvine et al. 2019). The potential for such outcomes, imperfect but delivered relatively quickly and at low cost, makes solar geoengineering compelling in a context where emissions reductions are costly and slow to reduce climate impacts and not being implemented fast enough to avoid serious climate change.

Yet this comparison has given rise to serious concerns that talking about, researching, or deploying solar engineering might work to reduce incentives to cut emissions; this prospect is typically referred to as "moral hazard." Moral hazard of this sort might occur as various actors lessen their efforts to decarbonize in the (mistaken) belief that solar geoengineering will achieve the same results at much less cost and much more quickly. This would be problematic because, as noted above, solar geoengineering is an imperfect substitute for emissions reductions and would fail to deliver all the benefits of mitigation while introducing new risks. "Mitigation deterrence" might also come about through actions taken by fossil-fuel interests or others opposed to emissions mitigation for commercial and/or ideological reasons; solar geoengineering might thus be presented or promoted as an alluring alternative to costly mitigation measures. But to repeat, solar geoengineering is not an effective alternative to or substitute for emissions reductions; at best it may serve as a useful complement to decarbonization.

Another key concern that has been raised relates to the need to continuously disperse aerosols. Specifically, if an aerosol layer were maintained for decades but atmospheric GHG concentrations remained high or increased further—perhaps due to moral hazard effects—any abrupt cessation of geoengineering operations would quickly unleash the warming potential previously held in check and result in very rapid warming. The rate of climate change induced by such a “termination shock” would be even faster than what would have occurred without solar geoengineering. Since the dangers of climate change are tied not only to the amount of change but also the *rate* of change, the rebound effects of abruptly discontinued solar geoengineering might threaten to overwhelm the capacity of societies and ecosystems to adapt and cause worse damage than would have occurred if an intervention had never taken place.

A separate concern relates to its apparently low direct costs and relative technical simplicity. The seeming affordability and accessibility of solar geoengineering, combined with its rapid global effects, render it a high-leverage technology. On one hand, the availability of a cheap, powerful method for offsetting significant impacts from climate change provides the world with a potential low-cost, fast-acting option for reducing climate harms. But on the other hand, the widespread availability of such a potent tool raises the specter of unilateral deployment by a single country (or minilateral deployment by a small group of likeminded countries).[5] This is sometimes referred to as the “free driver” effect (as opposed to the “free rider” effect epitomized by inadequate efforts to cut emissions) because the ease of deployment would seem to empower whatever country desired the most cooling to set the “global thermostat” for the rest of world (Weitzman 2015). A broad distribution of solar geoengineering capabilities would have serious implications for international stability and possibly security. The actual distribution of capabilities, however, may be quite narrow.[6]

Some observers have raised the prospect of weaponizing this technology, but the physics of solar geoengineering makes this implausible. In essence, longitudinal (east to west) control over climate effects from solar geoengineering is impossible, while latitudinal (north to south) control would be restricted to the regional level, with all regions at similar longitudes affected and movement toward the poles inevitable. Furthermore, such limited, crude latitudinal

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[5] The threat of unilateral deployment is sometimes linked to speculation that the occurrence of an extreme weather event might trigger a decision to deploy. The results of recent cross-national studies, however, demonstrate that extreme events typically do not influence climate policy decision-making (e.g., Nohrstedt et al. 2021; Peterson 2021).

[6] Specifically, the design and manufacture of the types of aircraft engines required for deployment is dominated by a mere handful of aerospace companies located in powerful countries; their market dominance is protected by very high barriers to entry as well as the privileged relationships they have with their home governments (Horton 2022).

control would affect only interannual (multiyear) temperature and precipitation trends and averages, *not* discrete weather events. Solar geoengineering simply lacks the precision required for use as a weapon.

Additionally, some observers have alleged that researching solar geoengineering could lead to technological lock-in. In this scenario, researchers, technology developers, and other vested interests might push for deployment even if objective assessments conclude that implementation should not be pursued. Such a dynamic is sometimes referred to as a "slippery slope."

Governance Challenges

These risks and limitations raise serious questions about the desirability of this technology, despite the potentially huge benefits it might deliver. Addressing them is fundamentally a task for governance. Thus, whether solar geoengineering comes to be regarded as a legitimate additional climate response option is highly contingent on whether adequate governance solutions can be devised to mitigate risks, manage uncertainties, and/or impose reliable safeguards. The following considers the most significant of these governance challenges.

The prospect of unilateral (or minilateral) deployment has already been mentioned. To the extent that capabilities are in fact widely distributed, the potential for implementation by one or a few countries against the wishes of others creates a need for mutual restraint. This might be achieved through international institutions. Whether or not such institutions are adapted or built, however, any state tempted to deploy unilaterally would almost certainly be confronted by other states opposed to unilateral deployment, with a range of carrots and sticks at their disposal; it is far from clear that the long-term, globally dispersed, and uncertain benefits that might motivate an actor to consider unilateral deployment would outweigh either the immediate costs of sanctions and/or the value of alternative rewards that others might offer it.[7] In addition, as noted above, the distribution of solar geoengineering capabilities may be significantly more limited than many observers have assumed.

Since solar geoengineering would entail global effects, any decision on whether and how to use it should reflect broad international agreement. Ideally, such agreement would cover, among other things, the conditions (if any) under which solar geoengineering could be implemented; the objectives that should guide deployment, including how much cooling to pursue, how quickly to pursue it, and for how long; specific institutional and logistical arrangements for carrying out deployment; and the conditions and protocols under which deployment should be slowed or halted, including planned wind-downs. Reaching agreement on such questions

[7] Some researchers have theorized that so-called counter-geoengineering—countervailing or neutralizing solar geoengineering through technical means—could also serve to limit the prospects of unilateral deployment (see Parker, Horton, and Keith 2018).

would itself require prior, more fundamental agreement on decision-making procedures, venues, and participation.

Finding common ground will be difficult because countries will have different opinions on which climate state is most desirable. Interrelated variations in geographic location, level of development, comparative economic advantage, adaptation capacity, climate vulnerability, historical and cultural context (including norms of risk tolerance and conceptions of nature), political system, geopolitical position—all these plus other factors will make it hard for countries to agree on whether and how to implement solar geoengineering. Conflicting interests will preclude easily struck bargains or compromises.

An especially difficult aspect of reaching agreement will pertain to the potential distributional consequences of deployment, or how the distribution of benefits, costs, and risks from implementing the technology would be spread across countries and over time. In principle, the "winners and losers" from solar geoengineering would depend on three factors. First, as noted in the previous section, possible deployment schemes would vary in terms of goals and designs, creating significant spatiotemporal scope for modulating impacts at the regional level. Specific goals and designs would ultimately be political decisions. Second, weighing the distributional effects of specific solar geoengineering schemes requires comparing them to the distribution of benefits, costs, and risks *in the absence of solar geoengineering*, that is, in the counterfactual. Crucially, the counterfactual would not be either present-day or preindustrial conditions, but rather projected future conditions in a warmer world without climate intervention. One noteworthy study shows that income inequality among countries would decline under warming scenarios *with* solar geoengineering compared to warming scenarios *without* geoengineering (because both the harms from warming and the benefits of cooling would accrue disproportionately to poorer countries) (Harding et al. 2020). But both types of forecasts—with and without geoengineering—would be subject to high uncertainty, the third key factor in assessing the distributional consequences of solar geoengineering. Given high uncertainty, reliance on counterfactuals, and the vagaries of planning (and implementation) processes, the reliability of any ex-ante distributional assessment will invariably be open to contestation, as will the relative acceptability of the expected distribution itself.

Moral hazard is another significant risk associated with solar geoengineering. Perhaps surprisingly, the few but growing number of studies aiming to assess whether, and if so, how much, learning about solar geoengineering causes people to reduce emissions reductions efforts generally fail to demonstrate moral hazard; in other words, when exposed to information about solar geoengineering, people either maintain their previous commitments to cut emissions or *increase* support for emissions cuts. Similarly, despite reasonable fears that opponents of mitigation might exploit the promise of solar geoengineering to weaken emissions reductions efforts, there is very little evidence that fossil-fuel interests or other actors dependent on or allied to carbon-intensive industries have promoted solar geoengineering as a cheaper alternative to mitigation. It would be irresponsible, however, to dismiss concerns about moral hazard based solely on current evidence, and future governance arrangements would need to take them into account through institutional or other safeguards. One notable proposal—called "pay to play linkage"—is based on linking substantial (delivered) emissions reductions to the right to participate in decision-making on solar geoengineering (Parson 2014).[8]

Regarding fears of termination shock, the long timeframes over which solar geoengineering, if deployed, might have to be maintained—decades to centuries—present a host of interconnected challenges. Obviously, any solar geoengineering system would need to be durable and resilient against a range of potential political and social shocks (given the apparent affordability of solar geoengineering, potential economic shocks would seem less worrisome). In this respect, redundancy of delivery infrastructure and implementation capabilities would be valuable. Inversely, any system would also need to be sufficiently flexible to allow for course corrections and possibly exit ramps (if decision-makers wanted to halt deployment but avoid termination shock). There appear to be relatively few examples of large-scale, long-term regional (let alone global) engineering systems or other megaprojects from which to draw insights potentially applicable to solar geoengineering (the Netherlands' extensive, centuries-old system of dikes presents one such possibility).

Uncertainty over the impacts of solar geoengineering, and varying levels of confidence in the science underpinning projections, points toward potential compensation in case things seem to go wrong as an additional governance challenge. Considering the changes in regional precipitation that would occur if solar geoengineering were implemented, attention has focused on possible harms resulting from droughts or floods. Would a country that blamed such harms on solar geoengineering be compensated for damages, and if so, how? The impossibility of attributing extreme weather events to changes in climate using traditional (deterministic) causal chains makes conventional liability instruments unsuitable for settling climate damage claims. Furthermore, the scale of potential awards implicit in such claims might overwhelm national and international legal systems. One possible alternative is parametric insurance, in which losses and subsequent payouts are tied to predefined values of objective environmental indicators, like rainfall (Horton 2018). Multilateral parametric insurance schemes already exist but would need to be substantially expanded and elaborated to play a role in compensating for possible harms from solar geoengineering (if such a role is possible).

Finally, the possibility of technological lock-in poses a further governance challenge, particularly with respect to solar geoengineering *research*. A slippery slope to deployment is not inconceivable, yet the lack of commercial potential associated with solar geoengineering (resulting from its apparent low cost) would probably curb the enthusiasm of any vested interest for promoting implementation. Regardless, research programs could and should build

[8] Pay to play linkage has been minimally theoretically elaborated, and no related policy proposals have been advanced (see Reynolds 2021).

viable exit ramps into their governance designs to guard against the possibility of unjustified continuation or expansion.

Table 1 summarizes the major risks and potential governance solutions associated with solar geoengineering. Risks vary in terms of their probability and magnitude, while governance solutions vary in terms of their likely feasibility and effectiveness.

Table 1: Major Risks and Potential Governance Solutions Associated with Solar Geoengineering

Risk	Governance Solution	Notes
Unilateral deployment	Mutual restraint	Uncertain distribution of capabilities and benefit-cost calculus
Conflicting interests regarding climate (e.g., where to set the “global thermostat”)	Cooperative decision-making mechanisms	Disagreement may center on reliability and acceptability of projected winners and losers
Moral hazard	Safeguards (e.g., pay to play linkage)	Weak evidence to date
Termination shock	Long-term adaptive management system	Seemingly few historical precedents
Climate response harms (e.g., from changes in precipitation)	Compensation for damages	Liability unsuitable, parametric insurance conceivable
Technological lock-in	Viable exit ramps	Low profitability limits vested interests

Current Global Governance

Compared to the scale of these challenges, the current global governance landscape for solar geoengineering is wholly inadequate. At the most general level of customary international law, or legal obligations among states arising from custom rather than treaties, three principles are particularly relevant to solar geoengineering. First, the “no-harm rule” holds that states have a duty to prevent or minimize significant environmental harm to the territory of other states or the global commons including the oceans and atmosphere; in theory the no-harm rule could be invoked as a basis of claims for compensation from harms caused by solar geoengineering. Second, the precautionary principle calls for caution in taking action even when definitive scientific evidence of the potential for harm is lacking; the precautionary principle has been invoked both for *and* against solar geoengineering. Third, states are generally expected to conduct environmental impact assessments (EIAs) prior to undertaking measures that might result in significant transboundary harms. While these three principles serve as useful starting points, they lack detail, their application to specific cases is necessarily open to interpretation, and such interpretations are frequently contested. Consequently, customary international law is limited in its capacity to provide concrete guidance on whether and how solar geoengineering ought to be pursued at the international level.

The following provides descriptions of those treaties and multilateral environmental agreements that have addressed at least some aspect of solar geoengineering or (in the case of the UNFCCC) are clearly relevant to the technology:

- United Nations Framework Convention on Climate Change (UNFCCC)—The UNFCCC is the principal international governance framework for addressing climate change and is the framework within which both the Kyoto Protocol and the Paris Agreement were developed. The UNFCCC is fundamentally structured around stabilizing atmospheric concentrations of GHGs. As noted above, however, solar geoengineering would not act on GHGs, but rather on radiative forcing. Because of this, in its current form, the UNFCCC provides little scope for governing solar geoengineering. One way in which the Paris Agreement departed from established UNFCCC practice, however, was in its explicit focus on global temperature targets, i.e., below 1.5 °C or 2 °C warming above preindustrial levels. In doing so, the Paris Agreement (at least in theory) opened the door to future UNFCCC efforts to address radiative forcing directly and hence future UNFCCC governance of solar geoengineering.[9]

- Convention on Biological Diversity (CBD)—The CBD is intended to protect global biodiversity. Given the certainty that using and large-scale testing of solar geoengineering would affect biodiversity, the CBD has taken some initial steps to address the technology. By far the most important was its Decision X/33 adopted in 2010, which urged parties to prohibit all geoengineering activities that could negatively impact biodiversity, except for “small scale scientific research studies.” This “invitation,” however, is not legally binding, and the US is not a party to the CBD. Nevertheless, the broad call to abstain contained in Decision X/33 is now widely referred to as an international “moratorium” on geoengineering, and much of the international political discourse on solar geoengineering proceeds on this (flawed) understanding.

- London Convention/London Protocol (LC/LP)[10]—The LC/LP regulates ocean dumping. In 2013, parties to the Protocol adopted Resolution LP4(8), which if ratified by enough countries to bring it into force would amend the agreement to prohibit “marine geoengineering” except for “legitimate scientific research.”[11] However, solar geoengineering is not explicitly recognized as a form of marine geoengineering, and the amendment has not entered into force.

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[9] For more on how the Paris Agreement relates to solar geoengineering, see Horton, Keith, and Honegger 2016.

[10] The LC, signed in 1972, specifies materials that either may not be dumped in the ocean or may be dumped but only if a permit is obtained; materials not specified may be dumped without restriction. In contrast, the LP, signed in 1996, specifies materials that may be dumped but only with permits (this is referred to as a “reverse list”); materials not specified may not be dumped. The LP is intended to eventually supersede the LC.

[11] LP4(8) originated with earlier resolutions that were adopted to control ocean fertilization, a controversial carbon removal method designed to promote atmospheric carbon drawdown by fertilizing phytoplankton. Such “marine geoengineering” is premised on interventions directly in the ocean rather than on interventions in the atmosphere to reflect sunlight. For this reason, most observers do not regard LP4(8) as applicable to solar geoengineering.

- United Nations Environment Assembly (UNEA)—UNEA is the governing body of the UN Environment Programme, the highest international political body for the environment. At its fourth session in 2019 (UNEA-4), Switzerland planned to introduce a draft resolution titled "Geoengineering and Its Governance" which would have initiated a formal technology assessment of solar geoengineering. Switzerland withdrew the resolution prior to the start of the meeting, however, due to disagreement over the level of precaution appropriate to solar geoengineering research (see below).

- Convention on the Prohibition of Military or Any Other Hostile Use of Environmental Modification Techniques (or ENMOD)—ENMOD, signed in 1977, outlaws the "hostile" use of environmental modification techniques among countries. As noted above, though, solar geoengineering is not weaponizable, hence ENMOD is not applicable, and in any case, it is a dormant treaty.

- Montreal Protocol—The Montreal Protocol (to the Vienna Convention for the Protection of the Ozone Layer) has been successful in phasing out substances that deplete stratospheric ozone. As noted above, sulfate is the aerosol most proposed for use in solar geoengineering, but it is known to contribute to ozone depletion. For this reason, the Montreal Protocol is now beginning to consider the implications of solar geoengineering for stratospheric ozone. The potential impacts of solar geoengineering on the ozone layer will be a subject of a scientific assessment conducted under the auspices of the Montreal Protocol due to be released later this year.

Civil Society

Current global governance specific to solar geoengineering is thus exceptionally weak, with very few international "rules of the road" to inform decision-makers on questions regarding small-scale research with transboundary implications, large-scale experiments, or possible deployment. A principal reason for this is the lack of well-developed national government positions on the technology, which further reflects the generally low level of awareness of solar geoengineering across the globe. The limited number of public opinion surveys about solar geoengineering that have been conducted consistently show sustained low levels of familiarity with the technology, with very few respondents able to define it.[12] The bulk of these studies have been carried out in the Global North, where most solar geoengineering research has taken place and where the technology is thus most visible. This suggests that awareness in the Global South is even lower.

In this context, a growing number of civil society actors have attempted to shape and influence emerging national and international policies regarding solar geoengineering. The following provides brief descriptions of the key civil society actors currently operating in this space.

[12] For a systematic review of public opinion surveys, see Cummings, Lin, and Trump 2017.

- 350.org—350.org is a relatively new US-based but internationally active nongovernmental organization (NGO) focused exclusively on climate and specializing in campaigns and grassroots action. 350.org has expressed criticism of solar geoengineering.

- Action Group on Erosion, Technology, and Concentration (the ETC Group)—The ETC Group is an activist NGO opposed to emerging technologies based on their exploitative potential. Starting in the late 2000s, the ETC Group shifted much of its attention to solar geoengineering; it was the driving force behind the call for a moratorium adopted by the CBD. In 2011, the ETC Group took aim at a proposed field test of a tethered balloon SAI delivery system in the United Kingdom (UK), organizing the "Hands Off Mother Earth" (HOME) pressure campaign to demand its cancellation. The test was ultimately called off (although the project managers who made the decision cited an unrelated intellectual property dispute as their primary reason).[13] In terms of impact on policy processes relevant to solar geoengineering, the ETC Group has been the most consequential civil society actor to date.

- Carnegie Climate Governance Initiative (C2G, formerly Carnegie Climate Geoengineering Governance Initiative or C2G2)—C2G was launched as an initiative of the Carnegie Council for Ethics in International Affairs in 2017, with the goal of raising awareness of solar geoengineering among global policymakers and climate governance stakeholders including NGOs. It is led by Janos Pazstor, a former UN Assistant Secretary-General for Climate Change. C2G played an important role in facilitating Switzerland's ill-fated plan to initiate a geoengineering technology assessment at UNEA in 2019.

- Center for International Environmental Law (CIEL)—CIEL is a transnational environmental NGO focused on international environmental law. CIEL specializes in publishing reports and exposés and has emerged as a vocal critic of solar geoengineering.

- Environmental Defense Fund (EDF)—EDF is a mainstream US-based environmental NGO grounded in scientific and economic analysis and frequently supportive of using market-based instruments to address environmental problems. EDF conditionally backs small-scale field research on solar geoengineering. EDF was instrumental in setting up and providing early support for what is now the Degrees Initiative.

- The Degrees Initiative (formerly known as the Solar Radiation Management Governance Initiative or SRMGI)—Degrees was founded in 2010 as a joint initiative of the Royal Society, the World Academy of Sciences, and EDF, with the goal of raising awareness and stimulating discussion of solar geoengineering in the Global South. For most of its

[13] Additionally, the ETC Group succeeded in pressuring the chair of the SCoPEx (see below) Advisory Committee (Louise Bedsworth) to step down temporarily by stoking controversy over her use of a California state email account to conduct committee business; Bedsworth has since rejoined the committee as part of a leadership team.

existence, the Degrees Initiative has focused on convening stakeholder meetings in developing countries. More recently, Degrees has broadened its efforts by launching the Developing Country Impacts Modelling Analysis for SRM (DECIMALS) Fund to support climate modeling research projects led by investigators from the Global South; the underlying aim of DECIMALS is to build technical capacity to research solar geoengineering in countries on the frontlines of climate change.

- Friends of the Earth-US (FOE-US)—FOE-US (the US branch of Friends of the Earth International) is an environmental NGO that focuses on campaigning. FOE-US has expressed strong opposition to solar geoengineering.

- Global Commission on Governing Risks from Climate Overshoot (Climate Overshoot Commission)—The recently launched Climate Overshoot Commission aims to compile and communicate an integrated strategy for reducing risks anticipated to result from exceeding the 1.5 °C temperature target contained in the Paris Agreement; this strategy is likely to include use of solar geoengineering. The Commission consists of sixteen eminent persons active in politics, diplomacy, environmental protection, and civil society, a majority of whom come from the Global South.

- Natural Resources Defense Council (NRDC)—NRDC is a mainstream US-based environmental NGO that specializes in legal advocacy and operates largely through the courts. NRDC conditionally backs small-scale field research on solar geoengineering. A former president of NRDC (Frances Beinecke) now serves as a member of the Climate Overshoot Commission.

- The Sierra Club—The Sierra Club is a long-standing progressive US environmental NGO. It has voiced skepticism toward solar geoengineering but not unconditional opposition to outdoor experiments.

- Solar Geoengineering Non-Use Agreement Initiative—This initiative launched in 2022 with an open letter calling for a global prohibition on using solar geoengineering, including no public funding, no outdoor experiments, no patents, no deployment, and no support in international institutions. It is organized by a group of academics closely affiliated with the Earth System Governance Project, a social science research network focused on issues related to global environmental governance. The letter has been signed by more than 300 academics and endorsed by more than two dozen civil society organizations.

- Union of Concerned Scientists (UCS)—UCS is a science-oriented environmental NGO based in the US. UCS conditionally backs small-scale field research on solar geoengineering. The former chief climate scientist for UCS (Peter Frumhoff) was a member of a National Academies of Sciences, Engineering, and Medicine (NASEM) committee that produced a report on solar geoengineering in 2021.

- SilverLining—SilverLining is a relatively new US NGO that calls for expanded research on solar geoengineering. SilverLining has cultivated some relationships with members of Congress and their staff and has sketched out its own plan for a ten-year federal research program. It also organized the Safe Climate Research Initiative (SCRI) (funded by Lowercarbon Capital, the Pritzker Innovation Fund, and others) to support individual solar geoengineering research projects, including via contributions to the Degrees Initiative's DECIMALS Fund.

It is also worth noting that another US-based organization (as yet unnamed) focusing on the climate justice implications of solar geoengineering, including by promoting deeper engagement on governance issues by stakeholders from the Global South, is planned for launch by the end of this year. (It will be led by Shuchi Talati, who previously held a senior position working on carbon management at the US Department of Energy, and prior to that worked on solar geoengineering at UCS.)

Table 2 provides an overview of civil society actors engaged on the issue of solar geoengineering. It is evident that the number of such actors—at global and national levels—is very small, a majority of them are based in the US, and none of the groups is politically conservative. In terms of level of engagement, it appears that transnational groups are generally more active than groups that operate primarily at the national level, and that, among US-based NGOs, those closer to the political center are more active than groups further to the left.

Table 2: Civil Society Actors Engaged with the Issue of Solar Geoengineering

Actor	Headquarters Country	Geographic Scope	Focus	Political Leaning	Notable Actions
350.org	US	Global	Climate change	Left	-
C2G	US	Global	Solar geoengineering (and carbon removal)	Center-left	Supported planned Swiss intervention at UNEA-4
CIEL	Switzerland	Global	Environment	Far left	-
Climate Overshoot Commission	France	Global	Climate change	Center	-
Degrees Initiative	UK	Global (South)	Solar geoengineering	Center-left	Established DECIMALS
EDF	US	Global	Environment	Center-left	Helped launch SRMGI / Degrees Initiative
ETC Group	Canada	Global	Emerging technologies	Far left	Orchestrated CBD "moratorium", claims credit for SPICE cancellation
FOE-US	US	US	Environment	Left	-
NRDC	US	Global	Environment	Center-left	-
Sierra Club	US	US	Environment	Center-left	
SilverLining	US	US	Solar geoengineering	Center-left	Established SCRI
Solar Geoengineering Non-Use Agreement Initiative	Netherlands	Global	Solar geoengineering	Left	Proposed Non-Use Agreement
UCS	US	US	Environment	Center-left	-

Current Research

Until the late 2000s, a taboo on researching solar geoengineering prevailed due to widespread concerns among scientists about the sociopolitical risks–especially moral hazard–associated with the technology. But in 2006, Paul Crutzen, an atmospheric chemist who won a Nobel Prize for his work on the ozone layer, published an article calling for research on solar geoengineering, which effectively broke the taboo. Since then, research on solar geoengineering has advanced, but very slowly. Natural science research has proceeded largely using global climate models to simulate future climates with and without different types of solar geoengineering. A smaller portion of natural science work has been conducted in laboratories and by observing natural analogs. Social science research has been pursued using integrated assessment models to quantify the costs and benefits of solar geoengineering under different assumptions, as well as through political, economic, and legal analyses of alternative deployment strategies and governance structures. Ethical aspects of solar geoengineering have also been studied. Research on the technology is highly interdisciplinary, with natural and social science research frequently integrated based on recognition of the tight couplings between potential climate responses to solar geoengineering, resulting climate impacts, and sociopolitical risks.

Table 3 details specific solar geoengineering research projects around the world over the period 2008-2021 whose total funding was greater than half a million dollars. Up to now, no country has established a comprehensive national research program.

Table 3: Significant Solar Geoengineering Research Projects Worldwide 2008-2021

Project Name	Location	Total Funding	Funding Type	Funder(s)	Years Active
Harvard's SGRP (Solar Geoengineering Research Program)	US	$ 23,000,000	Private	Hewlett Foundation, Open Philanthropy, Pritzker Innovation Fund, Sloan Foundation, Bill Gates, Lowercarbon Capital, others	2017-2024
NOAA ERB (Earth's Radiation Budget)	US	$ 22,000,000	Government	Congressional appropriations	2020-now
Reef Trust Partnership	Australia	$ 14,799,652	Mixed	DAWE, RRAP members	2019-2023
C2G (Carnegie Climate Governance Initiative)	US	$ 9,362,667	Private	V. Kann Rasmussen Foundation, OAK Foundation	2017-2023
FICER (Fund for Innovative Climate and Energy Research)	US	$ 8,015,000	Private	Bill Gates	2013-now
Degrees Initiative / SRMGI (Solar Radiation Management Governance Initiative)	UK	$ 7,117,213	Private	Environmental Defense Fund, Open Philanthropy	2010-now
SPP1689	Germany	$ 5,000,000	Government	DFG	2013-2018
GENIE (GeoEngineering and Negative Emissions Pathways in Europe)	EU	$ 4,938,106	Government	Horizon 2020-EXCELLENT SCIENCE - ERC	2021-2027
SCRI (Safe Climate Research Initiative) (SilverLining)	US	$ 4,500,000	Private	LowerCarbon Capital, Pritzker Innovation Fund, others	2020-now
GeoMIP (Geoengineering Model Intercomparison Project)	US	$ 3,214,700	Government	NSF	2008-now
IAGP (Integrated Assessment of Geoengineering Proposals)	UK	$ 2,738,483	Government	EPSRC, NERC, LWEC	2015
SPICE (Stratospheric Particle Injection for Climate Engineering)	UK	$ 2,600,000	Government	EPSRC, NERC, STFC	2014
RRAP (Reef Restoration and Adaptation Program)	Australia	$ 2,535,399	Government	DAWE	2018
Mechanism and Impact of Geoengineering	China	$ 2,200,000	Government	MOST	2015-2019
Cornell Climate Engineering	US	$ 1,841,666	Mixed	Cornell Atkinson Center for a Sustainable Future, SilverLining, others	2015-2023
COOL	Finland	$ 1,691,820	Government	Academy of Finland	2014
Climate Geoengineering Governance Project	UK	$ 1,634,641	Government	ESRC, AHRC	2012-2014
EuTRACE (European Transdisciplinary Assessment of Climate Engineering)	EU	$ 1,591,579	Government	EU 7th Framework Programme	2014
Reef intervention research	Australia	$ 1,356,143	Government	DAWE, Queensland state government	2017
EXPECT (Exploring the Potential and Side Effects of Climate Engineering)	Norway	$ 1,282,000	Government	RCN	2014-2017
IMPLICC (Implications and Risks of Novel Options to Limit Climate Change)	EU	$ 1,170,000	Government	EU 7th Framework Programme	2012
IASS (Institute for Advanced Sustainability Studies) SIWA (Sustainable Interactions With the Atmosphere)	Germany	$ 1,154,016	Government	BMBF, Brandenburg state government	2012-2018
Geoengineering Governance Project (UCLA)	US	$ 1,076,095	Private	Open Philanthropy	2017-2022
GLENS (Geoengineering Large Ensemble Project) (NCAR)	US	$ 999,999	Government	NSF	2017
ICA-RUS (Integrated Climate Assessment - Risks, Uncertainties and Society)	Japan	$ 801,000	Government	Ministry of the Environment	2012-2017
SOUSEI	Japan	$ 800,000	Government	MEXT	2012-2016
TOUGOU	Japan	$ 800,000	Government	MEXT	2017-2021
Evaluation of Suggestions to Geoengineer the Climate System Using Stratospheric Aerosols and Sun Shading	US	$ 699,846	Government	NSF	2008-2013
DECIMALS (Developing Country Impacts Modelling Analysis for SRM) Fund (Degrees Initiative)	UK	$ 650,000	Private	Open Philanthropy, Climate Pathfinders Foundation, SCRI	2018-now

Note: Significant projects are regarded as those with total funding greater than $500,000. Total funding amounts have been adjusted 1) to avoid double counting, 2) to exclude funding for research on carbon removal where project scope extends beyond solar geoengineering (for such "lumped" projects total funding is reduced by half to approximate spending dedicated to research on solar geoengineering), and 3) for Australia, to approximate the fraction of total spending devoted to MCB research.

The US leads in solar geoengineering research, most of which has been carried out at universities including (most prominently) Harvard University, Cornell University, and the University of California, Los Angeles. University-based natural and social science work has been funded largely by philanthropies, with early support coming from the Fund for Innovative Climate and Energy Research financed by Bill Gates. Harvard's Solar Geoengineering Research Program (SGRP), launched in 2017 with $23 million in funding committed through 2024, has been a pioneer in supporting solar geoengineering research. SGRP has sponsored a wide range of research activities including climate modeling, laboratory work, economic analyses, governance studies, and ethical inquiries.

Until recently, US government funding for research on solar geoengineering consisted mostly of National Science Foundation grants for computer modeling conducted by the university-based Geoengineering Modeling Intercomparison Project (GeoMIP) consortium and at the National Center for Atmospheric Research, a federally funded research and development center in Boulder, Colorado.[14] The National Oceanic and Atmospheric Administration's (NOAA) new Earth's Radiation Budget (ERB) initiative, also based in Boulder, represents a substantial increase in federal support with $22 million in research funding provided to date. ERB research is focused on enhancing stratospheric observational and modeling capabilities, establishing a baseline of stratospheric data (including to detect solar geoengineering), and improving understanding of marine clouds. In 2015 and again in 2021, NASEM published authoritative reports on solar geoengineering; the 2021 report recommended that the federal government launch an interdisciplinary national research program with funding of between $100 million and $200 million provided over five years. The White House Office of Science and Technology Policy is currently preparing an outline of priorities for federal research on solar geoengineering, due to be finalized later this year.

Australia is now the country with the second largest amount of solar geoengineering research funding due to a recent surge in government-led spending (totaling more than $360 million from 2017 through 2023) on Great Barrier Reef protection efforts provided via the Reef Trust Partnership and affiliated Reef Restoration and Adaptation Program; this burst of funding followed a series of high-profile coral bleaching events starting in 2016. Part of the funding has gone to support research on MCB as one potential "cooling and shading reef intervention" among a host of options (such as rubble stabilization, selective breeding, and cryopreservation) being considered; the remaining funding supports computer modeling, regulatory analysis, stakeholder engagement, and other activities. Notably, funders have framed MCB not as a type of solar geoengineering, but rather as a tool for reef "restoration and adaptation." These arrangements and strategies have kept the topic of Reef protection separate from Australia's contentious climate politics, but they have also obscured the connection between MCB and solar geoengineering as an approach to addressing climate change.

[14] GeoMIP is a transnational climate modeling consortium created in 2011 to conduct standardized solar geoengineering "experiments" across multiple global climate models in order to establish a robust baseline of knowledge about the probable climate effects of solar geoengineering. Similar results from simulating identical deployment scenarios using different computer models help increase confidence in the basic scientific understanding of solar geoengineering.

Apart from the US and Australia, research on solar geoengineering has been concentrated in three countries: the UK, Germany, and more recently China. In the UK, the government indirectly funded several solar geoengineering research projects from 2010 to 2015 but stopped doing so following cancellation of a controversial proposed field test, part of the Stratospheric Particle Injection for Climate Engineering (SPICE) project.[15] The privately-funded Degrees Initiative is headquartered in the UK, but it is active primarily in developing countries where it convenes informational meetings and, more recently via its DECIMALS Fund, supports modeling research. In Germany, the government supported a nearly $10 million "priority program" on "climate engineering" (SPP1689) from 2013 to 2018, although less than half the funding went toward research on solar geoengineering. The Institute for Advanced Sustainability Studies (IASS) in Potsdam engaged in a project of similar scale but more focused on governance over roughly the same period. And in China, the government recently supported a smaller $2.2 million effort focused on solar geoengineering from 2015 to 2019. Funded by the Ministry of Science and Technology and based at Beijing Normal University, "Mechanism and Impact of Geoengineering" encompassed both natural and social science research.

Virtually no outdoor field experiments have taken place. The most prominent proposed field experiment, Harvard's Stratospheric Controlled Perturbation Experiment or SCoPEx, would release a very small amount of calcium carbonate into the upper atmosphere to study its effects on aerosol microphysics and atmospheric chemistry; in 2021, an equipment test fight scheduled to launch in Sweden was canceled in response to opposition from the indigenous Saami Council. In 2020 and again in 2021, MCB delivery equipment field tests were carried out above Australia's Great Barrier Reef. A team at the University of Washington has drawn up similar plans to test MCB delivery equipment off the coast of California, but these have yet to be conducted.

At present, the most pressing research needs for solar geoengineering fall roughly into the following three interrelated categories.[16]

- Improve understanding and reduce uncertainties related to how solar geoengineering would interact with fundamental atmospheric processes. These uncertainties include, but are not limited to, the behavior and evolution of aerosols introduced into the stratosphere, including plume formation; changes in stratospheric chemistry and composition caused by aerosol injection; and aerosol impacts on the upper troposphere (below the stratosphere), including tropospheric heating. Reducing these and other uncertainties will allow researchers to improve climate models and enhance confidence in their predictions. Reducing uncertainties will require some combination of field campaigns to gather observational data (for example, following large volcanic

[15] The SPICE field test was planned to evaluate a tethered balloon delivery system but was canceled due to an intellectual property dispute.
[16] For a more detailed assessment of current research needs, see NASEM 2021.

eruptions), laboratory experiments (for example, to test alternative aerosols for potential stratospheric injection), and small-scale outdoor experiments (for example, to study aerosol dynamics under real-world conditions).

- Improve predictions of climate system responses to solar geoengineering by more extensive use of more sophisticated climate models. This includes improved modeling at the regional level and simulating more realistic implementation scenarios as well as alternative deployment schemes reflecting different design choices. The influence of plume processes on reflectivity merits particular attention. Modeling should continue to employ large ensembles for purposes of intercomparison.

- Improve knowledge of environmental and societal impacts. Such impacts, including the effects of changes in the ratio of direct to diffuse light (caused by aerosol scattering) on vegetation, should be assessed for a broader range of ecosystems. Integrated assessment models should be used on a more systematic basis to consider the socioeconomic impacts of solar geoengineering, and high-resolution "downscaling" studies should be conducted to assess regional and local impacts on ecosystems and society. The possible environmental and health effects of alternative aerosols require more research

Funding

Funding levels, sources, and characteristics provide further insights into research trends. Global funding for solar geoengineering research from 2008 to 2021 totaled approximately $95 million. For context, a recent study estimates global funding for all climate research totaled, at a minimum, $1.3 *trillion* from 1950 to 2021 (Overland and Sovacool 2020). Funding has been constrained by concerns over sociopolitical and other risks, which has limited research and left many questions unanswered.

Figure 2 shows a gradual growth in funding for solar geoengineering research over time, starting at a very low level of about $1.3 million in 2008 and increasing to about $23.0 million in 2021. The rise beginning in 2017 is attributable to the launch of Harvard's SGRP and the start of Australian government funding for MCB research, followed by the 2020 launch of NOAA's ERB initiative.

Figure 2: Annual Global Funding for Solar Geoengineering Research 2008-2021

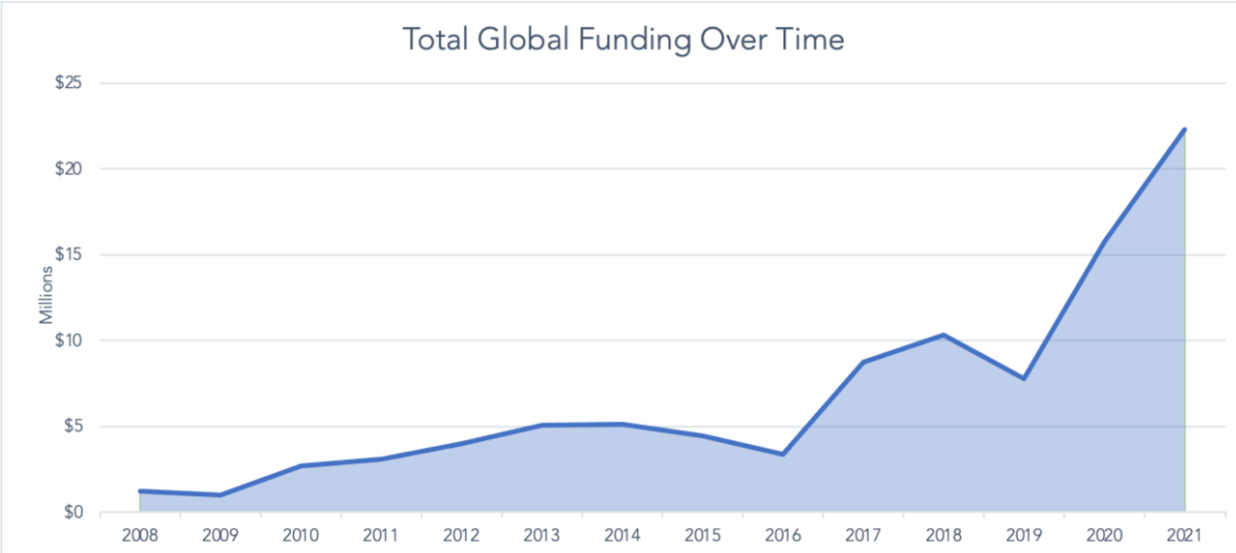


Table 4 breaks down cumulative global funding by research type. Natural science accounts for approximately 22 percent of the total, social science for 14 percent, and interdisciplinary research for 64 percent. The dominance of interdisciplinary research is striking.

Table 4: Total Global Funding for Solar Geoengineering by Research Type, 2008-2021

Research Type	Amount
Natural science	$21.2 million
Social science	$13.0 million
Interdisciplinary	$60.9 million
Total	**$95.0 million**

Figure 3 illustrates how the distribution of funding across research types has evolved over time. The surge in interdisciplinary funding starting in 2017 is due to the start of SGRP, sustained Australian funding for MCB research, and the launch of the ERB initiative, all of which support both natural and social science research.

Figure 3: Annual Global Funding for Solar Geoengineering by Research Type 2008-2021

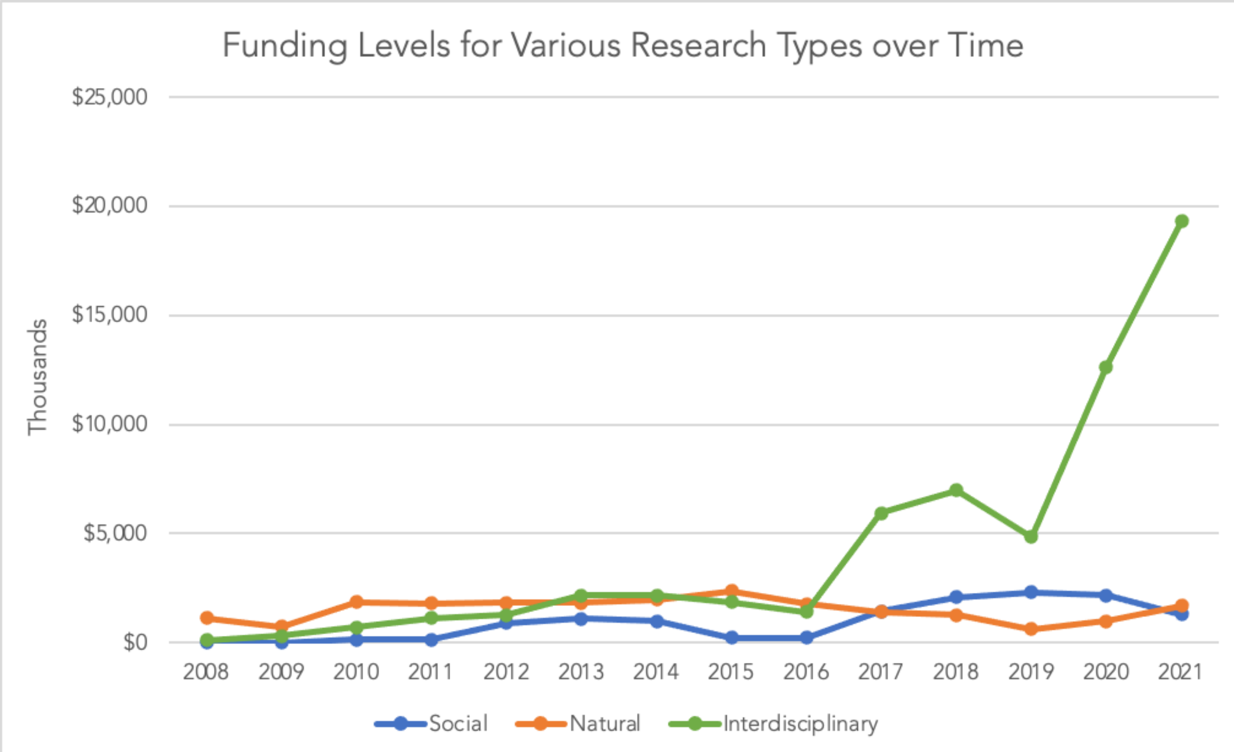


Table 5 breaks down cumulative global funding by funding source. Government support accounts for approximately 48 percent of research funding, private support for 40 percent, and mixed public-private funding makes up the remaining 12 percent.

Table 5: Total Global Funding for Solar Geoengineering by Funding Source, 2008-2021

Funding Source	Amount
Government	$45.5 million
Private	$38.4 million
Mixed	$11.1 million
Total	**$95.0 million**

Figure 4 charts changes in funding sources over time. The boost in private funding in 2017 reflects the program launch of SGRP, which is supported by private philanthropies. The temporary rise in public funding from 2017 to 2018, and the rise in mixed public-private funding starting in 2019, are explained by developments in Australia, where a rapid increase in government funding quickly transitioned to a public-private cost-share arrangement. The rapid expansion in public funding starting in 2020 is attributable to the beginning of NOAA's ERB project.

Figure 4: Annual Global Funding for Solar Geoengineering by Funding Source 2008-2021

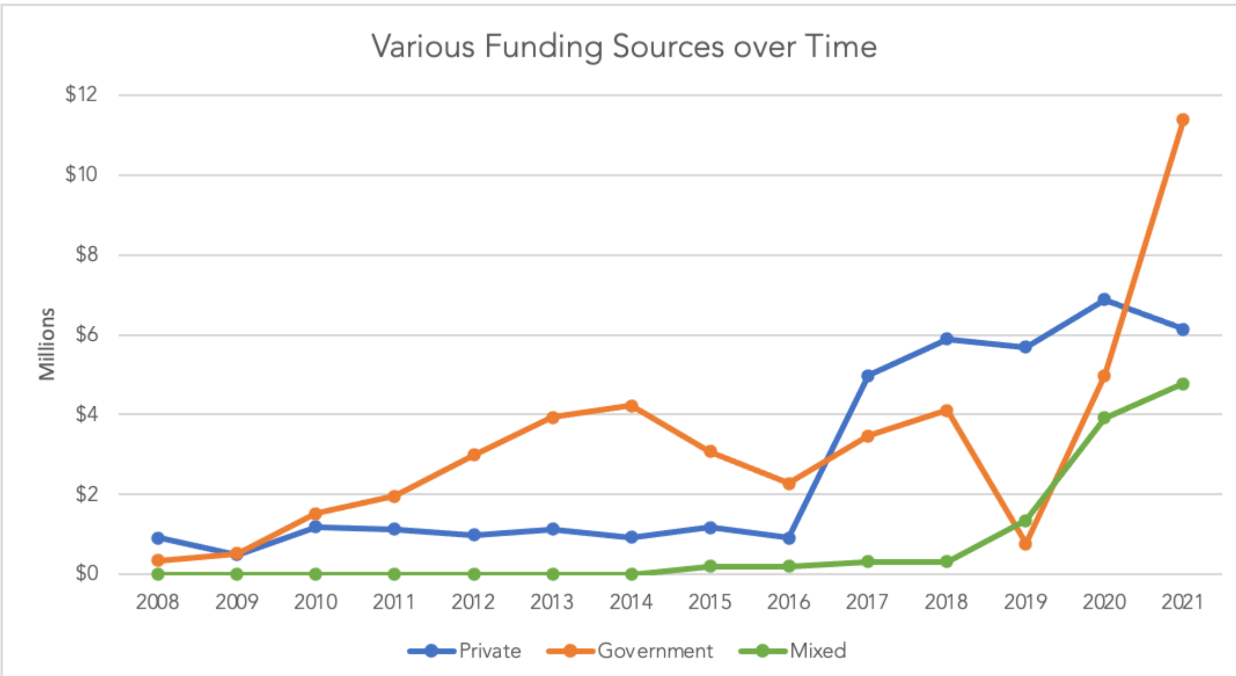


Table 6 breaks down funding by country. The US share of cumulative global funding for solar geoengineering research is 60 percent, by far the largest of any country. Australia is a distant second at 13 percent of the global total, the UK accounts for 9 percent, Germany for 5 percent, and China and Japan for 3 percent each.

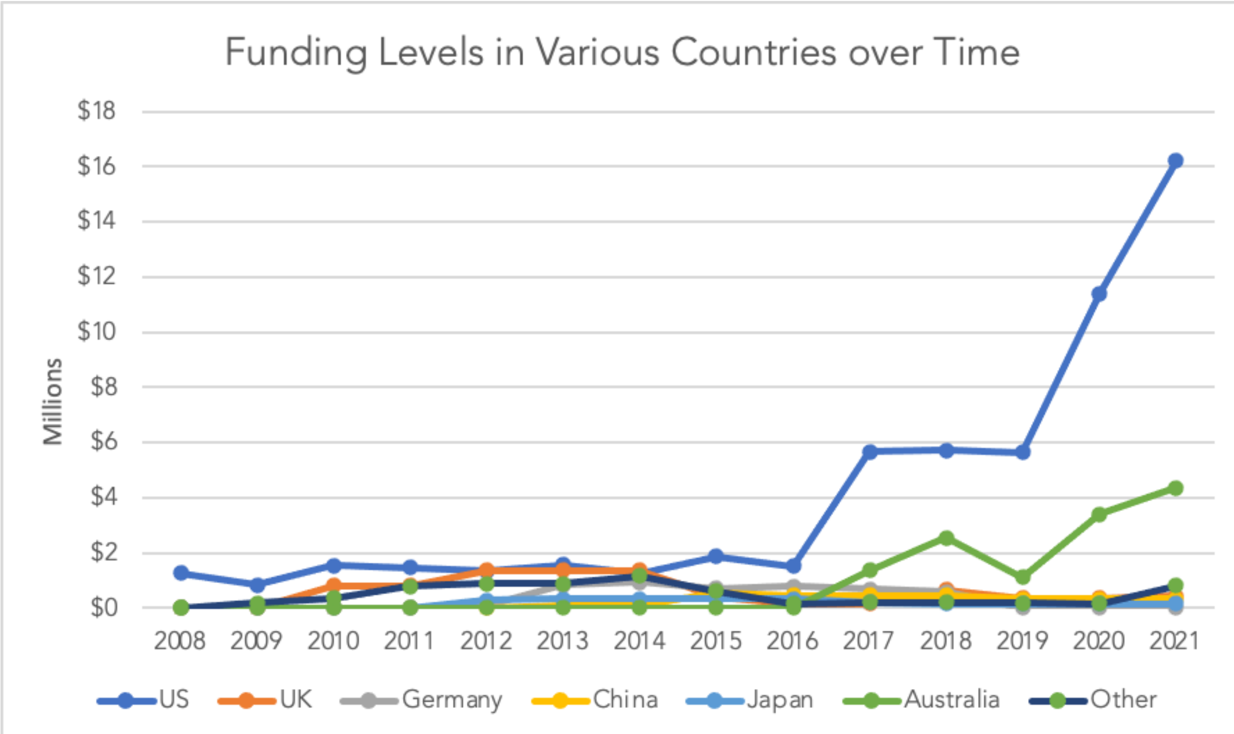
Table 6: Total Funding for Solar Geoengineering by Country, 2008-2021 (by rank)

Country	Amount
US	$57.3 million
Australia	$12.8 million
UK	$8.2 million
Germany	$4.6 million
China	$3.1 million
Japan	$2.4 million
Other	$6.6 million
Total	**$95.0 million**

Note: "Other" includes Canada, Denmark, EU, Finland, France, India, Norway, and Sweden.

Changes in funding by country over time are illustrated in Figure 4, which demonstrates the long-term status of the US as the global leader in funding for solar geoengineering, especially following the launch of SGRP and more recent Congressional support for NOAA's ERB initiative. Figure 5 also shows the emergence of Australia as a secondary locus of funding.

Figure 5: Annual Funding for Solar Geoengineering by Country 2008-2021



Note: "Other" includes Canada, Denmark, EU, Finland, France, India, Norway, and Sweden.

Most funding for solar geoengineering research and advocacy is broadly supportive of improving knowledge about the technology, its impacts and risks, and related governance challenges. Based on their patterns of giving, some *private* funders appear to favor boosting research on solar geoengineering. For example, Open Philanthropy, the Pritzker Innovation Fund, and Lowercarbon Capital have all provided financial support to projects like Harvard's SGRP and SilverLining's SCRI that promote significantly increased research on solar geoengineering. SilverLining, supported by the Pritzker Innovation Fund and Lowercarbon Capital, has emerged as the foremost advocate of expanded research on solar geoengineering. And Harvard's proposed SCoPEx field test, while not funded by SGRP, has been designed by scientists otherwise supported by SGRP.

These three private funders, as well as other more established entities including the Hewlett Foundation, the Sloan Foundation, and the MacArthur Foundation (which have also supported solar geoengineering research and advocacy), are sometimes referred to as "science philanthropies," or philanthropies that are willing to support high-risk, possibly controversial scientific research with potentially limited commercial prospects. Science philanthropy is largely an American phenomenon, as evidenced by the fact that all the private funders and funded projects discussed above are based in the US (Conn 2021). Historically, science philanthropies have supported projects that (US) public agencies are either unable or unwilling to fund.

Some *public* funders, on the other hand, appear more cautious about solar geoengineering. This is most pronounced in Europe. For example, in funding SPP1689, the German National Research Foundation (DFG) was clear that no money should go toward technology development or other research that could conceivably support deployment. At the European level, the European Union (EU) -funded project that produced the European Transdisciplinary Assessment of Climate Engineering (EuTRACE) report was led by researchers from IASS in Potsdam who were strongly influenced by the Science and Technology Studies research program, an academic community highly critical of solar geoengineering.

Most of the remaining funding—both public and private—for solar geoengineering reflects views that fall somewhere in the middle. The exception is funding for advocacy groups that support prohibitions on solar geoengineering. The CS Fund and the Heinrich Boell Stiftung, the latter an independent foundation affiliated with the German Green Party, are major providers of such support. Both have funded the ETC Group and, more recently, the Center for International Environmental Law.

Debating Research

To summarize, the solar geoengineering landscape is characterized by limited research constrained by worries about sociopolitical and other risks and weak global governance. A small number of civil society groups have stepped into this governance void, but their influence on the existing global governance architecture has been minor. More consequential has been their impact on the emerging discourse on solar geoengineering. In particular, they have contributed to shaping the nascent politics of solar geoengineering by helping orient it around the question, *should research on solar geoengineering be expanded?* Arguably, this question is a proxy for a more fundamental debate about whether the world should implement solar geoengineering in the future. For now, however, politics is centered on the question of research.

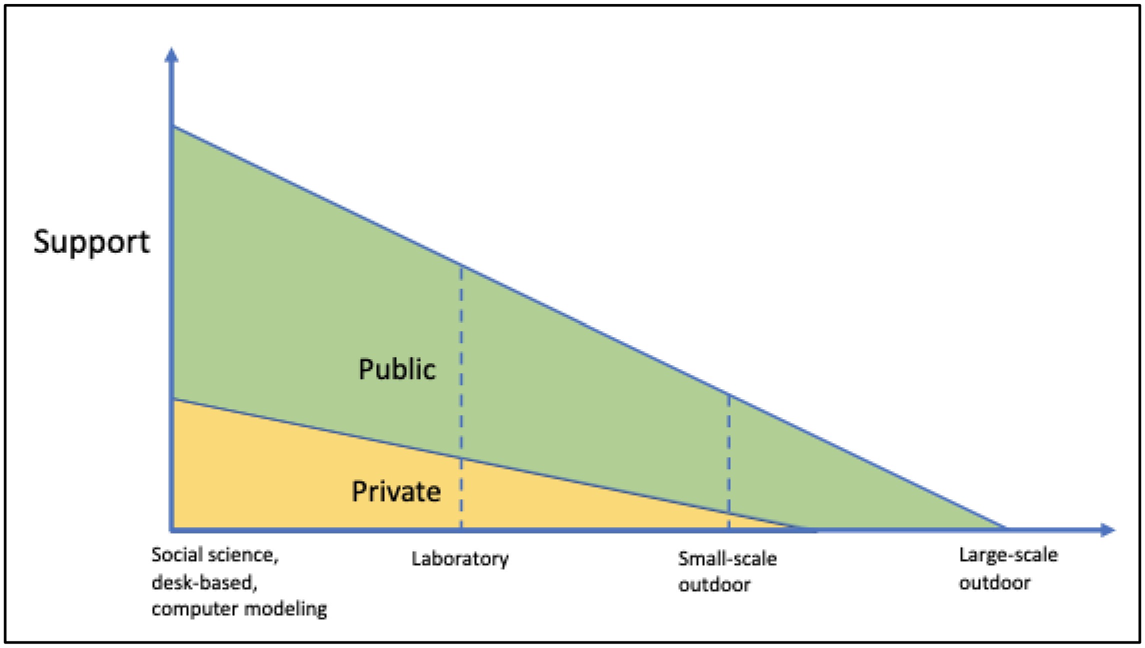
Among scientists, advocates of expanded research on solar geoengineering argue that the scale of the potential benefits associated with these prospective technologies, in terms of protecting nature and society from some of the worst impacts of climate change within a timeframe unachievable by other possible response options, justifies increased natural science, social science, and other forms of research, including small-scale outdoor experiments, to clarify risks and reduce uncertainties. Such benefits may be especially valuable for people in developing countries, who are least responsible for climate change, most vulnerable to its harms, and least able to afford costly adaptation measures. Both the American Meteorological Society and the American Geophysical Union have issued statements in support of expanded research on solar geoengineering.

Many scientists, however, oppose solar geoengineering. Raymond Pierrehumbert, a professor of physics at the University of Oxford, has rejected solar geoengineering primarily on the grounds that relying on the technology in the absence of emissions cuts would place the planet in a precarious position: “If we ever got into a state where we rely on solar climate intervention to prevent catastrophe, it would have to be continued without fail year after year, for 1,000 years or more — lest the termination shock from cessation of the intervention unleash pent-up global warming that would fry the planet in a matter of decades” (2018). Michael Mann, an atmospheric scientist at Pennsylvania State University, objects to solar geoengineering because of, among other reasons, the high uncertainty it would entail: “The fundamental problem of geoengineering … is that tinkering with a complex system we don’t fully understand entails monumental risk” (2021, 164). Mike Hulme, a geographer at the University of Cambridge, regards solar geoengineering as “undesirable, ungovernable, and unreliable” (2014, xii)—undesirable because of its misguided focus on symptoms rather than underlying causes, ungovernable in that global agreement on whether and how to use it would be impossible to reach, and unreliable due to the law of unintended consequences.

Comprehensive expert elicitations of scientific opinion on solar geoengineering have not been conducted (although views probably tend toward the skeptical). Public opinion surveys of populations at large show that majorities typically give conditional support to expanded research. Yet as noted above, these surveys also show low awareness of solar geoengineering, which cautions against interpreting such support as deeply held or well-informed.

Overall, the history of debates in the field suggests that support for research among informed observers generally declines as the scale of proposed physical interventions increases. This is illustrated by Figure 6. Thus, there is widespread support, and very little opposition, to social science research and natural science research that is purely desk-based or relies on climate models. Support is also wide for laboratory research. But support begins to drop when small-scale outdoor research is proposed; field tests planned as part of the SPICE and SCoPEx projects triggered opposition (although its true scale was difficult to gauge) even though neither would have involved actual aerosol release (they were designed strictly to test delivery equipment). In many ways, small-scale field tests have come to symbolize expanded research: proposals for them are typically viewed as pushing the research envelope, while responses to them are often treated as litmus tests for broader views on research (and deployment). There is virtually no support for—and strong opposition to—large-scale outdoor experiments, even among the most vocal advocates for expanded research. Since large-scale experiments by their very nature would be intended to cause detectable, measurable changes in the climate system, they would be essentially indistinguishable from small deployments (Robock et al. 2010). There is also strong opposition to developing technology for use in large-scale experiments due to similar boundary concerns.

Figure 6: Support for Research Falls as the Scale of Intervention Increases

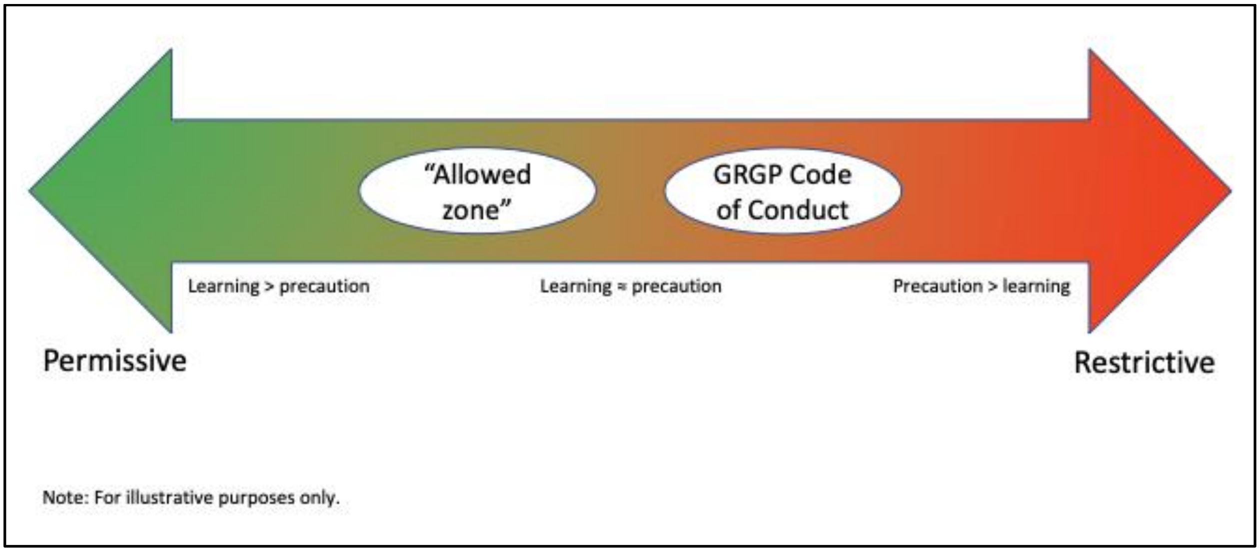


Furthermore, among proponents of expanded research, support for private funding declines as the scale of proposed physical interventions increases (see again Figure 6). Such opposition stems primarily from the widespread presumption that solar geoengineering should serve the public interest: advancing private interests—even when they are conceived as serving the common good—at the possible expense of impacts on the public is generally regarded as unacceptable.

Advocates of more research recognize that solar geoengineering involves a unique set of challenges, including both those specific to the research enterprise itself like the slippery slope, and more general concerns like moral hazard. Moving forward—especially in the direction of outdoor experiments— requires striking an appropriate balance between learning more about the possibilities and limits of solar geoengineering, on the one hand, and guarding against the risks inherent in researching the technology, on the other. Research governance seeks to institutionalize a balance between investigation and precaution.

Figure 7 illustrates how the two most notable research governance proposals put forward up to now—both focused on outdoor experiments—would lean toward one or the other end of a spectrum stretching from fully permissive to fully restrictive (i.e., prohibited). The proposal for an "allowed zone" sketched by Parson and Keith (2013) would permit outdoor experiments only when their effects on the climate would be smaller than routine commercial activities like transatlantic flights; existing national regulations would largely suffice to mitigate risks. Large-scale tests would be subject to a moratorium. Proposed experiments would be assessed based solely on the scale of their anticipated physical effects.[17]

Figure 7: Research Governance Proposals for Permissive to Restrictive



In comparison, the code of conduct developed by Hubert (2017), under the auspices of the Geoengineering Research Governance Project (GRGP), is more restrictive. Following this code, if the researchers proposing an outdoor experiment declare that their intent is to study geoengineering, then they must first demonstrate the soundness of the underlying science using an established assessment framework. If they succeed, a second assessment must determine whether the anticipated physical effects of the experiment would be negligible. If the answer is yes, the experiment may proceed, but if it is no, then a more comprehensive review would be required to show that 1) the experiment was informed by the precautionary principle, and 2) the public had meaningfully participated in the research design process, before the experiment could go forward.

Neither the allowed zone proposal nor the GRGP code of conduct has been adopted by any scientific or funding body, yet they have stimulated useful debates about how to balance learning and precaution in solar geoengineering research, including ways of integrating different tools such as research registries, public engagement mechanisms, intellectual property regimes, and EIAs into coherent research governance systems. Up to now, disagreement over the level of precaution appropriate to (different types of) solar geoengineering research has been the principal driver of international political deliberations about the technology. The debate that occurred at the 2019 pre-meeting of UNEA over the merits of the draft resolution on geoengineering technology assessment is illustrative. The

[17] Specifically, experiments likely to produce annual reductions in radiative forcing less than approximately 10^{-6} Wm^{-2} would be allowed, and those with anticipated reductions greater than approximately 10^{-2} Wm^{-2} would be prohibited; experiments in between have limited scientific value and are unlikely to be proposed in the foreseeable future (see Parson and Keith 2013).

original draft, which referenced the precautionary principle, raised "grave concerns" about geoengineering, and tasked UNEA with conducting the assessment, was criticized by the US (along with Saudi Arabia and Brazil) for being excessively restrictive; the US and others preferred that the Intergovernmental Panel on Climate Change, which they viewed as more scientific than UNEA, conduct any assessment. In response, the EU (joined by Bolivia) characterized the US-led position as too permissive, insisted on emphasizing risks and "grave concerns," and communicated that dropping reference to the precautionary principle was a "red line."[18] As noted above, the result was deadlock, and the draft was withdrawn prior to the formal start of the meeting.

While supporters of expanded research disagree among themselves about how permissive or restrictive research governance should be, others oppose research altogether, particularly when it comes to outdoor experiments. From this perspective, research governance should not attempt to balance freedom of inquiry against freedom from harm, but instead should simply prohibit at least some forms of research, for instance through bans. The question of whether (outdoor) research should be permitted to take place, regardless of how tightly it might be regulated, currently divides the US environmental community. On one side, "pragmatist" groups like EDF, NRDC, and UCS have expressed support for small-scale outdoor field tests on the condition that rigorous governance mechanisms are in place; such conditional support presumably leans toward the restrictive end of the regulatory continuum. On the other side, "purist" groups including FOE-US, the Sierra Club, and 350.org are hostile to solar geoengineering and generally oppose outdoor experiments.

In 2019, Climate Action Network (CAN) International, a global network of more than 1,500 climate advocacy groups (including all the abovementioned US groups), issued a position statement on solar geoengineering in which it declared its opposition to the technology. Notably, three organizations–EDF, NRDC, and UCS–added reservations to this statement in which they expressed conditional support for small-scale outdoor research. This illustrates the extent to which the research debate is centered in the US, no doubt due to US dominance of global research funding. Competing views among US NGOs are important not only as indicators of political sentiments, but also for their policy implications: a federal solar geoengineering research program will require the backing of an advocacy coalition, the composition and strength–and hence success–of which will depend heavily on whether and how disagreements over research are resolved (Felgenhauer, Horton, and Keith 2021.)

Table 7 provides a rough approximation of how differing perspectives on research map onto proposed research governance frameworks, active members of global civil society, key governments, and leading US NGOs. Clearly, such perspectives are neither fully developed nor fully reflected in existing governance proposals (which themselves are not fully developed). Similarly, no government has developed a comprehensive position on solar geoengineering,

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[18] In addition, the EU preferred to assess solar geoengineering and carbon dioxide removal jointly whereas the US preferred separate assessments.

and few NGOs have clearly articulated their views on the subject (few spend much time on it). Yet some outlines of the otherwise nebulous politics of solar geoengineering are coming into view, most conspicuously with regard to questions about research and research governance, and these outlines carry implications for how to move forward.

Table 7: Differing Perspectives on Solar Geoengineering Research

Perspectives	Permissive Regulation	Restrictive Regulation	Prohibition
Governance proposals	"Allowed zone"	GRGP Code of Conduct	Non-Use Agreement
Global civil society		C2G	ETC Group, CAN International
National governments	US, Brazil, Saudi Arabia	EU, Bolivia	
US environmental NGOs		EDF, NRDC, UCS	FOE-US, Sierra Club, 350.org

Recommendations

Given this landscape–huge potential benefits but significant risks, limited research and constrained funding, weak governance and immature politics, and, above all, high uncertainty–what recommendations are most suitable for a philanthropic foundation considering entry into this space? To answer this question, the place to start is to recognize that we still know relatively little about solar geoengineering, and we can only learn more by making substantial investments in research. Without more research, uncertainties regarding benefits, risks, and costs cannot be reduced, and without a better knowledge base, the world will never be in a position to make responsible decisions about solar geoengineering.

It is also necessary to recognize that funding for research is not limited by an absence of resources but rather by persistent concerns over the sociopolitical risks associated with the technology. These risks give pause to funders, especially public funding agencies capable of marshaling considerable support accompanied by a social license to conduct research with societal (indeed, global) implications. If these concerns are not addressed, funding is unlikely to flow at the rates necessary to reduce uncertainties to satisfactory levels.

Presently, these concerns about risk manifest primarily in debates about research, most prominently in arguments over proposals for small-scale outdoor field experiments. Because of its disproportionate share of research funding and effort, the most serious discussions about research and research governance–and the discussions with the most significant policy implications–have occurred in the US. The US environmental community, roughly divided into pragmatists in favor of restrictive regulation and purists opposed to research, is at the center of these discussions. As noted above, these debates remain at an embryonic stage both globally and within the US.

All this suggests that boosting research to resolve uncertainties requires addressing sociopolitical concerns, in the first instance by helping build a consensus regarding research governance, including governance of small-scale outdoor experiments, among US environmental NGOs. Any consensus of this sort would probably need to be based on a relatively restrictive regulatory model.[19] Purist groups opposed to solar geoengineering in principle are unlikely to accept this, at least in the short term. FOE-US, for instance, "would condemn any proposals to move geoengineering towards real world experimentation" (2015). Therefore, any attempt to help build a consensus on research governance within the US environmental community ought to focus primarily on mainstream, pragmatist NGOs.

The outlines of such a consensus are already discernible, ironically, as detailed in the reservations made by pragmatist groups to the CAN International position statement noted above. It is useful here to quote these reservations in their entirety:

> EDF and NRDC do not support an unequivocal ban on outdoor/real-world experiments on SRM. They believe, based on their best understanding of the current science, that engaging in transparent small-scale field research to further understanding of the climate system and the implications of any solar geoengineering proposals is prudent, and governance regimes should be established in parallel with the very first experiments. UCS believes that a precautionary approach to climate risks includes developing an understanding of the risks and efficacy of solar geoengineering: UCS strongly opposes large-scale tests and believes smaller-scale outdoor experiments should only go forward if legitimate independent governance mechanisms are established to ensure that proposed experiments have high scientific quality and value and that they pose negligible environmental, social and legal risks. Such governance mechanisms must be transparent and inclusive, ensuring meaningful engagement with climate vulnerable communities and other civil society stakeholders, and provide oversight over the duration of the experiments (CAN International 2019).

There is obvious overlap between these positions, creating the basis for a more comprehensive collective approach to (restrictive) research governance.

There is also potential to broaden this nascent coalition by bringing in groups with similar or at least compatible perspectives. The Sierra Club, for example, is deeply skeptical of solar geoengineering, but its position is not as absolutist as those expressed by FOE-US, 350.org, and others. Its Climate Adaptation Task Force, for instance, "does not see a major role for the Sierra Club on SRM issues, except to monitor U.S. actions and research and take action to oppose any U.S. deployment" (Sierra Club 2019). This points toward the possibility of

[19] This does not mean, however, that the GRGP Code of Conduct should necessarily form the basis of discussion.

expanding the coalition to include environmental groups that might also be willing to back a restrictive research governance regime.

None of the potential members of such a coalition is likely to support such a regime without feeling a sense of ownership, both because participating in an initiative is more likely to induce support for its outputs, and because the complexity of some of the issues involved requires the sort of understanding best cultivated by direct engagement in the problem at hand. Neither of the proposals advanced so far have attracted significant support from environmental NGOs. These considerations speak in favor of a collaborative approach toward outlining a research governance model for solar geoengineering that gains acceptance and support from pragmatic, US-based environmental NGOs.

Convening a collaborative process involving pragmatic NGOs, regulatory experts, and solar geoengineering researchers–especially those interested in conducting small-scale outdoor experiments–could be a crucial step in building support among environmentalists for expanded research regulated by a system designed and backed by key stakeholders, grounded in regulatory science, and compatible with the research necessary to enhance collective knowledge and enable decision-makers to make informed decisions about solar geoengineering.

Recommendation 1: Convene a collaborative process that includes pragmatic environmental groups, regulatory experts, and scientists with the goal of reaching consensus on a model of research governance for solar geoengineering applicable to small-scale outdoor experiments.

Using solar geoengineering would affect the entire planet, yet not every country can contribute equally to solar geoengineering research. Indeed, if current trends continue, the future distribution of research activity is likely to mirror contemporary power dynamics, with powerful countries in the lead and weaker countries minimally involved. Moreover, the research produced by powerful countries–especially research generated by dedicated national programs–is likely to reflect their national interests, potentially frustrating attempts to establish a shared global knowledge base widely viewed as addressing questions relevant to a diversity of national circumstances. Failure to build such a knowledge base could lead to international tensions over the prospect of deploying the technology and/or further marginalization of developing countries already victimized by climate change. Fears of such outcomes animate concerns over unilateralism and where and how to set the “global thermostat.”

This calls for determined efforts to establish and institutionalize international scientific collaboration in order to enhance trust and build confidence in the solar geoengineering research enterprise. Certainly many collaborations between researchers from different countries have taken place already, perhaps most regularly within GeoMIP. Yet these collaborations have been fundamentally research-driven and minimally informed by political goals. Such collaborations must be supplemented with what has been called “science for diplomacy," or international scientific partnerships designed to spill over and "improve international relations between countries" (Royal Society 2010, 4).

Looking forward, the two countries likely to play the biggest role in global decisions over solar geoengineering are the US and China (European skepticism toward solar geoengineering–exemplified by the EU stance at UNEA-4–makes Europe unlikely to lead on this issue).[20] These countries are currently engaged in "strategic competition" with one another, and disagreements and tensions between them are set to increase in the near term. Helping establish a nongovernmental international solar geoengineering research consortium involving scientists from a globally representative group of countries–including the US and China–could be an important step toward securing a global knowledge base with broad international support, including from the Global North and the Global South and from the two powers likely to dominate the international system in the decades to come. Ongoing tensions between the US and China might of course complicate such an effort, yet this sort of initiative might also create opportunities to reduce bilateral tensions.

An effort of this sort need not start from scratch. The Degrees Initiative's DECIMALS Fund is already helping build scientific expertise in developing countries; researchers associated with this project might be recruited to participate in such a consortium. The GeoMIP collaborative includes modelers based in China; its ninth (international) workshop was held at Beijing Normal University in 2019. And scholars from Harvard University and Tsinghua University have had early discussions about joint research possibilities (Xue Lan, a dean at Tsinghua University, is a member of the new Climate Overshoot Commission).

Recommendation 2: Facilitate or coordinate the formation of an international solar geoengineering research consortium involving scientists from around the world, including from the US and China.

Perhaps the biggest underlying concern about solar geoengineering is its potential to generate international tensions and possibly even conflict. Fears regarding international disagreements over the technology are at the core of anxieties about where to set the "global thermostat." Thinking about solar geoengineering in terms of setting a global thermostat is simplistic and potentially misleading, since any climate "control" afforded by the technology would be crude and imprecise. Nevertheless, this imagery does get at something fundamental: countries may have different preferences over climate, and these preferences may not be entirely compatible.

In the context of solar geoengineering, to the extent that national preferences vary, they will do so primarily in terms of *how much to cool the planet*. Some countries, for example, Pacific island countries facing existential threats from sea level rise, may prefer a lot of cooling, but some others, for example, Russia, might conceivably benefit from a thawing Arctic and a

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[20] For an extended analysis of how solar geoengineering is likely to figure in relations between the US and China, see Horton 2022.

warmer Siberia and thus may prefer only a little cooling, or even none at all. Given the novelty of solar geoengineering, no country has seriously considered this question, and this lack of consideration has fed deep concerns about potential limits to international cooperation.

A first step toward addressing these concerns would be to conduct a preliminary assessment of anticipated national preferences regarding desirable amounts of solar geoengineering among key countries. Such countries ought to include major geopolitical powers (the US and China), influential middle powers (for example, Germany, Japan, Russia), and major developing countries (for example, India, Brazil, South Africa). Such an assessment might be based on, inter alia, expert interviews, sociocultural and historical studies, public opinion surveys, and economic analyses of "optimal" climates (for example, see Burke, Hsiang, and Miguel 2015). Any assessment of this type must be informed by ongoing modeling efforts to ensure that considerations proceed on the basis of what solar geoengineering might reasonably be expected to achieve.

A project of this sort could make at least three significant, policy-relevant contributions to research on solar geoengineering. First and most basic, such an assessment could provide a critical estimate of the degree to which national preferences overlap. A large overlap would suggest a smaller number of less intense disagreements over the prospect of deployment, and thus a lower risk of geopolitical instability and greater potential for cooperation. A small overlap, on the contrary, would suggest that national interests are more conflictual and that the international politics of solar geoengineering will be relatively contentious (and at the extreme "ungovernable").

Second, and especially in the latter case, assessing and mapping anticipated preferences may help identify room for compromise. Improved understanding of the nature of possible disagreements, including different axes of concern and different degrees of salience, could help delimit an empirically grounded "solution space" within which viable compromises might be struck. Finally, carrying out this sort of assessment could help set the stage for subsequent, more authoritative and potentially official analyses intended to specify national preferences or even help define national positions. Preparing the way in this sense might entail stimulating questions, debates, and/or research taken up by formal policy bodies, shaping analytical frameworks in ways that promote constructive outcomes, or both.

Recommendation 3: Organize or sponsor a research project to assess anticipated national preferences regarding desirable amounts of planetary cooling, covering a representative set of countries and employing multiple methods.

Lastly, researchers and other stakeholders in the US need an advocate to press for expanded research, particularly in the public arena. An effective advocacy group dedicated to making the case for why more research on solar geoengineering is important and necessary has been conspicuously absent from debates about research and research governance. SilverLining has at times attempted to play this role, but its relations with some key members of the research community have frayed as a result of disputes over decision-making and funding; for now, its alienation from key constituencies prevents SilverLining from successfully playing an advocacy role. The new organization being launched by Shuchi Talachi (mentioned above) might conceivably take on this mantle, but its focus appears to be primarily outside the US.

Hence it may be necessary to start a solar geoengineering research advocacy group from the bottom up. This would require careful planning and consideration of organizational structure, strategy, and funding, and should draw on insights from the nonprofit, scientific, policy, environmental, and philanthropic communities. Groups advocating for expanded research on artificial intelligence, synthetic biology, and gene drives might serve as useful templates.

Recommendation 4: Cultivate or seed an advocacy group dedicated to pushing for expanded research on solar geoengineering.

References

CAN International. 2019. Climate action network position on solar radiation modification (SRM) [Press release]. Available from: http://www.climatenetwork.org/sites/default/files/ can_position_solar_radiation_management_srm_september_2019.pdf [Accessed March 26, 2020].

Cao, L., Duan, L., Bala, G., and K. Caldeira. 2017. Simultaneous Simulation of Global Temperature and Precipitation Through Cocktail Geoengineering. *Geophysical Research Letters* 44: 7429-7437.

Conn, R.W. 2021. Why Philanthropy is America's Unique Research Advantage. *Issues in Science and Technology*.

Cummings, C.L., Lin, S.H., and B.D. Trump. 2017. Public Perceptions of Climate Geoengineering: A Systematic Review of the Literature. *Climate Research* 73: 247-264.

Felgenhauer, T., Horton, J., and D. Keith. 2021. Solar Geoengineering Research on the U.S. Policy Agenda: When Might Its Time Come? *Environmental Politics* 31: 498-515.

Harding, A.R., Ricke, K., Heyen, D., MacMartin, D.G., and J. Moreno-Cruz. 2020. Climate Econometric Models Indicate Solar Geoengineering Would Reduce Inter-Country Income Inequality. *Nature Communications* 11: https://doi.org/10.1038/s41467-019-13957-x.

FOE-US. 2015. Geoengineering: unjust, unproven and risky [Press release]. Available from: https://foe.org/news/2015-02-geoengineering-unjust-unproven- and-risky/ [Accessed March 24, 2020].

Horton, J.B. 2018. Parametric Insurance as an Alternative to Liability for Compensating Climate Harms. *Carbon & Climate Law Review* 4: 285-296.

Horton, J.B. 2022. The Status of Solar Geoengineering: Stratospheric Aerosol Injection as a Prestige Technology in Strategic Competition Between the United States and China. In process.

Horton, J.B., Brent, K., Dai, Z., Felgenhauer, T., Geden, O., McDonald, J., McGee, J., Schenuit, F., and J. Xu. 2022. Solar Geoengineering Research Programs on National Agendas: A Comparative Analysis of the United States, Germany, China, and Australia. Under review.

Horton, J.B., Keith, D.W., and M. Honegger. 2016. *Implications of the Paris Agreement for Carbon Dioxide Removal and Solar Geoengineering*. Harvard Project on Climate Agreements Viewpoint.

Hubert, A.-M. 2017. *Code of Conduct for Responsible Geoengineering Research*. Calgary: University of Calgary.

Hulme, M. 2014. *Can Science Fix Climate Change? A Case Against Climate Engineering*. Cambridge, UK: Polity.

Irvine, P., Emanuel, K., He, J., Horowitz, L.W., Vecchi, G., and D. Keith. 2019. Halving Warming with Idealized Solar Geoengineering Moderates Key Climate Hazards. *Nature Climate Change* 9: 295-299.

Mann, M.E. 2021. *The New Climate War: The Fight to Take Back Our Planet*. New York: PublicAffairs.

NASEM. 2021. *Reflecting Sunlight: Recommendations for Solar Geoengineering Research and Research Governance*. Washington, D.C.: National Academies Press.

Nohrstedt, D., Mazzoleni, M., Parker, C.F., and G. Di Baldassarre. 2021. Exposure to Natural Hazard Events Unassociated with Policy Change for Improved Disaster Risk Reduction. *Nature Communications* 12: https://doi.org/10.1038/s41467-020-20435-2.

Overland, I., and B.A. Sovacool. 2020. The Misallocation of Climate Research Funding. *Energy Research & Social Science* 62: 101349.

Parker, A., Horton, J.B., and D.W. Keith. 2018. Stopping Solar Geoengineering Through Technical Means: A Preliminary Assessment of Counter-Geoengineering. *Earth's Future* 6: 1058-1065.

Parson, E.A. 2014. Climate Engineering in Global Climate Governance: Implications for Participation and Linkage. *Transnational Environmental Law* 3: 89-110.

Parson, E.A., and D.W. Keith. 2013. End the Deadlock on Governance of Geoengineering Research. *Science* 339: 1278-1279.

Peterson, L. 2021. Silver Lining to Extreme Weather Events? Democracy and Climate Change Mitigation. *Global Environmental Politics* 21: 23-53.

Pierrehumbert, R. 2020. When It Comes to Geoengineering, We're Still Very Much in the Dark. *Boston Globe*.

Reynolds, J.L. 2021. Linking Solar Geoengineering and Emissions Reductions: Strategically Resolving an International Climate Change Policy Dilemma. *Climate Policy* 22: 285-300.

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

Robock, A., Bunzl, M., Kravitz, B., and G.L. Stenchikov. 2010. A Test for Geoengineering? *Science* 327: 530-531.

Sierra Club. 2019. Tackling climate change: adapting to a changed world, while reversing global warming to protect communities & ecosystems and promote climate justice. Available from:

https://content.sierraclub.org/grassrootsnetwork/sites/content.sierraclub.org.activistnetwork/files/teams/documents/Tackling%20Climate%20Change%20Report%20Feb%202019.pdf [Accessed March 13, 2020].

Weitzman, M.L. 2015. A Voting Architecture for the Governance of Free-Driver Externalities, with Application to Geoengineering. *Scandinavian Journal of Economics* 117: 1049-1068.

Zhang, Y., MacMartin, D.G., Visioni, D., and B. Kravitz. 2022. How Large is the Design Space for Stratospheric Aerosol Geoengineering? *Earth System Dynamics* 13: 201-217.