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Reflecting Sunlight: Recommendations for Solar Geoengineering Research and Research Governance (2021)
Chapter: 2 Assessment of the Current Solar Geoengineering Research and Research Governance Landscape
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CHAPTER TWO

Assessment of the Current Solar Geoengineering Research and Research Governance Landscape

This chapter provides an overview of the current "landscape" of research and research governance related to solar geoengineering (SG), offering a critical departure point for thinking about the future of the research and research governance enterprise. Building upon the earlier analyses of the National Research Council (NRC) (2015) study, the following sections provide a brief discussion of currently proposed SG methods (2.1); a review of the current state of relevant technological, natural science, and social science research (2.2 and 2.3); observations about synthesis across these different research areas (2.4); and an overview of the current state of research governance that is relevant to SG applications (2.5).

2.1 OVERVIEW OF PROPOSED SOLAR GEOENGINEERING METHODS

As discussed in Chapter 1, current scientific understanding makes clear that the changes in climate are being driven by the rapid rate at which greenhouse gas (GHG) concentrations are increasing in the atmosphere. GHGs are relatively transparent to incoming solar radiation, but they absorb (and reemit) infrared (IR) radiation emitted from Earth's surface. As GHGs accumulate, energy is retained longer in the global climate system. This raises temperatures and causes many other changes within the Earth system. Aggressive action to stabilize and reduce atmospheric GHG concentrations can address this problem directly. However, given the enormous risks that climate change poses now and in the future, a variety of complementary strategies—including strategies based on increasing the amount of sunlight reflected back into space—are being considered as possible options to help stabilize the climate and protect human safety worldwide.

There are two main approaches considered herein for increasing how much incoming solar energy is reflected back to space: stratospheric aerosol injection (SAI) and marine cloud brightening (MCB). In addition, this report considers cirrus cloud thinning (CCT), which differs from the other strategies in that it focuses on increasing outgoing longwave radiation and thus is not technically "solar" geoengineering. Each of these three approaches would affect Earth's radiation balance in different ways, and they are described briefly below and illustrated in Figure 2.1.

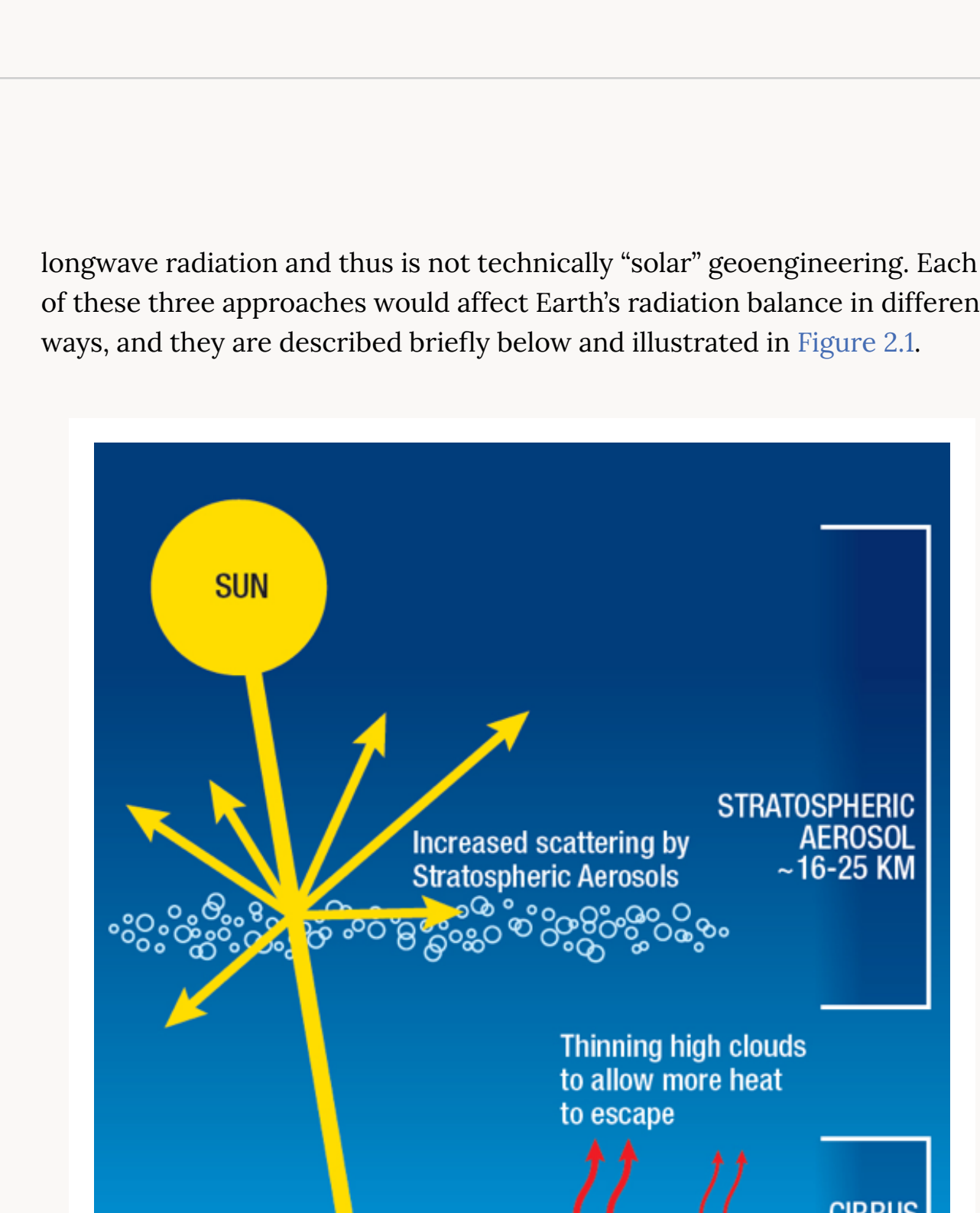
SUN
Increased scattering by Stratospheric Aerosols
STRATOSPHERIC AEROSOL ~16-25 KM
Thinning high clouds to allow more heat to escape
CIRRUS CLOUDS ~6-13 KM
Increased scattering by brightened clouds
MARINE CLOUDS ~0-3 KM

FIGURE 2.1a Illustration of the basic mechanisms involved in Stratospheric Aerosol Injection (SAI), Marine Cloud Brightening (MCB), and Cirrus Cloud Thinning (CCT).

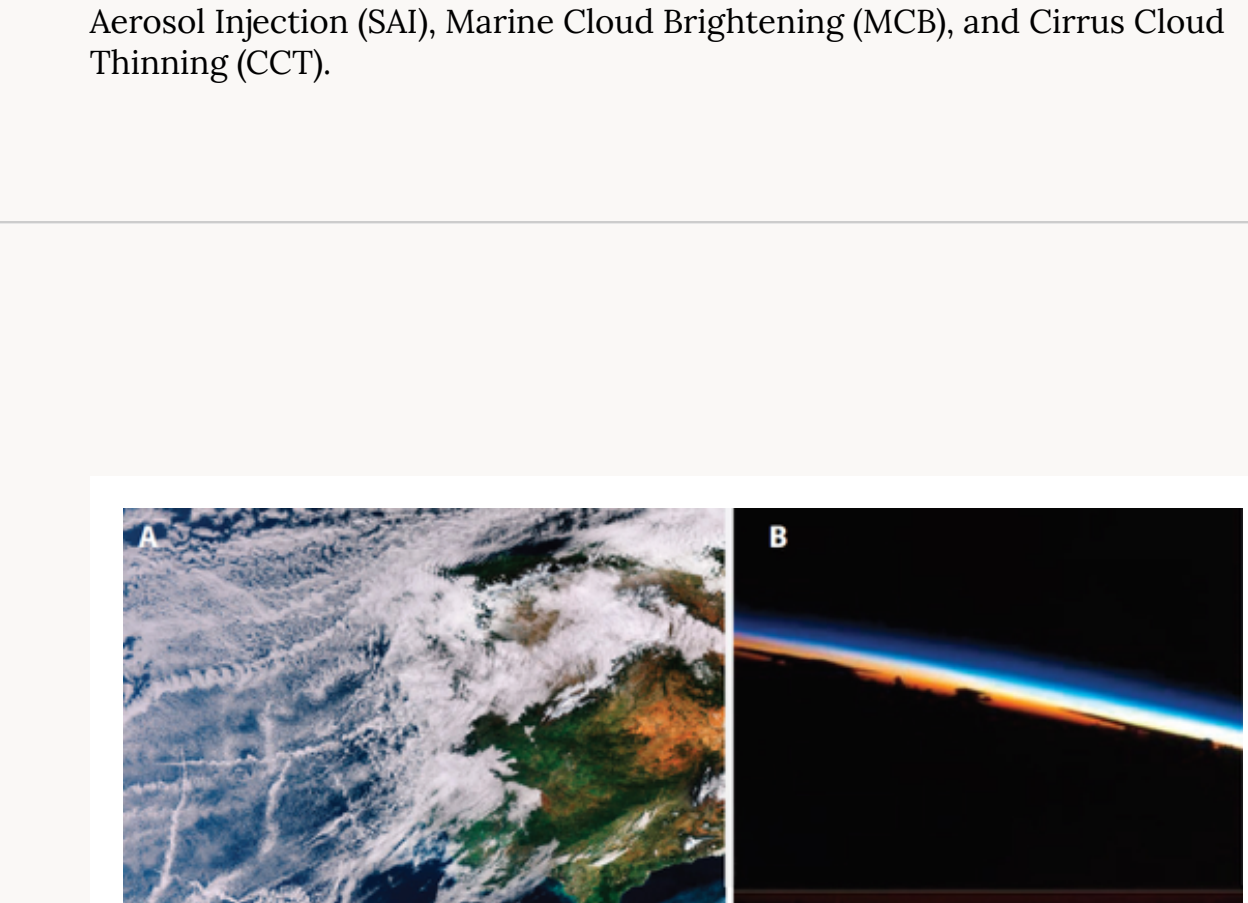

FIGURE 2.1b Photos to further illustrate the principles of SAI, MCB, CCT. A: satellite images (from Copernicus Sentinel-3A) over the Atlantic Ocean, showing both regular maritime clouds and criss-cross tracks from maritime shipping; B: images of Earth's horizon at sunset, highlighting the difference in the atmosphere before and approximately 1 month after the Mt. Pinatubo eruption (note the distinct layer of aerosols in second image); C: typical cirrus clouds. SOURCES: A and B: NASA, C: NOAA.

2.1a Stratospheric Aerosol Injection

SAI is the most studied and best understood of the SG approaches proposed to date. It is based on increasing the number of liquid or solid particles in the stratosphere, where they can reflect sunlight. Unlike the highly turbulent troposphere, the stratosphere is relatively stable, and the aerosols in this region of the atmosphere can remain for 1 year or more before being transported to the troposphere and eventually removed by sedimentation and precipitation.

Large volcanic eruptions (e.g., the 1991 eruption of Mt. Pinatubo) add significant amounts of hydrogen sulfide (H_2S) and sulfur dioxide (SO_2) into the stratosphere, where they are oxidized to form sulfuric acid (H_2SO_4), which then forms reflective sulfate aerosols. The Mt. Pinatubo eruption is estimated to have cooled global mean temperatures by approximately 0.5°C for 1 year or more (IPCC, 2013). A similar effect could, in principle, be achieved deliberately, either by adding SO_2 or H_2S gas, adding sulfate particles directly, or adding some solid particles such as calcite. While sulfate has the advantage that it is more directly analogous to material expelled by volcanoes, it also absorbs IR radiation and can pose undesirable effects on atmospheric chemistry (discussed later in this chapter); these concerns have motivated some exploration of other aerosol choices.

Because aerosols spread relatively uniformly in longitude and are transported broadly poleward in latitude during their lifetime in the stratosphere, the cooling effects of SAI would be inherently global. Regional-scale climate impacts may vary considerably, however, and the details of impacts at this scale are highly uncertain and will depend on how SAI is deployed (e.g., choices such as the latitude at which it is injected and the aerosol material used).

2.1b Marine Cloud Brightening

MCB is based on the idea of cooling Earth by increasing the reflectivity of low clouds over certain parts of the ocean. As an analogue, under the right conditions, the aerosol pollution from ships leaves behind a "ship track" caused by the emitted aerosols acting as additional cloud condensation nuclei. For the same total cloud water content, more droplets (from more nuclei) result in higher surface area and a more reflective cloud. It has been proposed that the same effect could be achieved by spraying a fine mist of salt water into the marine atmosphere. NRC (2015) provides a detailed review of the decades of research on aerosol and marine cloud interactions, including ship track studies. Yet despite this large research base, many uncertainties remain regarding MCB strategies, including limited understanding of aerosol-cloud interactions and how these interactions affect a cloud's total water content and lifespan. This understanding needs to be improved in order to reliably project where, when, and by how much cloud albedo could be modified.

The expectation is that MCB would be implemented at the regional level, potentially allowing more targeted interventions (e.g., to protect a specific coral reef ecosystem). However, if the MCB forcing could only be applied over a relatively small fraction of Earth's surface, actually reducing global mean temperature would require a relatively larger radiative forcing (RF) to be applied over that smaller area, likely inducing more spatially heterogeneous climate responses than SAI. It is also important to recognize that for MCB the albedo modification effect is localized, but the resulting cooling effects are not, since the atmosphere will transport the changes in heating to other areas.

2.1c Cirrus Cloud Thinning

Cirrus clouds—thin wispy clouds composed of ice crystals that form in the upper troposphere—warm the planet (particularly at higher latitudes) because they reduce outgoing longwave radiation more than they reflect incoming sunlight. Reducing cirrus cover would thus produce a net cooling. It has been hypothesized that in the right conditions, it may be possible to seed cirrus with ice nuclei that would lead to fewer, larger ice crystals, with higher fall velocities, thus decreasing lifetime and hence cirrus cover. This approach would only work in locations where cirrus clouds form through homogeneous freezing—that is, where there are not currently enough ice nuclei to allow heterogeneous freezing. If there are already sufficient ice nuclei in some regions, then adding more could have the opposite effect of leading to more, smaller ice particles with longer lifetimes—and hence a warming effect.

CCT is the least well understood of the three methods considered herein. If CCT were feasible, it has the advantage that it works by increasing the outgoing longwave radiation and thus more directly compensates for the radiative effects of increased atmospheric GHG concentrations. The maximum RF achievable with this method would be limited by the amount of cirrus cover currently formed through homogeneous nucleation.

It should be noted that applying combinations of SAI, MCB, and CCT strategies could offer possible ways to leverage the benefits and reduce the negative consequences of each approach individually. But there has to date been little to no focused study of these combined strategies.

2.1d General Research Status

As a general estimate, reflecting roughly 1 percent of the sunlight that Earth currently absorbs may be enough to counteract all of the warming caused by the current increase in atmospheric CO_2 levels above preindustrial levels (e.g., Kravitz et al. [2013]) shows estimated solar reduction for a CO_2 forcing roughly four times larger than today's). However, even if an increase in global mean temperature rise due to CO_2 were fully compensated by an SG-driven reduction in temperature, these different "climate forcing" mechanisms affect the climate in very different ways. SG interventions could lead to a variety of changes in regional-scale temperature, precipitation patterns, and other impacts—effects that are at present poorly understood and difficult to predict. For any of these SG methods, the climate response will depend on the specific method of forcing, as well as the spatial distribution of that forcing. This reality, together with existing uncertainties in climate modeling more generally, means that our ability to estimate climate responses and the downstream impacts of those responses is currently very limited.

There has been significant research conducted to date covering numerous dimensions of SG research. The literature search results presented in Figure 2.2 offer an indication of the distribution of different focal areas for published studies to date. The majority of research in the natural sciences has focused on climate and atmospheric modeling studies; social sciences research has been a mix of theoretical and empirical studies, with little experimental work and limited geographic diversity in the participants engaged. It is also worth considering the limited diversity of the research community itself, across both the natural and social sciences (see discussion in Box 2.1).

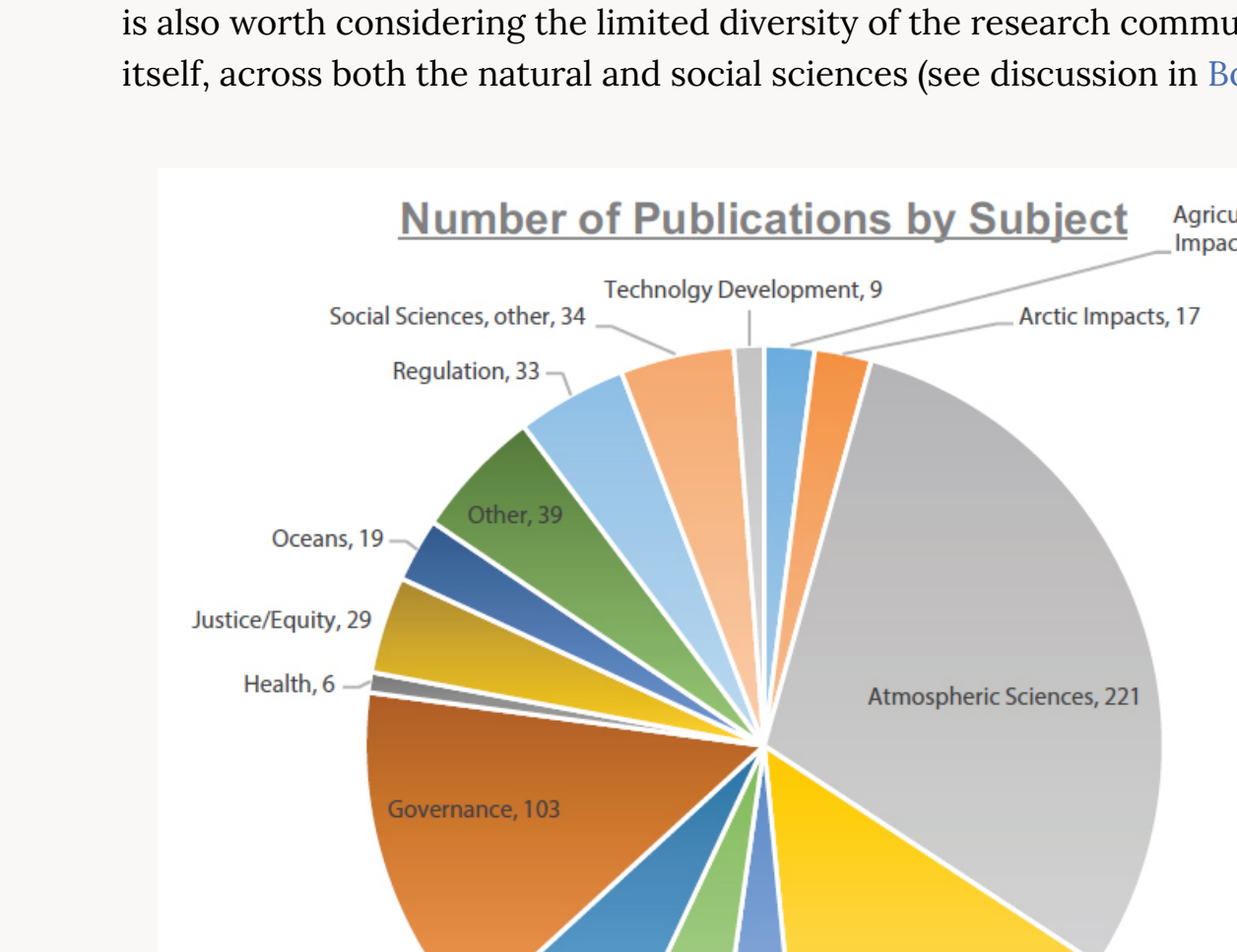

FIGURE 2.2 Distribution of subject matter for geoengineering publications (specific to SAI, MCB, and CCT) for the period 1983 to 2020. Data from Scopus literature search for the period 1950 to 2020.

BOX 2.1
Diversity Within the SG Research Field

A notable feature of SG research is that diversity within the research community is very limited. From its inception, the field has been dominated by a small number of researchers in North America and Northern Europe (though some research is being done in Australia and China) and very little representation of researchers from the Global South (Winickoff et al., 2015). It has been estimated that 90 percent of papers on geoengineering published between 2010 and 2019 were authored by researchers from North America and Europe (Jinnah, 2019). Women have also been significantly underrepresented in this research field; Buck et al. (2014) found that only 17 percent of the authors of the top-100 articles on geoengineering retrieved through a major academic database were women.[a] They further found that voices of women who carry out a substantial amount of work in this area are not often heard by the public as research indicates that the media shows a clear bias toward white male voices.

While such structural imbalances are not unique to geoengineering research,[b] one could argue that they are particularly important to address for this issue (Sax, 2019). Moreover, building more proportional representation in geoengineering research from women and scientists from underrepresented populations is important for reasons of fairness and balance, especially given expectations that women and people from the Global South will receive the brunt of damages from climate change and that the possible distribution of benefits and damages from climate intervention strategies are as yet unknown (Buck et al., 2014). This is both a normative concern related to equity and a substantive one related to research quality and legitimacy (Flegal and Gupta, 2018). Having a greater diversity of participants in the research enterprise results in higher rates of innovation (Hofstra et al., 2020) and allows for a greater diversity of perspectives (e.g.,when identifying research priorities,modeling scenarios,and impact concerns)—it further recognizes that people do not share the same values, perceive risks similarly, or find the same questions salient (McLaren et al., 2016).

One valuable step forward on this front is the DECIMALS (Developing Country Impacts Modelling Analysis for Solar Radiation Management) fund, launched in 2018 as an international SG research fund aimed at researchers from the Global South. The fund (administered by The World Academy of Sciences and funded by the Open Philanthropy Project, a U.S.-based donor-advised fund) has thus far distributed grants to research teams based in Argentina, Bangladesh, Benin, Indonesia, Iran, Ivory Coast, Jamaica, and South Africa, who are modeling how SG could affect their respective regions—in conjunction with additional, related efforts.[c]

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[a] The specific percentage has likely changed as the research field has grown in more recent years, but the general observation has not.

[b] See, for example, https://www.nsf.gov/statistics/2018/nsb20181/report/sections/science-and-engineering-labor-force/women-and-minorities-in-the-s-e-workforce.

[c] See https://www.srmgi.org/decimals-fund/ (also Da-Allada et al., 2020; Karami et al., 2020; Pinto et al., 2020; Rahman et al., 2018).

While this research base is a valuable foundation, it remains quite limited overall compared to the field of climate change science more broadly and is unlikely to provide adequate support for informed decision making. Furthermore, the United States has no coordinated national program responsible for ensuring that research is prioritized or comprehensively addressed. Most SG scholarship to date has been a collection of ad hoc and relatively small-scale efforts; this research has received scarce funding, which is dominated thus far by private funding sources.

2.2 NATURAL SCIENCES AND TECHNOLOGY DIMENSIONS

This section offers a broad overview of the core science issues related to understanding the potential feasibility of SG strategies (Section 2.2a), the research on how the climate system may respond to SG forcing (Section 2.2b), the human and ecosystem impacts of SG interventions (Section 2.2c), engineering feasibility issues (Section 2.2d), and detection and attribution issues (Section 2.2e).

2.2a Understanding the Atmospheric Microphysics and Chemistry of SG Strategies

Some central questions for researchers to ask about SG intervention strategies are: Will these strategies be effective in producing the desired amount of RF and actually cooling the climate? (See Box 2.2.) What other direct or indirect effects would this forcing have, for example, on the chemistry of the stratosphere? Many of the processes that need to be understood in order to answer such questions occur at the microphysical level, and the relevant mechanisms are fundamentally different for SAI, MCB, and CCT. Each of these approaches are discussed separately below.

Stratospheric Aerosol Injection

As reviewed extensively in NRC (2015), evidence from large volcanic eruptions serves as the essential demonstration that it is possible to reduce solar (shortwave) heating of the planet by at least ~1 W/m^2 (with the upper bound likely much larger) via increase in the surface area of stratospheric aerosol.

One of the key factors determining the amount of cooling for a given amount of added material (or the amount of material one would need to add in order to achieve a given cooling) is the size distribution of the aerosols—larger aerosols have both a smaller ratio of surface area to mass and a shorter lifetime in the stratosphere. Understanding aerosol size distribution, and how it depends on factors such as how and where such material is added, is thus a key factor in determining the effectiveness of SAI. Aerosols such as sulfate also absorb longwave (IR) radiation, causing heating of the lower tropical stratosphere; this both influences stratospheric circulation and results in increased water vapor in the stratosphere, the radiative effects of which offset some of the cooling obtained from reflecting sunlight. The amount of that heating also depends on the aerosol mass and type. The size distribution is determined by microphysical processes (i.e., nucleation, condensation, and coagulation) that occur at much smaller scales than a grid cell of a climate model, and thus such processes are all parameterized (i.e., are represented by simplified process) with varying degrees of complexity in global climate models. This subsection summarizes current knowledge focused on these small scales, while the next subsection addresses the resulting larger-scale climate response.

BOX 2.2
Units of Measurement for Climate Forcing

Earth's radiative balance results from the difference between incoming solar energy and IR energy radiated back out to space. The concept of radiative forcing (RF) is commonly used in climate science as a measure of the net change in Earth's energy balance resulting from some imposed perturbation—in particular GHGs or aerosols added to the atmosphere. RF is expressed in units of power per unit area—specifically, Watts per square meter (W/m^2)—that is, the number of extra watts of power that Earth is receiving for each square meter of Earth's surface. IPCC (2018) estimates of the RF caused by long-lived GHGs, atmospheric aerosols, and the other major components of Earth's overall radiative balance provide a useful basis of comparison for understanding the magnitude of forcing estimated to be feasible through SG.

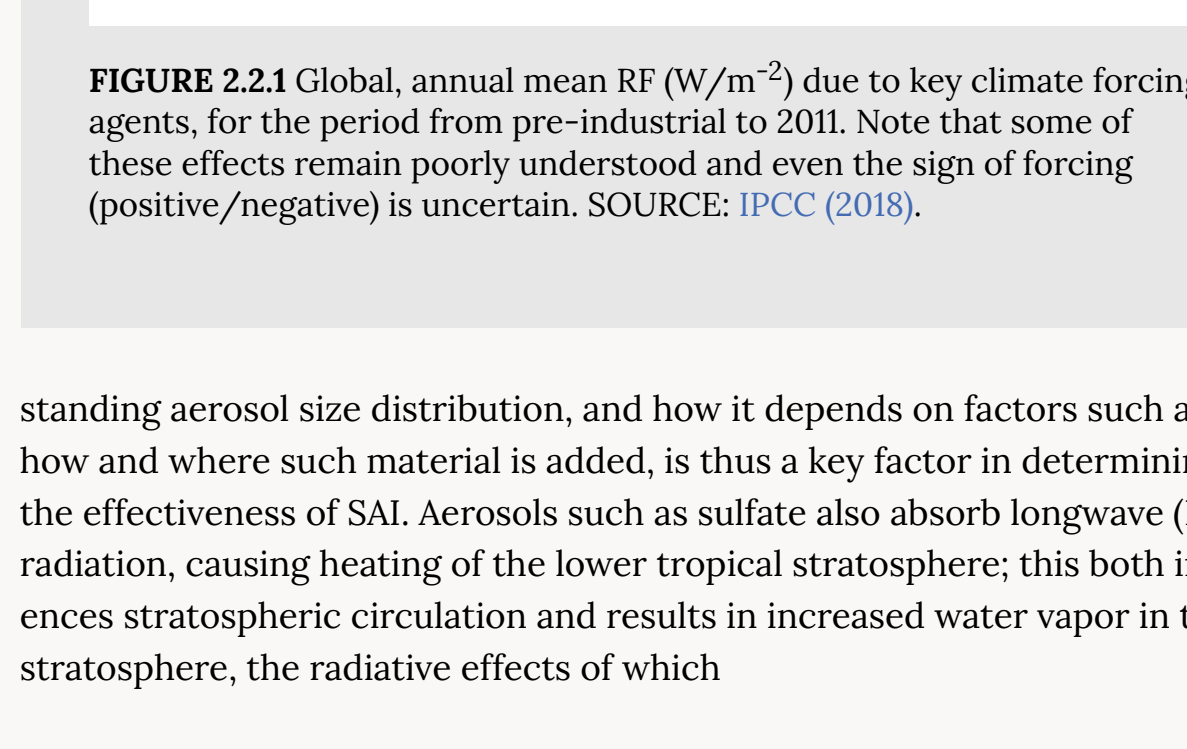

FIGURE 2.2.1 Global, annual mean RF (W/m^{-2}) due to key climate forcing agents, for the period from pre-industrial to 2011. Note that some of these effects remain poorly understood and even the sign of forcing (positive/negative) is uncertain. SOURCE: IPCC (2018).

Most peer-reviewed SAI studies described in NRC (2015) used imposed (prescribed) changes in solar reduction, sulfate aerosol burdens, or RF—suggesting that such changes could be "engineered" via addition of SO_2 to the stratosphere. In the past few years, many more simulations begin with SO_2 injection and include the relevant oxidation and microphysics needed to calculate the distribution of RF (e.g., Kravitz et al., 2017; Kravitz et al., 2019b; Mills et al., 2017; Tilmes et al., 2018b).

As illustrated in several studies, simulations of the relationship between RF and the amount of sulfur added (i.e., the resulting sulfur burden and the ratio of surface area to volume produced) are sensitive to several factors, including

- how the sulfur is added (H_2S versus SO_2 versus sulfate);
- the oxidation rate of the SO_2;
- the microphysical description of the gas to particle conversion, particle coagulation, and sedimentation;
- changes in the large-scale dynamics of the stratosphere (Kleinschmitt et al., 2018; Marshall et al., 2019); and
- the altitude (Dai et al., 2017; Tilmes et al., 2018b), latitude (Dai et al., 2017; Tilmes et al., 2017), and season of addition (Visioni et al., 2019).

Studies consistently find that the net change in RF per Teragram (Tg) SO_2 added to the stratosphere decreases as the total aerosol burden increases, but there is significant disagreement in how nonlinear the relationship is. Kleinschmitt et al. (2018) suggest that the largest RF that can be produced by SO_2 addition is -2 W/m^2, while other studies suggest that much larger RF can be obtained (Kravitz et al., 2019a; Niemeier and Timmreck, 2015). A detailed assessment of these differences has not been conducted, but presumably they result from different assumptions about microphysical coagulation rates.

Many existing models that include aerosol microphysics are able to simulate the changes in RF and stratospheric dynamics that were observed following the Mt. Pinatubo eruption (see, e.g., Gettelman et al., 2019; Marshall et al., 2019; Mills et al., 2016). Some models obtained reasonable representations of the observed changes in stratospheric aerosol optical depth (AOD; a dimensionless measure of how optically "thick" the aerosol layer is), ozone loss, excess stratospheric heating, and enhanced transport of water vapor to the stratosphere. However, these models use a variety of total sulfur emission estimates (ranging from 10 to 17 Tg of SO_2) and injection altitudes that differ by a few kilometers.

Demonstrating the ability to match one factor in particular, the enhancement in AOD, still allows too many degrees of freedom to provide sufficient constraints on model processes. Thus, it is possible that the model simulations might match some observed variables for the wrong reasons (i.e., due to compensating errors). Nevertheless, these models are developing rapidly, and the use of Mt. Pinatubo observations is a key constraint used to evaluate their dynamics and microphysics (Sukhodolov et al., 2018), along with observations after other smaller volcanic eruptions. The Model Intercomparison Project on the Climatic Response to Volcanic Forcing has organized an effort to improve the model descriptions of impacts from volcanic injection of SO_2 and resulting changes in RF and climate[1] (Zanchettin et al., 2016).

While the study of volcanic sulfur injection has been critical for advancing understanding to date, it is an imperfect analogue for deliberate SAI for several reasons. First, the chemical and dynamical impacts of enhancing aerosol surface area are sensitive to the background conditions (e.g., how much chlorine and bromine are present; the existing aerosol concentration and size distribution), where the enhancement occurs (season and latitude), as well as details of the microphysics that will likely be different between SAI and volcanoes. For example, SAI (unlike volcanic eruptions) would be applied in a strategic manner, and materials would be injected into a stratosphere already containing significant aerosols (which affects coagulation). Ion nucleation is also likely to be important in the wake of aircraft used to deliver the SAI materials. In addition, volcanoes add primarily sulfur to the stratosphere while SAI may involve other materials (e.g., calcite) that, by design, have different properties. Finally, there is a matter of timescale. Even following the largest volcanic eruptions, increased AOD and its climate impact lasts only a few years, while for deliberate SAI the goal would be to produce a sustained and likely uniform distribution of AOD for a duration of many years or decades; thus, the climate impacts would be long lasting. More observations of volcanic eruption impacts would thus be extremely valuable, but they may still be insufficient to constrain some processes.

Stratospheric heating. Addition of sulfur to the stratosphere would cause heating through absorption of near-IR solar radiation and IR radiation from Earth. The amount of stratospheric heating depends on the aerosol size and thus on accurately simulating microphysics. At present, different climate models, containing different microphysical parameterizations, do not agree on how much stratospheric heating there would be. As observed following large volcanic eruptions, this heating alters the stratospheric circulation (Aquila et al., 2014; Richter et al., 2018) and the transport of ozone. Changes in the heating will increase the temperature of the tropical tropopause, leading to increased stratospheric water vapor. The warming effects from this increased water vapor would require increased aerosol injection to compensate (Krishnamohan et al., 2019; Tilmes et al., 2018b). This stratospheric heating also has surface climate effects that will be discussed in the next section. Stratospheric aerosols may also affect upper cirrus cloud cover, either through the stratospheric heating modifying vertical velocities (Kuebbeler et al., 2012) or possibly through the aerosols themselves (Cirisan et al., 2013).

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[1] See http://www.volmip.org/.

Stratospheric ozone loss. One long-standing concern about SAI is the potential for reducing stratospheric ozone concentrations, which would result in increased exposure to harmful ultraviolet (UV) radiation at the surface. This issue has recently been reviewed as part of the 2018 World Meteorological Organization Ozone Assessment (WMO, 2018). It is known that enhancement in stratospheric aerosols can reduce stratospheric ozone (e.g., Klobas et al., 2017; Tilmes et al., 2020). This results from both changes in circulation and because the additional aerosol surface area reduces NO_x levels (via conversion of N_2O_5 to nitric acid[2]); in the lower stratosphere, this will enhance ozone loss due to increases in HO_2 and ClO levels (see Figure 2.3). During spring, ClO levels in polar regions will be further enhanced due to heterogeneous chemistry occurring on sulfate at colder temperatures. In contrast, in the middle and upper stratosphere, reductions in NO_x levels reduce ozone loss, as the reaction of NO_2 dominates the ozone destruction.

The net influence of NO_x reductions on the total stratospheric ozone column depends on the difference between ozone increases at high altitude and ozone losses at low altitude. This balance was negative (enhanced loss) following the Mt. Pinatubo eruption but is expected to decrease as total chlorine and bromine levels decline as a result of the Montreal Protocol controls (e.g., Klobas et al., 2017). An additional factor to consider is that enhanced IR heating associated with addition of sulfate will change stratospheric circulation, altering the distribution of stratospheric ozone. Simulations under high sulfate loading suggest that during winter, ozone levels in the northern extratropics may increase due to enhanced transport rates from the tropics (Tilmes et al., 2018b).

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[2] Other solid materials will likely also reduce NO_x levels, but the chemistry of these particles and the role of sulfate coatings is very uncertain.

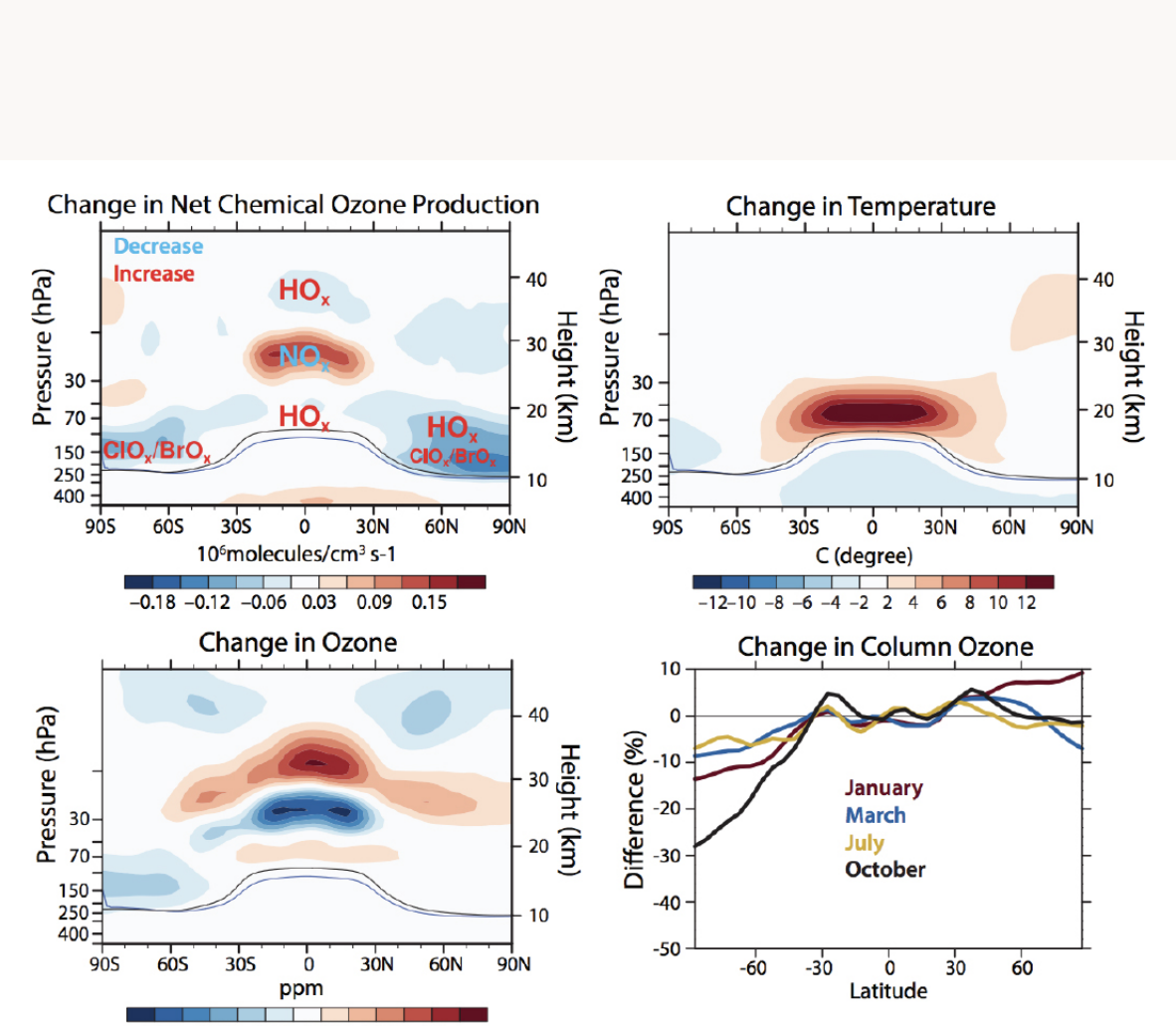

FIGURE 2.3 Processes impacting stratospheric ozone in 2042–2049 following RCP8.5 for 16 Tg S yr^{-1} injections at 15°N/15°S. Impact of enhanced sulfate aerosols on zonal and annual averaged net rate of chemical production of ozone (top left), temperature (top right), and ozone concentration (bottom left). Changes in the dominant ozone loss cycles are shown in blue if decreasing (net chemical production is increasing) and in red if increasing (net chemical production decreasing) (top left). Differences in column ozone (%) between the geoengineering and the control simulation in 2042–2049 are illustrated for different months (bottom right). SOURCE: WMO (2018).

Absent any interventions, it is anticipated that ozone concentrations in the stratosphere will recover (increase) over the next 50–100 years as a result of restrictions on the production of ozone-depleting substances (e.g., chlorofluorocarbons). But a deployment of SAI could delay this recovery, depending on timing of deployment, how much aerosol is increased, and what chemicals are utilized. For instance, studies have found that relatively small and constant injections of sulfur (2.5–4.0 Tg S/yr between 2020 and 2070, which would result in 0.5–1.0°C of surface cooling) would lead to ~4 percent annual reduction in the global stratospheric column ozone for 2020, and a 1 percent reduction by 2070[3] (Pitari et al., 2014; Xia et al., 2017). Tilmes et al. (2018b) found that larger injection amounts (12–16 Tg S/yr), which led to global cooling of around 2°C, resulted in reductions in column ozone reductions in the high latitudes of both the Southern Hemisphere (28–40 percent reduction) and the Northern Hemisphere (8–18 percent reduction). Specific values varied depending on the injection altitude.

Given the changes in ozone distribution due to heating and changes in chemistry, there have been studies on other potential materials for use in SAI (Dykema et al., 2016; Keith et al., 2016). These materials will, by design, have different physical and chemical properties, which limits the use of volcano analogues for evaluation. For instance, simulations suggest that stratospheric injection of solid materials such as alumina, calcite, or rutile (TiO_2) as an alternative to sulfate would enhance shortwave RF while minimizing stratospheric ozone loss and heating. However, the stratospheric aerosol microphysics of these compounds (especially coagulation on the surface of the aerosol after injection) is poorly understood (Dykema et al., 2016; Keith et al., 2016).

Finally, in addition to the SAI impacts discussed above (i.e., stratospheric heating and stratospheric ozone loss), injected stratospheric aerosols would scatter sunlight, resulting in an increase in the ratio of diffuse to direct light reaching Earth's surface (Kravitz et al., 2012; Madronich et al., 2018; Xia et al., 2016), an impact that can affect plant life and solar energy production as discussed in Section 2.2c.

Marine Cloud Brightening

Adding aerosols to marine clouds can, in certain circumstances, increase the albedo of the cloud; this is known as the aerosol indirect effect (AIE; Twomey, 1974, 1977). The basic mechanism is that if the same total water content is spread into more, smaller droplets, then the reflectivity increases. However, the net effect depends on cloud feedbacks. For example, depending on humidity above and below clouds, turbulence-driven entrainment and drop growth processes, adding aerosols might increase cloud evaporation (driven by entrainment) that could reduce cloud water and reflectivity (Ackerman et al., 2004; Albrecht, 1989). Such a change would not only fail to increase cloud reflectance, but also could cause a substantial reduction in reflectance. Alternatively, it might increase entrainment (i.e., drawing in drier air from above or around the cloud) from nearby regions, resulting in albedo increases immediately where the aerosols have been added but corresponding decreases in nearby regions. While some insights have been gained from observational studies (e.g., of ship tracks), none of these processes is yet well understood (Alterskjær et al., 2012; Bellouin et al., 2020; Boucher et al., 2014; Feingold et al., 2002; Gryspeerdt et al., 2016, 2017, 2019b; McComiskey and Feingold, 2012; Mulmenstadt and Feingold, 2018; Quaas et al., 2008; Rosenfeld and Feingold, 2003; Russell et al., 2013; Sanchez et al., 2017a; Seinfeld et al., 2016; Sorooshian et al., 2009; Stevens and Feingold, 2009; Toll et al., 2019; Witte et al., 2019; Wonaschuetz et al., 2013). As a result, there is high uncertainty regarding where and when cloud albedo can be modified by addition of particles and, if so, by how much.

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[3] This variation in ozone loss over time is due to a variety of factors, including the expected decrease in atmospheric concentrations of ozone-depleting substances, the projected (climate change-driven) trends in stratospheric temperatures, and the impacts of added sulfur on compounds that drive the chemistry of ozone loss (NO_x, ClO).

The processes that cause these critical uncertainties occur at much smaller scale than the spatial resolution (i.e., a gridbox) and the temporal resolution (i.e., a time step) of a global climate model, and hence these processes are all parameterized. As a result, climate model simulations are not a useful tool for better resolving process uncertainties except insofar as overall constraints can be imposed. Limited progress has been made in quantifying aerosol-cloud relationships by using either large eddy simulation (LES) modeling (Ackerman et al., 2004; Bretherton et al., 2007; Feingold and Koren, 2013; Feingold et al., 2002, 2017; Glassmeier and Feingold, 2017; Koren and Feingold, 2011; Lebo and Feingold, 2014; Lu and Seinfeld, 2005; Stevens et al., 1998, 2005; Witte et al., 2019; Xue et al., 2008) or from ship track observations (e.g., Durkee et al., 2000; Feingold et al., 2015; Gryspeerdt et al., 2014a,b, 2019a; Painemal et al., 2017; Platnick et al., 2000; Russell et al., 1999) and intentional particle release (Russell et al., 2013; Sanchez et al., 2017a; Shingler et al., 2012; Wonaschuetz et al., 2013).

A classical approach provides a framework for separating the physical mechanisms that contribute to aerosol-cloud interactions into the Twomey effect (cloud brightening) and the cloud "lifetime" effect (changes in precipitation, liquid water, vertical extent, and cloud fraction—sometimes referred to as "adjustments") (Quaas et al., 2008). These aerosol effects can be translated into surface temperature changes (primarily by the Twomey effect) and water budget changes (primarily by the lifetime effect). The interactions between aerosols and clouds proceed via a number of interacting physical mechanisms whose effects frequently cannot be measured individually (Stevens and Feingold, 2009), so care must be taken when inferring causation from observed correlations (Feingold et al., 2003; Gryspeerdt et al., 2014b, 2016, 2017, 2019b; Quaas et al., 2008, 2010; Sorooshian et al., 2009). Modeling studies that modify individual processes are an essential tool for causal inference (Mulmenstadt and Feingold, 2018) by using observations that constrain parameterized physics in a meaningful way (Lee et al., 2016; Mulmenstadt et al., 2020).

The AIE is incorporated in climate models in a variety of ways, resulting in a wide range of uncertainty in the amount of cooling that aerosol particles provide to offset GHG-based warming (Dionne et al., 2020; Kravitz et al., 2018; Lee et al., 2016; Mulcahy et al., 2018; Penner et al., 2004, 2011; Rotstayn et al., 2000; Wang and Penner, 2009; Wang et al., 2012; Zhou et al., 2012). Recent Intergovernmental Panel on Climate Change (IPCC) model intercomparisons suggest cooling in the range of −0.06 to −1.33 W/m^2, which implies there is a net cooling from anthropogenic aerosols (IPCC, 2013). This leads to an expectation that if aerosol is deliberately distributed optimally among the most susceptible clouds, this could achieve comparable amounts of cooling that scales roughly with area covered. Indeed, in MCB simulations, when aerosols are added to stratocumulus regions, the results range from −1 to −2 W/m^2 cooling (Korhonen et al., 2010; Kravitz et al., 2016, 2018; Latham et al., 2008; Rasch et al., 2008, 2009; Wang et al., 2011; Wood et al., 2017). While many cloud feedbacks reduce the magnitude of this cooling, some feedbacks could also contribute to increased cooling (Ahlm et al., 2017).

Since the addition of particles brightens clouds by changing the sizes of droplets in clouds, other cloud properties may also be changed (Boucher et al., 2014; Sherwood et al., 2015), notably the cloud vertical and horizontal extent, the amount of liquid water in the cloud, and the amount of precipitation. Droplet size controls drizzle formation (Albrecht, 1989), and drizzle removes water from the cloud. Some of the water falls to the surface, but much evaporates before reaching the surface, thereby cooling and moistening the air below the cloud and changing the buoyancy of the rising updrafts that formed the cloud. If droplets are too small to initiate precipitation, there could be enhanced evaporation of the smaller drops and turbulent entrainment of dry air into the cloud, leading to a reduction of cloud extent and cloud water (Ackerman et al., 2004; Bretherton et al., 2007).

Many global models determine drizzle rates using auto-conversion schemes that are poorly constrained, causing predicted cloud properties to vary widely between schemes (Dionne et al., 2020). These schemes do not account for the complex interplay of processes with different timescales. For example, faster updraft speeds could mean there is less time for droplets to grow (Ovchinnikov et al., 2013), or it could result in opposite effects including the possible "lofted drizzle" phenomenon (Takahashi et al., 2017).

While there is the potential for MCB strategies to have meaningful impacts in cooling the climate, several factors limit the current capacity to simulate these sorts of impacts and develop reliable projections of impacts. These limitations include the following:

- **Climate models rely on idealized theoretical cloud formation processes that are difficult to validate.** Climate model cloud formation processes could only be "validated" (by comparison to observations) if they can first adequately represent the present-day distribution and precipitation of clouds. No current climate model claims to pass this test. Instead, climate models are "calibrated" to zonal means and top-of-the-atmosphere radiative constraints, which are required to balance the energy budget of Earth. The variety of approaches and outcomes is expected to represent the range of possible behaviors of the planet under climate change, but the specific process components cannot be compared to observations for any given year or location because the clouds may not even be present (Mulmenstadt et al., 2020). Climate models tend to distinguish between "first-order" Earth system component processes and second-order "feedbacks" that modify those component parts. Because the cloud formation processes are not well represented, the second-order processes cannot be compared to the actual atmosphere. These deficiencies are particularly important for thin, low-level, and multilayer clouds and are even worse for mixed-phase and other polar clouds (Kay et al., 2016; Malavelle et al., 2017; Neubauer et al., 2014).
- **Climate models do not include reliable cloud formation or feedback processes associated with subgrid processes.** Despite computational advances, global-scale models (on the order of 100 km grid spacing) cannot yet represent the microscale processes and variability inherent to cloud formation (which occur on the scale of 1 m or less). Smaller-scale regional models and LES models that do represent the microscale have produced results that span the range of AIEs represented by climate models, but they also yield results with higher and lower sensitivities and stronger, nonlinear feedbacks (sometimes outweighing the cloud formation processes; see Ackerman et al., 2004; Bretherton et al., 2007; Feingold et al., 2002; Lebo and Feingold, 2014; Lu and Seinfeld, 2005; Stevens et al., 1998; Witte et al., 2019; Xue et al., 2008). The basic challenge even at small scales is that models often form clouds at times and places that are not consistent with observations, and the clouds may either dissipate too quickly or not dissipate at all. Because the existence of clouds is 50 to 100 times more important for reflectance than the brightening of a cloud (i.e., it has a cloud forcing of 50–100 W/m^2 compared to the indirect effect of 1–2 W/m^2), the lack or presence of cloud will overwhelm any signal related to brightening the cloud.
- **Observations do not show cooling as large or as consistent as models.** Since direct validation of climate models is not possible, AIEs have also been estimated from satellites (Bellouin et al., 2008; Chen et al., 2014; Penner et al., 2011, 2012); these estimates generally imply less cooling than that obtained from many climate models, which predict forcings in the range of −0.5 W/m^2. At the same time, some studies suggest that the strength of the forcing may be underestimated (e.g., Diamond et al., 2020; Rosenfeld et al., 2019; Shinozuka et al., 2015). Models are very sensitive to background conditions (i.e., the "starting point" for cloud properties), but these conditions are poorly characterized over much of the world's ocean regions, and models find strong nonlinear effects associated with the assumptions used for these ocean background conditions (Carslaw et al., 2013, 2017; Regayre et al., 2014, 2015).

- **Current satellite observations are limited in how well they resolve cloud and aerosol properties.** The longest satellite records provide column-integrated measurements of aerosol and cloud "optical depth," which allow multidecade comparisons of cloud coverage (Norris et al., 2016) but only indirect information about aerosol concentrations at different altitudes (Chen et al., 2014). Scattering-based retrievals of aerosols and clouds are inherently measuring mostly mass-based metrics of aerosol that provide limited information on the specific effects of particle composition, number, and size (Lowe et al., 2019). Cloud retrievals have similar limitations, but CALIOP/CALIPSO has provided some altitude-resolved cloud measurements, with limited paths and resolution (Mulmenstadt et al., 2018). There are proposed plans to launch satellites[4] that would improve capabilities for aerosol and cloud observations through better temporal resolution, radiation-relevant properties, and spatial coverage. But those plans (if funded) would be realized only several years from now (2030) and would still not resolve all of the process and feedback questions that are relevant for subgrid processes.
- **Ground-based monitoring and balloon technologies do not measure the quantities needed to constrain processes and feedbacks.** Existing observational networks of atmospheric measurements were designed for predicting weather and monitoring air quality and impacts of stratospheric ozone loss, not for quantifying AIEs (for either background emissions or deliberate injections). Balloon-borne sensors measure temperature, pressure, water vapor, and ozone as functions of altitude in the atmosphere. Some have suggested that ground-based observational networks and balloon-borne platforms could be utilized in MCB studies; however, there are a number of challenges with utilizing these approaches. Innovations to add aerosol, radiation, and cloud measurements significantly increase the size and costs of these balloon-borne platforms, making it infeasible to add these other observations to the current networks that use large numbers of unrecovered, disposable balloons. Ground-based networks for air quality measure aerosol mass and some chemical components, but since clouds are generally not located at fixed location observational sites (with the exception of a handful of mountaintop sites), they do not collect information on cloud properties. Typically, the best instrumented ground sites are in populated areas, biasing sampling toward regions with human activities (not regions where one can measure cloud properties for susceptible regions) (Feingold and McComiskey, 2016; Grosvenor et al., 2018; McComiskey et al., 2009). In addition, few of the sites have maintained long-term measurements of critical parameters such as aerosol size distributions.

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[4] A-CCP. See, for example, https://earth.gsfc.nasa.gov/missions/accp.

Cirrus Cloud Thinning

The efficacy of CCT is currently highly uncertain. Unlike low clouds, cirrus clouds in the upper troposphere warm the planet by reducing outgoing longwave radiation more than they reflect incoming shortwave. Reducing cirrus cover would thus provide cooling, particularly in mid-to-high latitudes during non-summer months where the longwave effect dominates relative to the shortwave effect. Cirrus form either through heterogeneous nucleation (where there are sufficient ice nucleating particles [INP] surrounded by ice) or homogeneous nucleation (where there are insufficient nuclei, and the resulting ice particle is only ice). The latter mechanism requires higher relative humidity with respect to ice (around 150 percent, rather than 110–120 percent on dust) and results in smaller ice particles with larger radiative effect. The idea behind CCT (Mitchell and Finnegan, 2009) is that efficient seeding in places currently dominated by homogeneous nucleation would thus result in fewer, larger ice crystals with smaller net radiative effect and shorter lifetimes. Relative to SAI and MCB, CCT has received relatively less attention, and there is relatively higher uncertainty, due to uncertainty in the current fraction of cirrus formed through homogeneous versus heterogeneous nucleation (Cziczo et al., 2013; Gryspeerdt et al., 2018; Krämer et al., 2016; Mitchell et al., 2016, 2018; Sourdeval et al., 2018) and uncertainty in the microphysics (e.g., Gasparini and Lohmann, 2016; Gasparini et al., 2020).

There have been several climate model studies to explore what the climate response would be if the method did work, either directly simulating an increase in INP or artificially increasing ice fall velocity. The simulated RF from CCT varies widely, depending on the climate model—ranging from almost no effect to several W/m^2 (e.g., Gasparini and Lohmann, 2016; Gasparini et al., 2020; Gruber et al., 2019; Penner et al., 2015; Storelvmo et al., 2014). It must be recognized, however, that models do not necessarily represent relevant cirrus processes correctly, including capturing the prevalence of homogeneous versus heterogeneous freezing.

2.2b Climate Response to Solar Geoengineering

Before implementation of any SG strategies would ever be considered, the potential impacts of any given approach must be understood to the fullest extent possible—hence one of the central goals of SG research is to predict how the climate would respond to a hypothetical deployment. Here we examine current scientific understanding about possible climate responses to different SG approaches, assessing what is known and unknown as a foundation for assessing future research priorities.

It is first important to recognize that no SG approach can simply reverse the climate effects of increased atmospheric GHG concentrations. While SG interventions could reduce global mean temperature, this would not restore the same climate as one without the increased GHGs. This is due in part to the fact that GHGs reduce outgoing longwave radiation and warm the entire troposphere, while SAI and MCB reflect incoming shortwave radiation that would otherwise be (primarily) absorbed at Earth's surface. In addition, the spatial and seasonal distribution of RF (and thus the climate response) resulting from SG depends on choices regarding how it is deployed, as well as other factors that can affect the climate response (e.g., heating of the stratosphere from sulfate aerosol injection).

For these reasons, it is critical to be clear about the comparisons being made in climate modeling studies; in particular, is one comparing SG against a warmer world with the same GHG emission scenario or evaluating how an increase in GHGs offset by SG compares with the climate where neither has changed? The former comparison may be more relevant for policy considerations, while the latter comparison is more relevant to understanding the physics (i.e., how do the two forcing mechanisms affect the climate differently?). Generally, SG compensates for many of the changes that a warmer climate would bring, but the compensation is not perfect and there are important residual differences.

Use of Climate Models in Solar Geoengineering Research

Climate (or Earth system) models are the critical tool to assess feedbacks and mechanism-specific changes associated with SG intervention strategies. The limitations of climate models are well documented and include factors such as incomplete representations of atmospheric chemistry and its interactions with climate; deficiencies in simulating the seasonality, altitude, and water content of clouds globally; inadequate simulations of the duration, frequency, and intensity of precipitation; and simulated patterns of climate variability that differ from observations in terms of magnitude and spatial structure. And, as discussed earlier, one major challenge of representing SG strategies in climate models is the need for parameterization of certain subgrid-scale physical processes: such processes are reasonably well represented but always parameterized for SAI, while the processes for MCB and CCT are poorly represented in current climate models.

Yet despite these shortcomings, climate models are still essential for SG research, as they are the only tool available to estimate the large-scale climate response prior to deployment and to characterize both local forcing (efficacy) and large-scale feedbacks. Climate models must be employed with their strengths and limitations in mind. For instance, climate models do a reasonable job at simulating the climatological distribution of precipitation (as well as its seasonal to longer timescale variability) driven by changes in circulation. There is a long history of using climate models to explain the time evolution of hydrological change over the observational record (e.g., Seager and Ting, 2017). Also, the dynamical (circulation) responses to stratospheric and tropospheric heating anomalies are understood from both theoretical and modeling studies, and this has important implications for studying regional SG impacts.

Early SG climate simulations (e.g., the G1/G2 simulations from the first phases of the Geoengineering Model Intercomparison Project [GeoMIP, Kravitz et al., 2011]) use a simplified global cooling representation (simply "turning down the sun") as opposed to simulating the details of how specific SG implementation strategies would affect solar radiation. This captures fundamental differences between how the climate responds to changes in atmospheric GHG concentrations (affecting outgoing longwave radiation) and how it responds to changes in incoming shortwave radiation. One conclusion from early research, for example, is that SG will "over-compensate" global-mean precipitation relative to global-mean temperature (Bala et al., 2008; Kravitz et al., 2013; Tilmes et al., 2013). Uniformly reducing sunlight will also over-cool the tropics and under-cool high latitudes, simply due to more solar energy being absorbed in the tropics (Caldeira and Bala, 2017; Govindasamy and Caldeira, 2000; Kravitz et al., 2013).

Many solar-reduction simulations suggest that the climate resulting from an increase in GHGs offset by SG intervention is likely to be closer in many places to the original climate than one with the same increased GHG but without SG—not just in global mean temperature but regionally and for hydrological variables and extremes as well (e.g., Irvine et al., 2019; Kravitz et al., 2014). However, the climate response to any given intervention (SAI, MCB, or CCT) will differ from these idealized solar-reduction simulations owing to differences in the spatial and seasonal pattern of RF. Furthermore, specific features such as the stratospheric heating that occurs with sulfate aerosols can have important surface climate effects that are not represented in solar-reduction simulations (e.g., Kravitz et al., 2017), as well as feedbacks from vegetation response (e.g., Dagon and Schrag, 2019; Jiang et al., 2019; Simpson et al., 2019).

SAI has been studied the most, and as noted earlier, there is substantial modeling and empirical evidence (from volcanoes as a natural analogue) for effectiveness in cooling on a global scale. Furthermore, the ability to match observations of stratospheric aerosols after Mt. Pinatubo or other eruptions leads to some confidence in using a general circulation climate model to predict the temperature response.

The efficacy of MCB is more difficult to determine and is very difficult to model. Fewer climate model-based studies have assessed this approach as a means of cooling the climate; the confidence in these predictions is lower, as there is very limited basis for making assumptions about where and when increased albedo can be obtained. (The divergence in model projections of climate response to MCB stems at least in part from lack of agreement among models regarding where clouds that can be brightened exist.) Developing a stronger understanding of aerosol-cloud interactions (discussed earlier) will allow climate modeling studies to be more effectively applied. Another reason why there are larger uncertainties in MCB climate response (compared to SAI) is that the intervention would be applied over smaller areal extent; thus, the forcing over those regions would need to be larger in order to obtain substantial effects on global cooling—this introduces stronger gradients in the forcing that would likely introduce additional uncertainties in modeling the climate response. There are fewer-still climate model simulations of CCT, and what simulations exist have diverse conclusions, in part because the parameterizations of CCT within climate models is not necessarily sufficient.

Research on all of these SG strategies needs to characterize both local forcing (efficacy) and large-scale feedbacks. Non-local feedback processes, including "tele-connections," will affect the response (especially hydrological responses, discussed below); these processes cannot be observed on the spatial and temporal scales reasonable for an experiment, because some parts of the response can occur outside of the regional boundaries of a study. Thus, the only way to attribute such effects to an SG perturbation is by the use of climate models.

Temperature Responses

Existing research suggests that SG intervention would lead to a reduction in global mean temperature relative to scenario of climate change without any intervention but with residual regional variations in climate relative to that which would have occurred without SG. These variations depend on assumptions made in creating the simulation. For example, injecting aerosols into the tropical stratosphere results in over-cooling in tropical ocean regions but with residual warming in high-latitude regions. Off-equatorial injection can largely compensate for this effect (Kravitz et al., 2017, 2019a; Tilmes et al., 2018b), but there would still be regionally different effects. If a deployment of SG were ever abruptly terminated, the temperatures would return over a period of a few years back to roughly the values they would have been if SG had never been deployed (and this would likely constitute a rapid warming).

In addition to changes in annual mean temperature, the seasonality of temperature may be altered by SG, particularly at high latitudes, because there is more sunlight to reflect in summer than winter, and for SAI, aerosol-induced stratospheric heating leads to residual winter-warming over Eurasia. The Stratospheric Aerosol Geoengineering Large Ensemble (GLENS) studies (Tilmes et al., 2018b) find that SAI diminishes the amplitude of the seasonal temperature cycles at many high latitude locations, with warmer winters and cooler summers (relative to a baseline without either increased GHGs or

SAI). The seasonal temperature shift significantly influences the seasonal cycle of snow depth and sea ice, with Arctic sea ice recovery overcompensated in summer by 52 percent and undercompensated in winter by 8 percent (Jiang et al., 2019). The many possible subsequent impacts of these changes (e.g., on Arctic communities, permafrost, and communities that depend on winter snowpack for water resources) are not yet studied, which underscores the nascent state of impacts research and the challenges of assessing impacts when SG does not simply restore the climate back to a previous state.

Precipitation Responses

Aside from direct temperature impacts, one of the primary climate responses and risks associated with SG are regional hydrological cycle changes. Precipitation changes can be driven by a variety of factors such as changes in wind and circulation patterns, cloud composition and formation, and stratospheric heating. Energetic constraints and theoretical understanding make it clear that globally averaged precipitation will decrease disproportionately with temperature for SAI, and this is well captured in experiments with climate models (e.g., Cheng et al., 2019; Kravitz et al., 2013; Simpson et al., 2019; Tilmes et al., 2013).

Regionally there is no such constraint that governs precipitation change, since alterations to the atmospheric circulation and other factors come into play. For example, over the Amazon, SAI may be less effective at counteracting hydrological changes from global warming owing to the plant physiological response to CO$_2$ and to a re-

gional dynamical response related to subtle sea surface temperature changes in the Pacific (Jones et al., 2018). Over Europe and Eurasia, the stratospheric heating caused by SAI produces a stronger polar vortex, which lowers Arctic sea level pressure and increases the zonal wind over the North Atlantic, leading to a shift in storm tracks that result in widespread warming with wetting over northern Europe and drying over southern Europe—these changes are small however, compared to a scenario with increased GHGs but no SAI (e.g., Simpson et al., 2019).

Some SAI studies have noted the potential for significant changes to the Indian and Asian monsoons and rainfall in the Sahel region of Africa—although these responses are sensitive to the details of the SAI approach employed (e.g., where and when aerosols are injected into the stratosphere; see Visioni et al., 2019) and the amount of cooling (e.g., whether compensating for all of the increase in global mean temperature, or only part of it; see Irvine et al., 2010). Any substantial shifts in precipitation patterns for regions with large, vulnerable populations could have major societal impacts, and much more work is needed to identify the robustness of such responses.

At the same time, modeling studies suggest that SAI will result in more low-intensity rainfall events and fewer extreme precipitation events, relative to scenarios of climate change without SG. For example, in a modeling scenario in which SG offsets half the RF and temperature increase from GHGs, this offsets most of the CO$_2$-induced increase of (simulated) tropical cyclone intensity and does not cause other exacerbations of extreme temperature or precipitation (Irvine et al., 2019).

Modeling results predict that MCB would reduce the increase in average global temperature and precipitation that will otherwise occur with anthropogenic climate change, but again regional weather patterns would likely be different, creating regional changes in temperature and precipitation. One study (Jones et al., 2010), for instance, indicated warmer and drier conditions over South America with MCB, including substantial reductions in rainfall over the Amazon. All such simulations should be interpreted cautiously, however, given current shortcomings in the robustness of climate response simulations with MCB and CCT (discussed earlier in this chapter). The key point is that model results suggest that both SAI and MCB produce changes in precipitation that will not be uniformly distributed around the globe. However, it is worth noting that the magnitude of these changes is typically less than what it would be for climate change without SG.

The vertical distribution of heating in the atmosphere is another factor that can affect precipitation patterns. GHGs increase longwave radiation in the atmosphere; SG interventions can offset that change by decreasing shortwave radiation, thus resulting in a redistribution of shortwave and longwave radiation streams in the atmosphere.

MCB and SAI affect this vertical distribution differently, since the shortwave reflection occurs at a lower altitude for MCB. Differences in spatial patterns of forcing (e.g., the global nature of SAI versus the more localized forcing of MCB) also affect precipitation response. Because CCT would increase outgoing longwave radiation, rather than reduce incoming shortwave, the effects on precipitation will likely be quite different from SAI or MCB.

Finally, SG affects both precipitation and evaporation, and the net effect may be more important for some impacts than changes in precipitation alone. The net global effect on land-average runoff or changes in soil moisture might be small (compared to a climate with neither the increased GHG or SG), but substantial regional changes can result (Cheng et al., 2019).

Understanding Implications of Model and Deployment Scenarios

SG modeling work to date has been conducted with a limited set of scenarios, typically designed more toward enhancing understanding of physical effects and mechanisms (Kravitz, 2011b; Kravitz et al., 2016) than for direct policy relevance. These include entirely idealized experiments wherein SG is applied in conjunction with simultaneous quadrupling of atmospheric CO$_2$ (as in GeoMIP G1 scenario), a 1 percent per year increase in atmospheric CO$_2$ (G2), or on top of a moderate warming scenario (RCP4.5; G3-G4), including termination effects after some time period.

On an ad hoc basis, individual research initiatives have also explored outcomes of a broader range of forcing and implementation scenarios. Papers have proposed different scenarios, including maintaining a fixed temperature (Kravitz et al., 2017; MacMartin et al., 2019; Ricke et al., 2010; Tilmes et al., 2018b) or a fixed rate of change of temperature (MacMartin et al., 2014a), or cutting the rate of change of net RF in half (Irvine et al., 2010, 2019; Keith and MacMartin, 2015), in climate models and economic models. The background scenario may include high GHG forcing (as in GLENS; see Tilmes et al., 2018b, which used an RCP8.5 background), which is useful for generating high signal-to-noise ratio but would exaggerate differences in the climate response that would occur if a more limited cooling was being considered. Emulators have also been used (MacMartin et al., 2016, 2019) to predict the response to a more moderate scenario based on the simulated response to more extreme scenarios.[5]

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[5] As explained in MacMartin and Kravitz (2019), "Climate emulators...are trained based on a limited number of simulations with GCMs and allow for prediction of climate response for a much broader set of trajectories, trading the fidelity of a GCM simulation for computational efficiency."

The climate response to SG depends not only on how much is being deployed (e.g., amount of aerosols injected or the amount of cooling desired) but also on choices about how SG is deployed—for example, choices such as latitude, altitude, or season of aerosol injection for SAI (Dai et al., 2017; Kravitz et al., 2016, 2017; MacMartin et al., 2017; Tilmes et al., 2018a,b; Visioni et al., 2019, 2020b). These choices could in principle be made to manage multiple climate variables, such as avoiding the tropical-overcooling and polar-undercooling that would result from equatorial injection, by managing not global mean temperature but also meridional temperature gradients (as in Kravitz et al., 2016, 2017; Tilmes et al., 2018a). Choices could also be made to balance different climate objectives, whether focused more on precipitation, Arctic sea ice, or some regional responses.

For instance, because of concerns about climate change in the Arctic in particular, a number of simulations have explored strategies focused on the Arctic (using SAI [e.g., Jackson et al., 2015; Nalam et al., 2018; Sun et al., 2020], solar reductions, or surface albedo modification). By injecting aerosols at higher latitudes it is possible to have preferentially greater cooling in the Arctic than elsewhere, although the effects cannot be isolated to the Arctic (due to stratospheric transport of aerosols and changes in heat transport when cooling the Arctic; e.g., Tilmes et al., 2014). For example, if Arctic cooling is not balanced by Antarctic cooling, such strategies would shift tropical precipitation (Haywood et al., 2013; Kravitz et al., 2016; Robock et al., 2008).

While choices such as latitudes or seasons to inject aerosols affect the spatial response, choices regarding how much to inject in any given year are ultimately iterative and would likely be adjusted in response to changing circumstances and observed climate responses. For example, feedback of observations can be used to adjust SAI injection rates to manage desired outcomes (Cao and Jiang, 2017; Jarvis and Leedal, 2012; Kravitz et al., 2016, 2017; MacMartin et al., 2014b; Tilmes et al., 2018a). Adjustments might also be made in response to detection and attribution of regional responses that lead to new information about how SG affects the climate. Thus, while there will still be uncertainty about the climate response to a particular strategy at the time a deployment decision is made, the strategy would undoubtedly evolve post-deployment.

Equivalent scenario design questions have thus far been only minimally explored for MCB or CCT. Combining different methods (SAI, MCB, and CCT) might be able to achieve better outcomes than any one method alone (Cao et al., 2017).

Little work has also been done thus far to explore questions about fundamental trade-offs in terms of different types of climate responses (e.g., if SG could restore the climate in region A, or in region B, but could not do both at the same time). Studies

to date have been ill-equipped to address such questions, in part because they have involved only a single model, have not used all of the possible decision variables, and have not explored the full range of possible goals and strategies but also because the uncertainty of specific regional responses is higher than that for the global mean.

2.2c Potential Impacts on Critical Human and Environmental Systems

Understanding the direct climate responses to SG intervention strategies is an important starting point, but ultimately one must understand how these changes in climatic variables translate into impacts on the many ecological and societal factors upon which all life depends. This section builds on the NRC (2015) analysis with an updated assessment on the state of understanding, including key knowledge gaps and uncertainties, related to the potential impacts and risks that SG may pose for biodiversity and ecosystem functions and services, and for some key aspects of human well-being and sustainable development.

The Complexities of Assessing SG Impacts

The types of SG approaches discussed herein will alter numerous environmental conditions that natural and human systems depend upon (Irvine et al., 2016)—not only temperature and precipitation patterns but also many other factors (e.g., solar radiation levels and the ratio of direct to diffuse light, sea level rise, carbon cycle dynamics, ocean biogeochemistry, and extreme weather events) that affect the hazards to which natural and human systems are exposed and the risks of impacts on these systems.

For example, *temperature changes* affect biodiversity, ecosystem functions and services on land and in the ocean, and many aspects of human well-being. Changes in absolute temperature ranges and shifts in seasonal temperature cycles impact biogeography, primary production, predator-prey interactions, crop production, fisheries catch potential, and distribution of pathogens. Long-term temperature patterns also contribute to critical environmental changes such as ice sheet loss and sea level rise. *Temperature extremes* such as heat waves on land and in the ocean affect natural and human systems through impacts such as terrestrial and oceanic vegetation mortality, increase in wildfire risks, occurrence of harmful algal blooms, and human mortality and other indirect health impacts. *Hydrological cycle and precipitation patterns* are of course critical to human and natural systems through impacts on freshwater availability, agricultural and livestock viability, and hazards from extreme precipitation events. Changes in *sunlight/UV intensity and quality* (the ratio of direct to diffuse light) affect

primary production of natural vegetation, phytoplankton, and crops through photosynthesis. SAI impacts on *stratospheric ozone concentrations* will affect how much UV light reaches Earth's surface—an impact that affects biota and humans. Figure 2.4 offers an illustration (specifically for SAI) of the wide-ranging impacts, both positive and negative, that must be considered in any comprehensive assessment.

Speculation about SG impacts must be viewed with caution for several reasons. The SG literature frequently describes the impacts of a particular strategy as if they applied to all possible strategies, but the magnitude and spatial/temporal patterns of many impacts will depend upon details of how an intervention is implemented—that is, the specific approach used (SAI, MCB, or CCT), how that approach is deployed, and how much cooling is pursued. Many of these details will be highly contingent on the socioeconomic and geopolitical background conditions and decision-making framework through which different types of interventions are implemented. Such factors are difficult, if not impossible, to predict, and there is a dearth of robust research scenarios for exploring such dynamics.

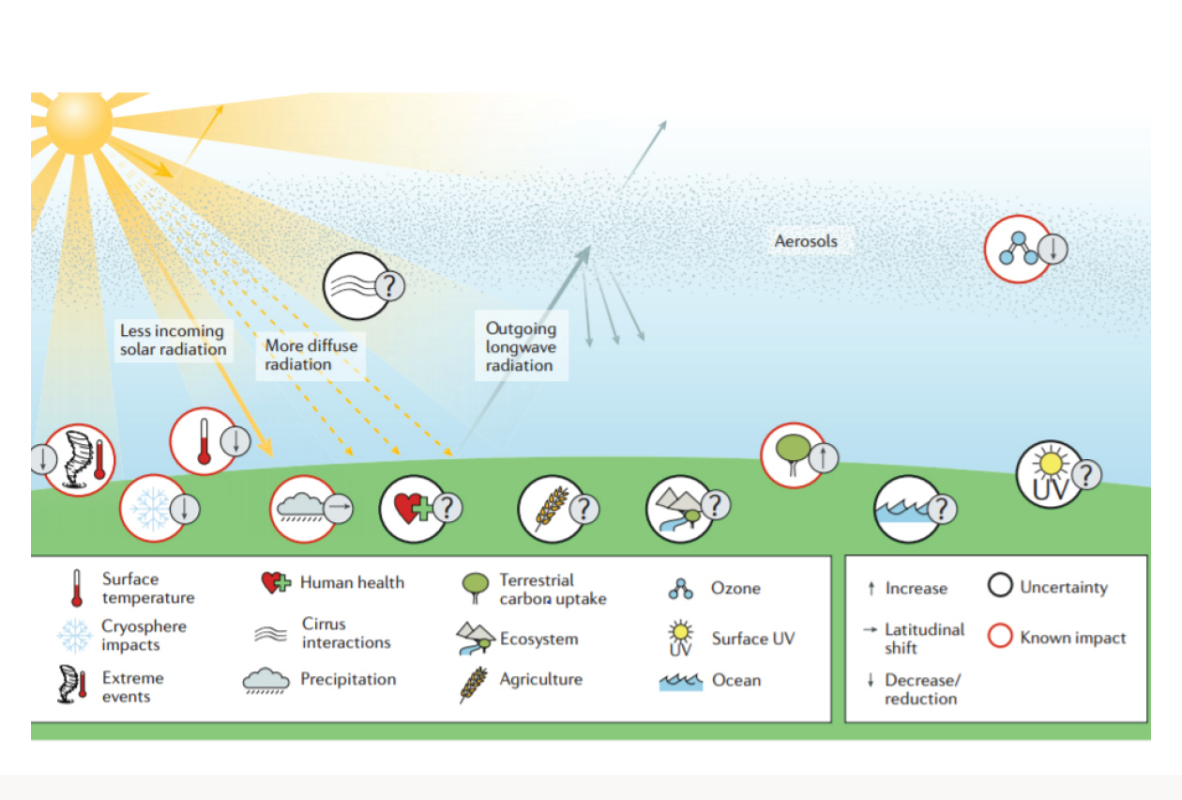

FIGURE 2.4 Illustration of some potential benefits from SAI along with some possible risks. SOURCE: Kravitz and MacMartin (2020).

Most importantly, the potential impacts of SG interventions ultimately need to be balanced against the potential impacts of climate change without such interventions, and, as discussed in earlier sections, SG does not affect the climate the same way that GHGs do; thus, using SG to reduce global climate change to some specific target level would not mean that all climate change impacts would be reduced correspondingly.

In international climate change negotiations, constraining global mean temperature increase (e.g., the Paris Agreement targets of "well below 2°C or 1.5°C") is used as a proxy for constraining impacts on specific environmental or societal systems of concern (e.g., extreme weather events, agriculture, natural ecosystems and landscapes, freshwater availability, and human health and well-being). The scientific community has developed relatively robust understanding of how risks to these critical systems are reduced as one reduces GHG concentrations in the atmosphere. However, one cannot use this same approach to simply add geoengineering options into the mix and then re-characterize risks. This is in part because SG impacts do not simply scale with global temperature; rather, for some systems, risks are driven by multiple environmental attributes—for example, temperature, humidity, precipitation, CO$_2$ concentrations, and surface energy balance. These attributes are often correlated when there is climate change with no geoengineering, but the relationships become more complex when SG is added to the mix.

For instance, in a 1.5°C world where an additional 1 degree of warming is being offset with SG, this may constrain surface ocean temperatures, which would mitigate bleaching of warm water corals; however, this cannot reverse ocean acidification, and thus coral bleaching problems overall may be worsened. In contrast, on average crop yields may be slightly higher in a 1.5°C world with SG than one without—because excess atmospheric CO$_2$ (the same thing that hurts corals) fertilizes plants.

A final reason for caution is that for most of these impact areas, there have been very few published studies (only one or two in some cases), and even the methodologies of how to study some of these impact areas are in their nascent states. The risk reduction estimates associated with GHG emission reductions alone represent consensus on a large literature on the impacts of global warming. (The IPCC impact assessments synthesize work from thousands of papers and involved deliberation among hundreds of climate scientists.) There has not been any comparable level of work of SG impacts research, and it is not possible to make sound decisions about relative benefits and harms in the presence of such information asymmetry. Thus, for some potential impacts, it is ill-advised to interpret these limited studies as indicating any real confidence in scientific understanding.

Specific Impact Areas

Sea level rise. Sea level rise poses large risks to coastal ecosystems, infrastructure and countless human communities situated along low-lying coasts and in small islands (Bindoff et al., 2019; Oppenheimer et al., 2019). If SG interventions are able to reduce surface warming, this would directly reduce "thermosteric" sea level rise (from thermal expansion of seawater) and likely reduce the intensity of sea level rise driven by polar (Greenland, Antarctica) ice sheet melting. One can confidently assume the overall sign of the effect of SG cooling effects on sea level rise, but the details are highly uncertain because (i) ice sheet loss depends not only on changes in air surface temperature but also on changes in precipitation and cloud cover as well as temperatures of the surrounding ocean water (e.g., Irvine et al., 2016; Moore et al., 2019) and (ii) ice sheet responses to warming are likely to be nonlinear. Some ice masses are thought to already be destabilized by current rates of warming; therefore, an SG-driven reduction in warming would not be able to reverse the "committed" contributions of these ice sheets to sea level rise. Additionally, deep ocean warming may contribute to sea level rise despite SG-driven reductions in surface warming (Fasullo et al., 2018).

Carbon cycle dynamics and acidification. Several studies have concluded that SAI would increase net uptake of carbon by terrestrial and oceanic ecosystems, resulting in lower atmospheric CO$_2$ concentrations relative to a scenario without deployment (Cao and Jiang, 2017; Muri et al., 2018; Yang et al., 2018). However, these effects of SG interventions are marginal compared to the overall amount of carbon uptake required to achieve desired climate targets. In addition, the sensitivity of net carbon uptake to SG depends on the varying ways that temperature and precipitation can affect vegetation and primary production. For instance, by lowering ambient temperatures, SG could slightly enhance the solubility of CO$_2$ in ocean waters and thus increase ocean acidification. Some limited studies suggest that SG could increase terrestrial carbon uptake in lower latitudes, while reducing this uptake in higher latitude regions. Very few SG-related modeling studies include the feedback effects of primary production on carbon update. Increases in the acidity of rainfall or ocean waters may impact sensitive vegetation, natural habitats, and organisms directly and indirectly; the effects of such changes will vary considerably among different biomes and regions.

Studies have suggested that SG might help maintain the strength of the Atlantic Meridional Overturning Circulation relative to scenarios of climate change without SG (Fasullo et al., 2018; Hong et al., 2017; Tilmes et al., 2020). While this could reduce atmospheric CO$_2$ concentration (by increasing the transport of inorganic carbon to the ocean interior), it will result in increased acidification of ocean deep waters.

Regarding concerns that stratospheric sulfate aerosols would ultimately reach the surface as acid rain, a significant effect on ocean pH is not expected, and in most places over land the effect would be small compared with current tropospheric sulfate emissions. They could, however, increase acid rain in currently pristine areas (Visioni et al., 2020a).

Ocean productivity and mixing. SG-driven changes in global temperature and hydrological cycle intensity can affect the ocean in many ways—for instance, by altering the loss of sea ice and the stratification of the water column—with consequences on ocean biogeochemistry, nutrient mixing and distributions, and oxygen concentration. Global ocean modeling experiments suggest that SG interventions could lead to a global decrease in ocean net primary production (NPP) relative to scenarios without SG interventions (Lauvset et al. 2017), although reduction in ocean NPP with climate change in the North Atlantic may be somewhat mitigated with SG interventions (Tilmes et al., 2020). As discussed in Lauvset et al., 2017, these impacts are dominated by changes in ocean circulation but are also affected by drivers such as incoming radiation, temperature, availability of nutrients, and phytoplankton biomass. For SAI and MCB, changes are found to be largest in the low latitudes. (Changes induced by CCT were relatively small by comparison.) Such findings illustrate the complexity of SG impacts on ocean productivity, with outcomes influenced by a variety of environmental factors that may all change in different ways.

Terrestrial vegetation. Natural vegetation provides the fundamental habitats for most animal life and supports many vital ecosystem functions and services for human societies, such as climate regulation and food provision. Global vegetation modeling suggests that SG-driven changes in temperature and precipitation patterns can affect vegetation production in complex ways, resulting from a balance among changes in transpiration, CO$_2$ fertilization, and soil respiration. Increased levels of diffuse light relative to direct light (an expected result of SAI interventions) can penetrate through the canopy to the shaded leaves below, which increases their photosynthesis; yet it is uncertain whether a decrease in direct light would decrease productivity of the sunlit leaves. Under SG implementation scenarios in which the effects of anthropogenic CO$_2$ fertilization on plants are removed, this results in large regional variations in NPP on land—with a decrease in NPP at high latitudes and an increase in tropical regions. The direction and magnitude of NPP changes is also affected by the balance between precipitation and evaporation (Glienke et al., 2015). Furthermore, these ecological changes are inextricably linked to many aspects of human and societal well-being. Figure 2.5 illustrates these linked social-ecological systems and underscores why SG impact assessments must be framed in a broad systems-level perspective.

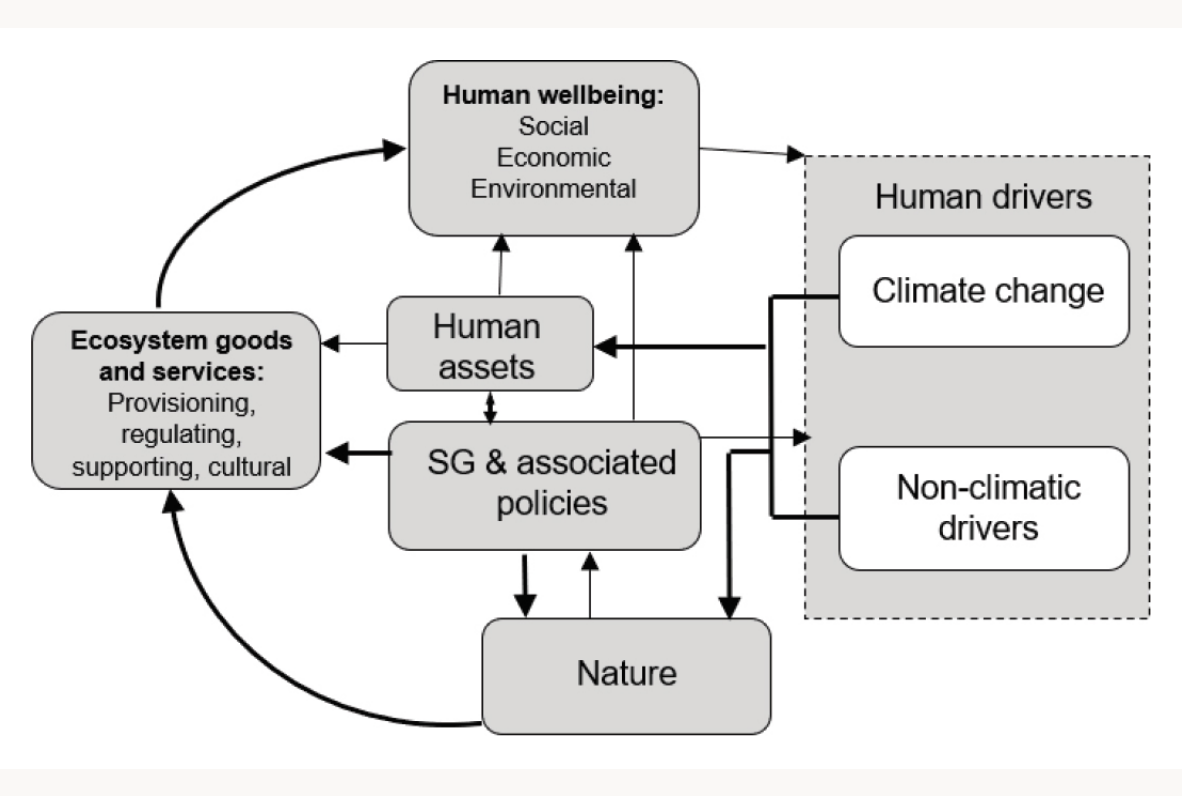
Human wellbeing: Social Economic Environmental
Human drivers
Climate change
Ecosystem goods and services: Provisioning, regulating, supporting, cultural
Human assets
SG & associated policies
Non-climatic drivers
Nature

FIGURE 2.5 Illustration of the "impact pathways" of SG on linked social-ecological systems. SOURCE: Drawing upon the conceptual framework developed for the *Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services* (Díaz et al., 2015).

Coral reefs. Tropical coral reefs are highly vulnerable to climate change, as are the diverse biota sheltered in these ecosystems. Warming ocean temperatures can lead to large-scale coral reef "bleaching" and mass mortality (Anthony et al., 2008). A few modeling studies have found that SG might be able to help protect these ecosystems (relative to scenarios of future GHG emissions without SG) by cooling sea surface temperatures and reducing the intensity and frequency of marine heat waves (Couce et al., 2013; Kwiatkowski et al., 2015; Latham et al., 2013)—for example, see Figure 2.6, which shows shallow water coral reef habit suitability in 2070 under different GHG emission scenarios and different levels of SG deployment. MCB interventions in particular are being actively explored as mechanisms for targeted cooling of waters around coral reefs.[6] However, even with cooler water temperatures, coral reefs will still be vulnerable to biogeochemical changes such as ocean acidification, although reducing heat stress could also reduce the sensitivity of corals to these biogeochemical changes.

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[6] See Marine Cloud Brightening for the Great Barrier Reef, savingthegreatbarrierreef.org.

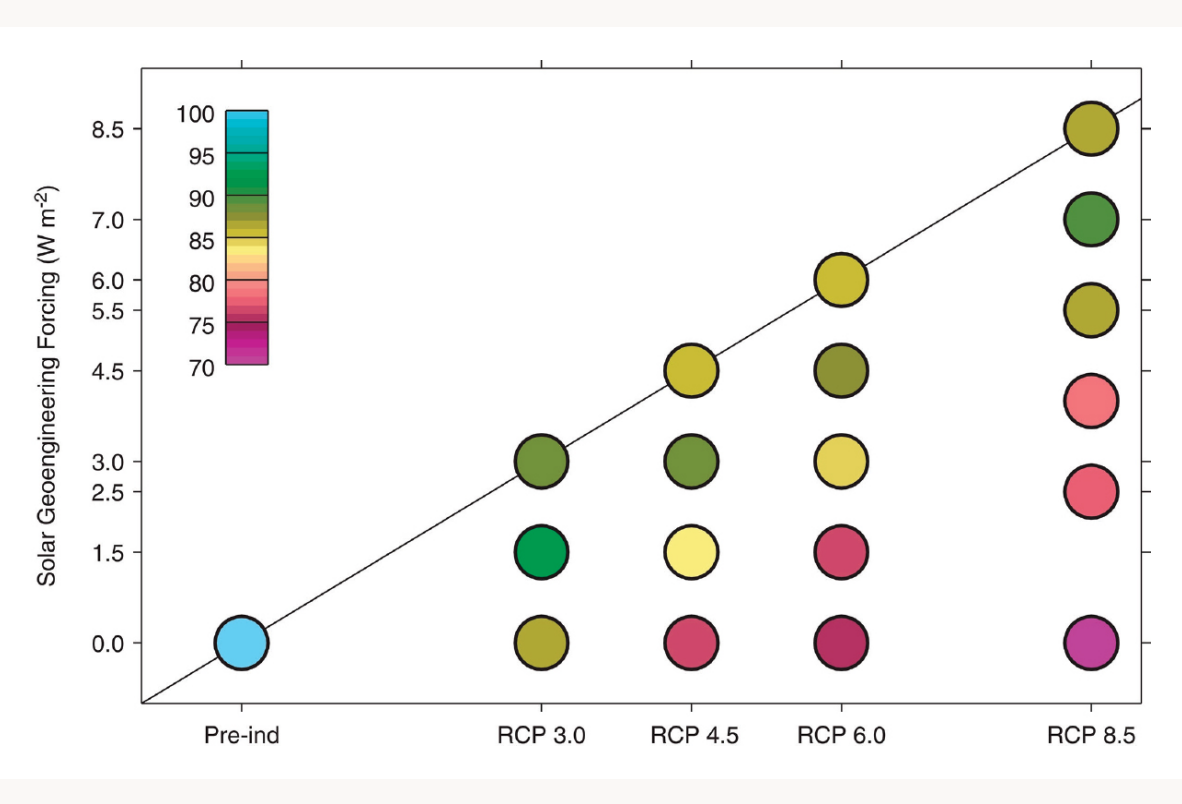

FIGURE 2.6 Shallow water tropical reef suitability in 2070 (plotted as a percentage relative to preindustrial) under four emission scenarios (x-axis) and different levels of solar engineering (y-axis). Habitat suitability is defined as the mean probability of a coral reef being present (as a single environmental niche, without resolving biodiversity or community composition). SOURCE: Irvine et al. (2017).

Biodiversity. The distribution and abundance of species in both terrestrial and oceanic ecosystems is greatly affected by climate change because species' distribution range is driven by shifts in temperature, precipitation, and other environmental conditions. In one of the few studies to date looking specifically at how SG implementation may affect biogeography, Trisos et al. (2018) focus on the concept of "climate velocity," which quantifies the speed and direction that species would need to migrate in order to track climate change (i.e., to maintain steady environmental conditions). The study modeled how climate velocities (broken down into temperature and precipitation velocities) would be affected under a moderate climate change scenario (RCP4.5), compared to a scenario with rapid implementation and rapid termination of SAI.

It was found that the global cooling resulting from rapid SG implementation results in temperature velocity vectors with the opposite direction of current warming; this rapid switch could halt or even reverse current climate-driven migration pressures on many species. Sudden termination of SG was found to cause extremely rapid temperature velocities for both land and ocean environments (far exceeding the values pre-

dicted for future climate change without SG)—thus placing much greater migration pressure on most species—with particularly acute effects seen in "hotspots" for biodiversity including the tropical oceans, the Amazon basin, Africa, Eurasia, and the polar regions. For most regions, differences in precipitation velocity with and without SG are much less pronounced, reflecting the greater variability in precipitation response to geoengineering. Rapid divergences in temperature and precipitation conditions can accelerate fragmentation of "climate niches" that enable the survival of many species. Such results illustrate that more research will be needed to better understand these complex linkages between climate velocity changes and species-specific migration rates and extinction risks.

Crop production. There have been a few studies examining crop responses to SG, ranging from global crop models to regional crop-specific models (Parkes et al., 2015; Yang et al., 2016). Crop production is sensitive to temperature, precipitation, quality and quantity of sunlight, and atmosphere CO$_2$ levels—environmental variables that would all be altered by SG interventions. Sensitivity of crop production to SG interventions is dependent on the characteristics of specific crop species and varieties and farming practices, including the susceptibility to changes in heat stress or length of growing season, precipitation-to-evaporation ratio, direct and diffuse light ratios, and availability of irrigation. Thus, available impact projections vary substantially, with increases in yields (and reduction in crop failures) in some crops and regions but decreasing yields in others (e.g., Parkes et al., 2015; Yang et al., 2016).

While agricultural yields are clearly an important impact to assess, there are a wide variety of conclusions reached from these modeling studies, with unclear dependency on the specific scenario, the details of the SG approach simulated, and the specific climate model and crop model employed.

Proctor et al. (2018) attempted to disentangle how agricultural yields were affected by the dimming effects from volcanic eruptions and separate from the temperature and precipitation effects, but such analyses are difficult and preliminary results should be interpreted with extreme caution.

Human health. Climate change poses a wide array of serious risks to human health, stemming from factors such as more frequent heat waves, the spread of vector-borne infectious diseases, and air pollution exacerbated by higher temperatures that increase surface-level ozone and other pollutants (e.g., see Rasmussen et al., 2013; USGCRP, 2018). Thus, if SG interventions were able to successfully offset some fraction of global warming that would otherwise occur, some substantial health benefits could emerge globally. At the same time, concerns have been raised about the potential for adverse impacts of SG on human health.

One such concern is that SAI deployment could reduce stratospheric ozone concentrations and delay recovery of the southern polar region's "ozone hole" (Pitari et al., 2014; Tilmes et al., 2009), resulting in increased flux of UV radiation at Earth's surface (see more detailed discussion of ozone impacts earlier in this chapter). Studies have attempted to estimate premature mortalities caused by increased human exposure to UV under such scenarios, but such projections are considered highly uncertain. This is in part because the responses of stratospheric ozone to SG interventions remain uncertain and in part because population exposure to these UV hazards can be affected by complex atmospheric processes, by changing human practices (e.g., occupational exposure interventions), and by other factors (Nowack et al., 2016). Studies have also shown that SG interventions could instead increase stratospheric ozone, which would result in decreased surface UV flux (Madronich et al., 2018), and tropospheric and surface ozone may be impacted depending on the intervention (Xia et al., 2017). Regardless, such work highlights that ozone changes must be considered in the assessment of any SG scheme, due to the resulting impacts on UV exposure and air quality.

Another health concern is that material that could be considered for injection may pose hazards, either as acute occupational exposure (during the manufacture, transportation, and deployment of materials), as chronic population exposures occurring transdermally, or through ingestion of food and water contaminated with deposited particles. For example, some of the aerosols that have been proposed for SAI contain aluminum, which could be a hazardous contaminant if inhaled (Effiong and Neitzel, 2016). To our knowledge, however, there is no serious consideration being given to use of this compound in SG deployment. Direct human toxicity is generally of little concern for most proposed gaseous precursors such as SO_2. In addition, a large faction of aerosol particles injected in the stratosphere would be removed by wet deposition as they descend to Earth's surface, thus causing little impact on surface-level particulate matter concentrations (Eastham, 2015). Projections of such hazards must also account for actions that could be taken to mitigate exposure hazards—for example, use of ventilation controls and personal protective equipment to mitigate occupational exposure.

Solar energy production. Another concern sometimes raised about SAI is the potential effect on solar energy production. A climate modeling analysis by Smith et al. (2017) looked at a scenario of SAI deployment designed to offset global temperature rise by 1°C. They found that the resulting reduction in direct radiation would reduce concentrating solar power[7] output by ~6 percent, while solar photovoltaic energy production is generally less affected, as it can use diffuse radiation, which increases under SAI.

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[7] Concentrating solar power systems use mirrors to reflect and concentrate sunlight onto receivers that collect the light energy and convert it into thermal energy.

2.2d Technology Development

The previous sections suggest that some overall lessons from research to date include the following: (i) If aerosols were added to the stratosphere through some form of SAI deployment, it is certain that some solar energy could be reflected back to space, resulting in global cooling; however, the limit to how much cooling could be achieved is currently unknown. (ii) In the right meteorological conditions, marine clouds could be brightened, but there is currently large uncertainty in how effective this would be and under what circumstances it could occur. (iii) It is plausible that some cooling could be obtained through CCT. Bringing any of these approaches to fruition, however, requires having the technological capability for practical deployment. Here we examine questions about the status of technological developments that would be needed to deploy SAI and MCB. (The physics of CCT are sufficiently uncertain at present that there has yet been no serious attention paid to implementation strategies.)

For SAI, the principal challenge is lofting sufficient material to sufficient altitude. At low latitudes, lofting material to ~20 km would be sufficient to achieve cooling, but injection at higher altitudes would increase efficiency and reduce the amount of material that would need to be added to achieve a given cooling, thus reducing some potential unwanted side effects. This efficiency benefit is a result of both longer aerosol lifetime and—at least with sulfate aerosols—reduced stratospheric heating, which in turn means smaller increases in stratospheric water vapor that counteract some of the cooling (Krishnamohan et al., 2019; Tilmes et al., 2018a)

Initial broad technology assessments suggest that aircraft are likely to be the cheapest method of deployment; see, for example, McClellan et al. (2012) and Moriyama et al. (2017). More recent and detailed aircraft design studies (Bingaman et al., 2020; Janssens et al., 2020; Smith and Wagner, 2018) illustrate a very high probability of deployment being feasible at 20 km altitude but with deployment being much more difficult at substantially higher altitudes (note that the GLENS study mentioned earlier [Tilmes et al., 2018b] injected SO_2 at 23–25 km).

Costs for such deployment have been estimated in the range of a few billion dollars in the early years of deployment for a very slow ramp up in forcing (Smith and Wagner, 2018), with costs rising if more cooling is desired (to perhaps $15 billion/yr to achieve 1°C cooling). Development costs would be on the order of a few billion dollars as well. These costs are small compared to the costs of climate change but large enough to be out of reach for some potential actors.

Given our familiarity with how volcanic eruptions inject large quantities of SO_2 gas into the stratosphere (which oxidize and ultimately form sulfate aerosols), using this

"aerosol precursor gas" has frequently been the default assumption for SAI implementation; dispersal for gaseous injection is thought to be straightforward. In contrast, for directly injecting either sulfate (as SO_4 or H_2SO_4) or alternate aerosols, additional technology development would likely be required; this has not yet been investigated. Smith et al. (2018) have explored in situ (on aircraft) combustion of sulfur into SO_2 and then into SO_3 or SO_4; they found that this would reduce the payload mass, but it would require additional system mass, and the trade-off remains unclear.

There are other options for lofting material to the stratosphere—ranging from rockets, to ballistic payloads accelerated from the ground (e.g., artillery, rail guns, etc.), to balloons. These alternative deployment methods are likely more expensive (McClellan et al., 2012; Smith and Wagner, 2018), although it is possible that could change over the ensuing decades. These methods also offer the potential for more widely distributed deployment—which could offer a benefit of broader international participation but at the same time would increase coordination challenges (Reynolds and Wagner, 2019).

For MCB, the deployment technologies involved are expected to be easier to develop, relative to SAI, in part because the particles are expected to be emitted from the surface (e.g., ship-based). But there has been much less work on these technologies, possibly because the fundamental effectiveness of this method is more uncertain and has received less research attention overall. There has, however, been some significant engineering development of the nozzles that would be required to produce salt spray with appropriate size distribution. These have been tested in a laboratory setting (and recently tested outdoors in Australia) and have produced particle numbers that may be sufficient for scale up. However, adaptation of such methods to a seawater source will require additional research and development.

There have not been any thorough cost estimates made for MCB deployment. For global-scale cooling, cost might be commensurate with those projected for SAI (in the few billions of dollars per year); unlike SAI, however, it may be possible using MCB to obtain local and regional climate effects with much smaller-scale efforts. There are as of yet no published cost estimates for such actions.

2.2e Monitoring and Attribution

Some of the most critical challenges of SG research and deployment relate to questions about monitoring and attribution of induced changes and resulting impacts:

- Can we measure the direct changes in key atmospheric variables (e.g., AOD and RF) resulting from controlled-release experiments?

- If SG deployment occurred unilaterally (in the absence of international cooperation or notification), would we be able to detect that it is happening?
- If interventions were deployed, how would we assess whether they are having the intended effects? Could we confidently attribute specific climate outcomes—including extreme weather events—to the SG intervention versus natural (unforced) variability or anthropogenic climate change?

The latter question is likely to be of particular salience to decision makers, as it underlies the difficult governance challenges of dealing with liability for any harms/damages incurred (discussed in Chapter 5). It is also one of the most challenging questions to address from a scientific standpoint.

Measuring and Attributing Direct Atmospheric/Radiative Changes

The difficulty of detecting and attributing the direct RF signal from a given SG intervention would depend on the method and spatial extent of the dispersion (e.g., NRC, 2015; Seidel et al., 2014). For SAI, changes in AOD[8] could be detected at relatively small forcing levels. The background AOD depends on altitude, and higher altitude injection would have even higher signal-to-noise level. Thus the AOD change resulting from any deployment sufficient to produce meaningful cooling (e.g., 1 Tg SO_2/yr might produce on the order of 0.1°C cooling; see Kravitz et al., 2017) would be easily detectable. The potential risk of "undetected deployment" of SAI is therefore indeed very low.

NRC (2015) points out that AOD peak change of 0.2 for a 10-megaton sulfur injection would be easily detectable by existing satellites. However, an injection of this magnitude is considerably larger than realistic early deployment scenarios (e.g., simulations indicate that 10 megatons SO_2/yr (5 MtS/yr) would yield AOD of 0.125 [Kravitz et al., 2017; Tilmes et al., 2018a]). As a comparative reference point, the eruption of Mt. Pinatubo (which released ~20 Tg SO_2) increased stratospheric AOD roughly a factor of 60 above the background level, and even smaller eruptions that reach the stratosphere (e.g., 0.3–0.6 SO_2, from Manam in 2005) are clearly above the AOD background level (Kremser et al., 2016).

More difficult to detect with satellite observations is the size distribution of aerosols. Several size bins can currently be detected if AOD exceeds ~0.15 or 0.2 (NRC, 2015); at smaller AOD, balloon observations would presumably be capable of detection.

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[8] AOD describes how much direct sunlight is prevented from reaching the surface by the presence of aerosols that absorb or scatter light.

Measuring and Attributing Climate Response

Assuming that only very small-scale material injections are used for outdoor experimentation (see discussion in Section 6.3), this would mean only negligible effects on any climate-related outcomes such as changes in extreme weather. But if one considers the possibilities of future deployment done at full scale, questions about attribution of SG outcomes (and associated "liability" concerns) may become critical to consider.

Attributing observed climate outcomes in the presence of natural variability is primarily a question of signal-to-noise ratio. Detection of changes in climate relative to natural climate variability and/or forced climate change will depend on the variables under consideration, the spatial scales and timescales considered, and the magnitude of the SG intervention. Measuring a significant decrease in global mean temperature would be relatively straightforward, but measuring shifts in some regional climate variable or the statistics of extreme events and other weather phenomena will be more difficult to detect and thus attribute over any reasonable time frame. In the context of anthropogenic climate change, attributing to SG any changes in individual climate events will be even more difficult (but perhaps possible).

Significant uncertainty in projecting regional climate responses to SG is likely to remain an ongoing challenge because of the large influence of natural variability regionally. MacMartin et al. (2019) considered a scenario wherein SG is used to cool the climate from ~3°C warming to 1.5°C. It would be straightforward to rapidly detect whether SG was working in the sense of having a lower global mean temperature than would have occurred without SG. But if the question is whether SG is affecting the climate *differently* from how GHGs affect the climate, one may need to identify differences between the "1.5°C climate" produced by GHG forcing offset by stratospheric aerosols and the "1.5°C climate" that would have occurred with the hypothetical world of lower GHG levels. For this sort of comparison, in many locations the differences in annual-mean temperature and precipitation would be difficult to detect by the end of this century; changes in the probabilities of extreme events could take even longer to detect.

These sorts of attribution questions are a major challenge, and thus a major research focus, for climate science more generally. In fact, the science and our understanding of this issue continues to rapidly evolve, and the analysis "toolbox" is much greater now than a decade or two ago. Attribution research for SG can leverage these developments. For instance, one approach now being used in general climate change research (which could be applied to SG research) is "optimal fingerprint analysis," in which one

BOX 2.3
Existing, New, and Needed Satellite Instruments for SG Detection and Attribution

Satellite remote sensing is an indispensable tool for collecting large-scale observations of atmospheric composition,which advances understanding across numerous fields of atmospheric, climate,and Earth system science (as detailed in the Earth Science Decadal Survey [NASEM,2018a]). For SG research, remote sensing observations allow us to better characterize the normal background concentrations and properties of key aerosol and gaseous compounds, and to potentially observe changes that may be induced by SG experimental injections.

For instance, global monitoring of aerosol properties is an essential component of any SG research program. In addition to current instruments operated by U.S. and foreign space agencies, NASA's upcoming Plankton, Aerosol, Cloud, and Ecosystem Mission, planned for launch in 2022–2023, will provide at high spatial resolution high-quality observations of aerosol and cloud properties for SG research and attribution. Recently, NOAA has recognized the value of adding atmospheric composition capabilities to the Next Generation Geostationary and Extended Orbits missions. Some of the contemplated sensors could assist in SG research, but launch of these missions is more than a decade away.

For stratospheric SG, global monitoring of the vertical column of ozone, aerosols, and so-called tracers that enable diagnosis of changes in stratospheric circulation are needed.While current sensors can provide these data, there is serious concern about the future capabilities at the required high-vertical resolution. While NASEM (2018a) recommends that a possible occultation spectrometer be considered for such observations, any proposed mission would compete against other similarly prioritized missions.

Absent such a mission, the 10th report of the World Meteorological Organization's Ozone Managers' Meeting (WMO, 2019) suggests that the observations of key stratospheric parameters to help understand changes in ozone will cease in 6–8 years. The report noted the following specific concerns:

- After SAGE-III and the OMPS-Limb on Suomi-NPP, the only planned high-altitude ozone satellite is another OMPS-Limb on JPSS-2 in about 2022. This will provide ozone and aerosol profiles but not the other key observations currently provided by the Microwave Limb Sounder (MLS) instrument on the Aura satellite.Aura is projected to keep operating until roughly 2023.
- The ALTIUS mission, scheduled for launch in 2023, will measure the vertical profile of NO_2, H_2O, CH_4, and a few other trace gases; however, no space program to date includes the capabilities for limb emission and IR solar occultation profiling that are needed to continue the monitoring of key ozone-related species (HCl, ClO, HNO_3, CCl_4, etc.), tracers of the Brewer-Dobson circulation and other atmospheric transport (N_2O, SF_6, CO_2, etc.), and ozone-depleting substances and their substitutes.
- With several existing missions—OdinOSIRIS, ACE-FTS,MAESTRO,AuraMLS—now nearing the end of their lifespan, there is likely to be a major gap in observational capabilities (e.g., for limb emission and IR solar occultation profiling) in the coming years.

determines the pattern of change predicted by models and projects the observed climate response onto that pattern; this provides the highest signal-to-noise ratio signal.

Better understanding these many questions about "limits to attribution" needs to be a high priority for future research, given the substantial implications for how the prospect of SG will be perceived, accepted, and governed by decision makers around the world. This is, in fact, an area in which research and research governance will likely need to "co-evolve" in the coming years, with new scientific insights and capabilities helping to shape new governance approaches and with input from stakeholders helping to shape new research directions.

2.3 SOCIAL DIMENSIONS

This section explores some of the critical social dimensions of SG that have been raised and explored in the research literature. This includes consideration of ethical issues (2.3a), public perception (2.3b), economic and political strategic incentives (2.3c), and governance research (2.3d). This is not an exhaustive review of all relevant social dimensions to be considered but provides a sense of the rich, complex areas of scholarship to be explored. Chapter 3 further expands upon many of the issues raised here, in considering the "decision space" for advancing SG research.

2.3a Ethics and Geoengineering

The prospect of SG raises a wide range of ethical issues that are not confined to the prospective use of SG. They also concern how research is organized, conducted, and prioritized; what governance mechanisms are appropriate; and processes for making decisions on these matters. In addition, there are ethical questions about the fundamental permissibility of SG research and deployment. The committee was charged with developing recommendations for a research agenda and mechanisms for research governance; thus, it worked under the basic presumption that it is reasonable to proceed with appropriately structured and governed research and that research may help to clarify the extent to which SG approaches are worth further pursuing. The research program outlined in Chapter 4 envisions ongoing assessment and checkpoints, including exit ramps (as needed), for research (see Section 4.2 and Figure 4.1).

The following discussion reviews a number of ethically salient questions that are raised by SG research and how these issues have been addressed to date in the exist-

ing literature.[9] In Chapter 3, the relevance of ethics, justice, and equity to the decision space and governance for SG research is considered (see, especially, Sections 3.2 and 3.4 and Box 3.2), and Chapter 6 provides a description of the ethical dimensions of the proposed research agenda (see Section 6.2).

Moral Permissibility of Intentionally Manipulating the Climate

Some scholars have explored fundamental questions regarding the very prospect of intentionally manipulating the climate on a global scale and the concerns this raises about "playing God," or excessive hubris on the part of humanity, and about fundamentally changing human relations with the broader natural world (Carr, 2018; Clingerman and O'Brien, 2014; Hamilton, 2013; Jamieson, 1996; Robock, 2008). Some also question whether human beings have the capacity to manage large-scale geoengineering, given the likelihood of unintended consequences and the scales of the technologies involved (Carr and Yung, 2018). Others question whether it is right, regardless of consequences or practical considerations, to allow the continuance of a harm (adding CO_2 to the atmosphere) by introducing a second strategy that allows the original harm to continue unabated (Hale and Dilling, 2010). Others argue that because humans are already altering the climate, to do so intentionally would be no more morally problematic than humans' intervention through GHG emissions.

Social science research on people's fundamental concerns about the permissibility of SG suggest that many people are open to further research, if undertaken with care and subject to conditions such as oversight, transparency, inclusive engagement, and attention to fairness and equity (this has been described as "conditional acceptance" or, in some cases,"reluctant acceptance" of research: see Carr and Yung, 2018; Kaplan et al., 2019; Pidgeon et al., 2013). Nevertheless, existing research is not fully representative of a diverse, global public; additional work is needed to characterize people's ethical views on SG research, the fundamental permissibility of large-scale geoengineering, and the conditions under which geoengineering might be considered acceptable.

Some scholars have argued against further research on geoengineering on grounds that SG will distract from the critical work of mitigation (e.g., Cairns section of Long

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[9] This discussion, which focuses on normative issues, connects with issues raised in Sections 2.3b, c, and d, because public perception research can clarify how various publics view ethical and justice issues in relation to SG research and development (2.3b); research on economic and political incentives can show how these incentives may align or conflict with ethical conduct and governance of SG research and possible deployment (2.3c); and governance research can explore not only the relevance of existing laws and institutions for SG research but also the objectives of SG governance and approaches to developing ethically informed SG governance mechanisms (2.3d).

and Cairns, 2020), because geoengineering would be "ungovernable" (e.g., Hulme, 2014), or because geoengineering research is proceeding without the consent of indigenous peoples (Whyte, 2012; 2018). Others argue that SG research is important because additional knowledge can support better decisions; if geoengineering were attempted in the future—perhaps as a desperate measure to address serious climate impacts—it would be better if such efforts were informed by an understanding of what approaches might work (or not work) and what the risks and uncertainties might be (Long section of Long and Cairns, 2020; NRC, 2015).

Philosopher Stephen Gardiner (2020) has argued that two important questions regarding the ethics of geoengineering are (i) Under what conditions would geoengineering be morally acceptable? and (ii) How likely is it that those conditions will be met? Some might argue that SG should be undertaken if the benefits significantly exceed the costs or if SG would be expected to reduce the net harm associated with global climate change. However, others would argue that it is not just aggregate benefits and costs that matter; rather, the distribution of benefits and costs is important, and policies that generate net benefits might not be justified if they impose significant costs on some (e.g., violating their human rights) or if the costs are borne primarily by those who are already disadvantaged. From an ethical perspective, additional research is needed to identify the kinds of risks, harms, and benefits that matter most in relation to SG, and how best to consider and evaluate these in research on SG's technical and social feasibility.

Determining the Goals of Geoengineering

Early literature on the ethics of geoengineering emphasized the possibility of disagreement about the goals to be pursued and how such disagreements should be settled. These concerns are often expressed in the question,"Who gets to set the global thermostat?" While the thermostat metaphor may be overly simplistic, it does capture the general concerns about what goals to aim for and how they would be determined. The Paris Agreement goals for limiting global mean temperature increase may provide one obvious reference point, but this does not necessarily capture all of the specific climate outcomes one must consider for geoengineering implementation. Because modeling outputs and impact assessments depend on assumptions about how geoengineering might be used (e.g., to fully offset anthropogenic warming, to offset a certain portion of warming, or to maintain a constant temperature), questions about goals arise early in the research phase. This raises ethical questions about how best to identify such goals, what criteria should be used to set them, and who should have a say (Preston, 2012; Tuana et al., 2012).

Justice, Fairness, and Equity Concerns

Concerns about fairness and equity have been raised in relation to SG research, development, and possible deployment. Fairness and equity considerations concern both processes and outcomes. Some basic questions include the following: How might the benefits and burdens of SG research and/or deployment be distributed, and could or would the distribution be fair? What would count as a fair distribution of benefits and burdens in this context? What would count as fair opportunities to participate in decisions about geoengineering research, development, and deployment? How should disagreements be addressed? What, if anything, is needed to address already-existing inequities in the capacities of different nations to undertake SG research, influence SG governance, and shape the global discourse surrounding SG?

Existing research suggests that procedural justice is important to consider (e.g., fair opportunities to participate and fair decision processes) in relation to SG (Callies, 2019b; Luwesi et al., 2016; Morrow et al., 2009, 2013; Svoboda et al., 2011), especially given the concentration of research thus far in wealthy countries and limited participation by those in the Global South (Biermann and Möller, 2019; Winickoff et al., 2015). Because merely providing opportunities for participation does not ensure that diverse voices will be heard and considered, a number of scholars have highlighted the importance of "recognitional justice," which requires not only basic respect for persons but also respect for difference, including attention to various mechanisms, institutional structures, and power dynamics that marginalize some individuals and groups and impede fair participation in research and governance (Hourdequin, 2016, 2018; Preston and Carr, 2018).

There are also questions of "distributive justice" (whether impacts of SG would be fairly distributed) (Svoboda et al., 2011) and whether and how people could be fairly compensated for any SG-related harms, including harms associated with SG experiments (Svoboda and Irvine, 2014). Some authors suggest that SG could ameliorate some of the distributive injustices associated with global climate change (Horton and Keith, 2016; Svoboda et al., 2018b), although others question whether SG constitutes an ethical response to existing climate harms and injustices (Baard and Wikman-Svahn, 2016). Injustice in one domain (e.g., procedural injustice) can exacerbate injustice in others (e.g., distributive injustice). Conversely, fair processes can increase the likelihood of fair outcomes.

Literature on ethics, equity, and justice in relation to geoengineering focuses on relations among contemporaries but it also involves important questions of intergenerational ethics as well (Burns, 2011; Gardiner, 2011; Smith, 2012). SG research, development, and

potential deployment raise complex questions of intergenerational equity. Intergenerational equity might support SG research aimed at countering climate harms and risks that present and prior generations have imposed on future generations (Weiss, 2019). But intergenerational equity might also support drastic and immediate mitigation of GHG emissions that would obviate the need for SG, and it might also counsel against any SG deployment that potentially commits future generations to prolonged deployment.

Burns (2011) has argued that it may be difficult to utilize SG "in a way that comports with principles of intergenerational equity." Gardiner (2011) pointed out the temptation of "intergenerational buck passing" in relation to climate change, in which current generations are tempted to postpone mitigation because the costs of mitigation are borne in the present, yet many of the benefits of mitigation accrue to future generations due to lags in the climate system's response. In the absence of specific institutions and governance measures that address the interests of future generations, SG may exacerbate intergenerational buck passing. However, some argue that SG research would benefit future generations by giving them a wider range of options for managing global climate change. Regardless, because any use of SG is typically envisioned as a multigenerational endeavor at the timescale of decades to centuries, both the intergenerational impacts and the intergenerational institutions needed to manage SG should be carefully assessed.

Ethics and the Governance of Geoengineering

Decisions about how to govern geoengineering, beginning with research, involve important ethical considerations. A number of prominent governance proposals focus on identifying key normative principles to guide SG research and development, as well as future decisions about whether and how to utilize SG. See, for example, the Oxford Principles, discussed later in this report, as well as Abelkop and Carlson (2012), Chhetri et al. (2018), Gardiner and Fragnière (2018), Jinnah (2018), Morrow et al. (2009), and Smith (2018) for further discussion of principles and normative underpinnings of geoengineering governance.

Other research on ethical governance of SG has focused on the possibility of and challenges for democratic governance (Horton, 2018; Szerszynski and Galarraga, 2013); the conditions for and challenges in establishing fair, legitimate, and equitable governance (Callies, 2018); the need to incorporate intergenerational considerations into SG governance (Gardiner and Fragnière, 2018); the role of risk-risk trade-offs, the precautionary principle, and other approaches to risk and uncertainty in decision

making (Hartzell-Nichols, 2012; Möller, 2020); the possibility and limits of monitoring SG adaptively; and the question of how to phase out and terminate SG without causing significant harm or injustice (Preston, 2013). Recent literature has also considered the relationship between SG and human rights (Adelman, 2017; Svoboda et al., 2018a; Whyte, 2018), and how to make ethical decisions in relation to SG under non-ideal conditions (when all options may be morally problematic in some way) (Morrow and Svoboda, 2016; Svoboda, 2017).

2017).

Relationships Among Mitigation, Adaptation, and Geoengineering

Numerous studies and reports have identified the possibility that geoengineering may reduce commitments to climate mitigation, slowing the pace of emissions reductions and the transition away from fossil fuels (e.g., Lin, 2013; Reynolds, 2019; Robock, 2008). The idea that geoengineering might undermine mitigation efforts is commonly known in the literature as "moral hazard" (Keith, 2000).[10] The worry is that if geoengineering is viewed as a partial remedy for near-term climate impacts, it may reduce commitment to investment in mitigation; also acknowledged (though less frequently discussed) is the possibility that geoengineering could diminish adaptation efforts (Lin, 2013; Preston, 2013).

Whether and to what extent geoengineering research, development, and possible deployment pose a moral hazard is to some extent an empirical question, but it is in practice difficult to assess. This is because a precise empirical measure of mitigation deterrence would require comparison to a counterfactual baseline (e.g., to know whether and to what extent SG research serves as a deterrent to mitigation, one would have to know how much mitigation would have occurred in the *absence* of SG research) (McLaren, 2016). Despite persistent concerns about mitigation deterrence, some social science research has suggested that individuals may *increase* their commitment to mitigation when the prospect of geoengineering is introduced (see, e.g., Merk et al., 2016), though results from a variety of studies on this topic are equivocal (see Burns, 2016). Additionally, the responses of laypeople may not reflect the ways in which policy makers would respond to geoengineering research or use of the technology (Flegal, 2019). Furthermore, those with vested interests in fossil fuels might seize on the prospect of geoengineering as a "solution" to climate change to support their interests, even if researchers and governments do not promote this framing. Corner and Pidgeon (2014) distinguish individual-level moral hazard (direct changes in individual behavior as a result of the prospect of SG) from social (changing norms that in turn may change behavior) and political (changes in the behavior of corporations and policy makers) dimensions of moral hazard, suggesting that it is important to disambiguate these and to consider particularly the political and collective effects.

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[10] Recently, some have argued that the term's roots in insurance language limits the scope of what is, in reality, a complex set of governance challenges, suggesting that mitigation deterrence encompasses mitigation foregone through imaginary offsetting of greenhouse gas emissions—a scenario "closest to a classic 'moral hazard' effect." See McLaren (2020). For a brief discussion of how moral hazard can operate at multiple levels (individual, social, and political), see Section 2.3a in this report.

Given the challenges in precisely measuring moral hazard, a prudent approach may be to safeguard against it through SG research governance and research program design (e.g., by making SG research a modest proportion of overall climate research budgets, as recommended in this report; linking any future use of SG to specific mitigation requirements [Lin, 2013; McLaren, 2016; Parson and Ernst, 2012; Preston, 2013]; or other measures).

Regardless of whether SG is likely to deter mitigation and adaptation, SG will need to be considered in relation to other climate responses and as part of a broader set of possible strategies for addressing global climate change (Preston, 2016). It is often suggested that SG should be evaluated using a risk-risk framework, where the risks of not using SG are compared to those of using it (for discussion of such approaches, see, e.g., Parker, 2014 and Flegal and Gupta, 2018; for discussion of risk-risk trade-offs more generally, see Graham and Wiener, 1995). However, in practice such assessments will be extremely complex, because there are many possible combinations of climate response, some with and some with SG, and all will be under-described (i.e., one cannot fully know how any of the options will play out, and there will be risks and uncertainties associated with each). Additionally, each option will have benefits and drawbacks that may be difficult to assess on a single scale.

Ethical Considerations for SG Research

Many of the ethical issues discussed above are crosscutting in that they apply both to SG research and to any future deployment. However, certain ethical issues are particularly salient in relation to SG research, specifically. They include concerns about the risks and impacts of research, including but not limited to field experiments; the potential that investment of time, effort, and financial resources in SG research will create momentum in favor of SG, facilitating a "slippery slope" toward deployment (see discussion in Cairns, 2014; Callies, 2019a); concerns that research will prematurely close down consideration of a full range of options and instead generate path dependence and "sociotechnical lock-in" on a particular approach (Cairns, 2014); and concerns that SG research will pose a moral hazard, increasing the likelihood that mitigation will be reduced or deferred if interest in geoengineering grows (Lin, 2013). A number of these issues are further considered in Chapters 3 and 4. For example, slippery slope issues are addressed in Section 3.2.c, and the research program design described in Chapter 4 incorporates public engagement and ongoing research assessment and checkpoints, which have been recommended as approaches to mitigating path dependence, lock-in, and slippery slopes (Callies, 2019a; McKinnon, 2018).

There are also procedural justice questions in relation to research, involving what constitutes appropriate public and stakeholder engagement, how to engage vulnerable and marginalized peoples, and what role consent should play in SG research processes (see, e.g., Carr and Preston, 2017; Frumhoff and Stephens, 2018; Whyte, 2012; Wong, 2015). Ethical issues also arise in relation to the structure of SG research processes more broadly, and existing ethics literature has suggested that SG research should be inclusive (both geographically and demographically), politically legitimate, socially responsive, integrated across disciplines, and transparent. A number of authors have identified the need to build institutional capacities to support research with these characteristics (see, e.g., Bellamy, 2015; Callies, 2018; Stilgoe, 2015). Tuana et al. (2012) proposed an integrated approach to SG research, which would embed consideration of ethical issues within virtually all aspects of an SG research program. Examples of integrated scientific–ethical questions include the following:"What is the best way to compare and weigh changes in temperature, precipitation and other climate conditions? For example, how should we trade off harmful impacts from precipitation change with respect to beneficial impacts from lower temperatures?""If temperature and precipitation anomalies resulting from solar radiation management cannot simply be aggregated, what is the best way to quantify them?" (Tuana et al., 2012).

Ethical Considerations for SG Implementation

The possibility of actually implementing SG interventions of course raises ethical issues at multiple stages (Preston, 2013). For instance, who would decide whether, when, and how to deploy? How should risk and uncertainty be weighed in making such decisions? If SG causes unintended harms (e.g., to particular communities or ecosystems), what should be done to compensate for these harms? If the benefits of SG are not evenly distributed, should this be addressed and, if so, how? By what processes could and should SG be phased out? How would termination decisions be made and by whom? A more comprehensive list of questions that need further exploration are offered in the discussion of ethics research in Chapter 6.

2.3b Public Perception

Over the past decade there have been numerous studies of public perception of climate intervention strategies, including both carbon dioxide removal (CDR) and SG. Examples include Bellamy et al. (2017); Borick and Rabe (2012); Burns and Flegal (2015); Burns et al. (2016); Corner and Pidgeon (2014, 2015); Corner et al. (2012, 2013); Cummings et al. (2017); Flegal et al. (2019); Mahajan et al. (2019); Mercer et al. (2011); Scheer and Renn (2014); Tingley (2019); Visschers et al. (2017); and Wibeck et al. (2015, 2017). More generally, pioneering studies on risk perception demonstrate that various publics can have very different perceptions of risk than calculated by or perceived by technical experts, which in turn can affect public trust or acceptance of technologies or agreement on safety precautions (e.g., Slovic, 1987).

Research on public perception of SG is valuable both to assess the state of public understanding and opinion regarding SG as a potential climate response and to inform measures to engage public and stakeholder input in decision making over SG research and research governance (see Chapter 5).

Before examining what such research has demonstrated, it is important to recognize several aspects of geoengineering as a subject of public perception research.

- Because geoengineering is not currently being implemented and SG research is at a very early state, there is low public familiarity with the subject; thus, studies of public perception are actually studies of "constructed imaginaries" of the subject rather than studies of formed public opinion based on experience, media coverage, statements of politicians, or other input. In fact, some researchers worry that the very process of doing public perception research on a currently non-existent technology may create the perception that the technology is more "real" than it actually is. This has prompted a search for ways to legitimately study and engage the public that does not lead to "premature sociotechnical lock-in." (Bellamy and Lezaun, 2015)
- Studies of public perception have been done almost exclusively in developed countries, predominantly in European countries, the United States, and Canada (with a few exceptions of work that occurred in Japan, New Zealand, and China). The Global South is not well represented in public perception research, nor is there awareness of how the populations most vulnerable to climate change perceive the concept of SG.
- There is not one monolithic "public" but rather numerous publics, with different values, worldviews, and perceptions. It has been stated that "publics are made, not found" (Jasanoff, 2019)—meaning that groups of people concerned about an issue do not necessarily exist a priori but rather may be designated or designed by others, which affects how one should view public perception itself.

- Public perception is not fixed but can be and is shaped by events, experiences, other people, and more over time. It can be said that SG research is a sociotechnical system, with research and public opinion of research co-constructing each other.

Caveats aside, existing research on public perception of SG does provide some consistent messages overall and reveals gaps that will need to be addressed if a fuller picture is desired. Some of the key issues are discussed below.

Types of Public Perception Efforts

Research to date has primarily relied on either large public surveys (conducted by firms specializing in survey research) or smaller qualitative studies such as focus groups or deliberative dialogues with more open-ended formats that allow participants more latitude in drawing comparisons, framing arguments, or forming opinions about the concepts the researchers are studying. Some of the specific forms of these deliberative exercises have included: (i) "deliberative mapping," which aims to open up to a broader diversity of framings, knowledges, and future pathways (Bellamy et al., 2016); (ii) a deliberative focus group methodology that focuses explicitly on the kinds of world(s) that would result from the deployment of SG (MacNaghten and Szerszynski, 2013); and (iii) experimental deliberative workshops that place majoritarian, individualistic, and consensual forms of public deliberation on an equal footing (Bellamy et al., 2017).

Wright et al. (2014) describe an evaluation of public responses to climate engineering and suggest distinguishing among three types of public engagement with science: *deliberative* (which "provides opportunities to build a shared understanding of the local, cultural and social factors that affect engagement with science"); *persuasive* (which "may effect behavioral change, but can be contested if its objectives do not have broad scientific or community support"); and *descriptive* (which "seeks to provide inputs for decision making, providing controlled comparisons between techniques and methods for tracking changes on public perception over time").

Public Awareness and Understanding

General awareness of SG in the lay public is low. While the term "climate engineering" seems to elicit higher levels of recognition in some studies (perhaps from intuiting the meaning rather than being familiar), the level of public awareness hovers around 8 or 9 percent; however, more recent work suggests that 20–30 percent of the general public may be somewhat or very familiar with the term SG (Mahajan et al., 2019). Studies have found that even when participants are unfamiliar with the concept of SG at the outset, they are able to engage in sophisticated discussion and nuanced debate about some of the concerns that have emerged from experts (e.g., slippery slope concerns, discussed elsewhere in this report). Others have found that there is skepticism that research could be kept separate from actual deployment (Burns et al., 2016). Participants allowed to explore concepts in a group with minimal guiding or prompting are skeptical of SG and tend to start out with a negative view, but by drawing on analogies, comparisons, and metaphors, they are able to reason through how to make sense of SG and place it in a framework with mitigation and adaptation (Wibeck et al., 2017).

Finally, publics are not merely found, they are also formed. Just as public understanding of climate change in general is understood to be important for forming better and more effective responses, public understanding of SG will likewise be important. Several engagement mechanisms have evolved over the years to better explain new and emerging technologies to the public, to understand public responses to these technologies, and to enable greater realization of the differences of values and interests among various actors, including researchers, different publics, and those who make choices about deploying technologies (Stirling, 2007). Some of these engagement strategies have been applied to the issue of SG (Bellamy et al., 2017; Kaplan et al., 2019; Parkhill and Pidgeon, 2011).

Public Acceptance

When studies have included both CDR and SG, there is generally higher acceptance for CDR than for SG. In recent public deliberation research with small groups in two U.S. states, preference for SAI was near the bottom of the six SG methods presented, and modeling, indoor research, and small-scale trials were preferred to larger efforts (CSPO, 2019).

Studies to date have found conditional support for SG research, with much lower support or opposition to the notion of SG deployment (Corner et al., 2012). This conditional support depended on participants' views on factors such as the seriousness of climate change as a problem, the ways that the research is conducted, the scientific robustness of the project, the "foreseeability" or the efficacy of the research, the existence of effective governance mechanisms, and the presence of democratic conditions in society (MacNaghten and Szerszynski, 2013). In studying the acceptability of SG experiments, Bellamy et al. (2017) found the essential condition was "controllability," which has several facets including the degree of containment, the uncertainty surrounding the experimental outcomes, the reversibility of impacts, and the scientific purity of the enterprise (i.e., basic research versus a commercially driven enterprise). Studies found conditional support for indoor work, with appropriate levels of public scrutiny (MacNaghten and Szerszynski, 2013), but many concerns about outdoor experiments (Burns et al., 2016).

Conditional support has been found in international-scale studies as well, though in some cases such support might better be characterized as "deeply reluctant and highly conditional" (Carr and Yung, 2018). In a study of vulnerable populations in the Pacific, sub-Saharan Africa, and North American Arctic, many respondents emphasized the importance of SG research being inclusive of people in developing countries, and they raised concerns that research might overlook local needs, worsen global inequalities, or "make vulnerable populations even more dependent upon the decisions and actions of more powerful actors in distant places" (Carr and Yung, 2018).

Moral Hazard Concerns

The concept of "moral hazard" (also discussed in Chapter 3) has also been explored in public perception studies. Some public perception research showed that lay publics felt that if SG technology existed, it would reduce commitment to mitigation efforts; yet other research has suggested that this response is not consistent and may depend on how questions are framed, an individual's level of climate-related concern, or other factors (Mahajan et al., 2019; Raimi et al., 2019). The differing findings may reflect the fact that people with different value orientations simply hold different views on this issue. Given that SG technologies are still in a very early stage of exploration, it is difficult to know how utilizing these technologies will affect mitigation options. Regardless, public perception research overwhelmingly demonstrates that among participants who agree that climate change is an urgent issue to be solved, mitigation is always a preferred alternative to SG—and that SG is not a substitute for mitigation (Scheer and Renn, 2014).

Public Trust

Another thread that research has explored is who is trusted on issues related to SG. Mercer et al. (2011) found that university researchers are most trusted, government is less trusted, and private industries benefiting from SG are least trusted. Recent public deliberation research in two U.S. states found the same level of high trust in universities and then philanthropies, with corporations and the military least trusted (CSPO, 2019).

Framing Considerations

Because public familiarity with SG is so low, the structure of a study—including how the topic is framed by researchers—can affect how the research subjects respond to questions about the topic. Narrowly framed evaluations can hide uncertainties and complexities and can close down the space for deliberation; in contrast, new forms of deliberative research show that the framing of SG can be opened up by engaging with a broader set of people with differing views (Bellamy et al., 2016). Huttunen and Hildén (2014) suggest three main ways of framing used by scholars, which can lead people to draw very different conclusions about geoengineering: (i) a "risk-benefit" frame, which, as the name suggests, focuses on the calculus of, and balance between, estimates of risk and benefits; (ii) a "governance" frame, which emphasizes the roles and needs for institutions and procedures; and (iii) a "natural balance" frame, which focuses on the ethical aspects of geoengineering. Raimi et al. (2019) suggest that the framing of geoengineering as a major solution to climate change leads to a reduction in mitigation support among people, while more moderate framing is less susceptible to these moral hazard concerns (discussed above).

Empirical public perception framing research thus far has revealed concerns that SG can evoke a frame of "messing with nature" (Corner et al., 2013), and, indeed, the framing of SG as either "natural" or "industrial" influences the degree of public support. Corner and Pigeon (2015) found that natural framings, such as comparing SG to volcanoes, influenced participants to see SG in a more positive light (although later research did not find this difference [Mahajan et al., 2019]). Framing SG as a "fast and cheap" response option predicted support for SG (Mahajan et al., 2019), and framing the climate problem as one of a "climate emergency" tended to enhance the acceptability of research and create favorable opinions for geoengineering strategies viewed as fast acting and more impactful (Bellamy et al., 2017).

The discourse around SG is also shaped by (and in turn shapes) coverage in the media. The frames used can narrow and shape the ways in which SG as a concept is interpreted in the media by different actors (Luokkanen et al., 2013; Nerlich and Jaspal, 2012). Porter and Hulme (2013) found that in UK media discourse, the issue of SG is often covered using "innovation" framing, or framing around "risk, governance and accountability, economics, morality, security and justice."

2.3c Economic and Political Strategic Incentives

Economics research to date has focused largely on questions about how individuals and nations would respond to the introduction of SG as a policy option for addressing the dangers of climate change. Most of these publications ask two fundamental types of questions: (i) how SG ought to be used (normative approach) and (ii) how SG would likely be used under different socioeconomic settings (descriptive approach). Each of these approaches are discussed below.

Descriptive Analysis: How Could Solar Geoengineering Affect Economic Outcomes?

Chronologically, the economics literature initially focused on questions about how SG would alter the international politics of climate change. Schelling (1996) suggests that the threat of climate change makes SG more likely, but the use of SG comes at the cost of political stability. Barrett (2008) builds upon this foundation, using a simple game theoretical model to show that geoengineering reduces the problem of cooperation usually associated with the free-riding behavior in climate change policy to one of coordination. Barrett (2008) also shows that the introduction of SG creates incentives for countries to reduce mitigation efforts.

Subsequent publications suggest that the strategic space is more complicated and nuanced. Millard-Ball (2012), Moreno-Cruz (2015), and Urpelainen (2012) find that under a scenario with asymmetrical preferences among nations over the amount of SG to use, the outcome can be an increase in the amount of mitigation efforts pursued rather than a reduction in such efforts. In all cases, a coalition arises such that some amount of both mitigation and SG is implemented by several countries. The possibility of increased mitigation arises due to the intrinsic characteristics of SG that make it possible for single actors to implement a substantial amount of geoengineering on their own.

Weitzman (2015) coins the term "free-driver" (as opposed to "free-rider") to capture the strategic interactions resulting from the introduction of SG. Free-driver refers to a country, organization, or individual that can alone implement an SG program (given the relatively low cost). He discusses the challenge of finding international governance structures that induce a free-driver to abstain from over-implementing SG. Moreno-Cruz (2015) shows that free-driving can induce even larger amounts of mitigation because it can be used to deter the use of SG. This does not, however, address the issue of compliance.

Ricke et al. (2013) introduce the concept of "exclusive coalitions" (in which countries gather just enough international support sufficient for establishing an SG program) and find that plausible coalitions can emerge and are stable under a large number of scenarios, and that the difference in welfare gains between an exclusive coalition and a full global coalition are so small as not to warrant the political cost of exclusion.

Recently, researchers have begun to study the strategic implication of "counter-geoengineering" technologies that could be used to negate the cooling effects of SG (e.g., Heyen et al., 2018).[11] The results of such analyses are mixed. For instance, Parker et al. (2018) find that developing capacity for counter-geoengineering is likely to face serious practical obstacles, but if such capacity were developed, it could either help reduce the prospects of unilateral deployment or it could lead to "dangerous brinksmanship" among nations.

Normative Analysis: What Is the Role of SG in Achieving Different Climate Goals?

In addition to these sorts of questions about international relations are fundamental questions about how to best incorporate SG into economic models of climate policy. The dominant class of models used in the literature, integrated assessment models (IAMs), are used to simulate the effects of alternative future climate policies. The general approach of IAMs is to link an economic module and a climate module—via GHG emissions and via a climate damage function that attempts to capture how climate change impacts will alter aggregate economic outcomes.

Introducing SG in these models requires adjustment in the RF equation that drives changes in temperature and introduction of a damage function to represent new adverse impacts created by SG. Using these models, researchers have studied the effect of SG on factors such as carbon prices (Bahn et al., 2015; Heutel et al., 2018), decision under uncertainty (Bickel and Lane, 2009; Emmerling and Tavoni, 2018; Goes et al., 2011; Heutel et al., 2018), regional outcomes (Heyen et al., 2015; Moreno-Cruz et al., 2012; Rickels et al., 2020), and climate tipping points (Heutel et al., 2016). While there are of course large uncertainties in these complex coupled economic modeling studies, most analyses portray SG as a plausible complement to mitigation policy.

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[11] Heyen et al. (2018) note that counter-geoengineering (as applied to SAI) could be either"neutralising" (e.g., injecting a base to counteract the effect of sulfate aerosols) or"countervailing"(e.g., releasing a warming agent to reverse the effects of aerosols).

2.3d Governance Research

A substantial body of research has examined how existing law, domestic and international, might apply to SG (Hester, 2018; Lin, 2018; Reynolds, 2018, 2019). This literature, which focuses primarily on environmental law, but also discusses human rights and intellectual property law, generally has concluded that SG lacks coordinated and systematic governance (Flegal et al., 2019; Long, 2013). Some commentators have viewed SG governance as relatively manageable (Reynolds, 2019), while others have suggested that SG may be ungovernable (Hulme, 2014; Szerszynski et al., 2013).

Beyond this descriptive work, much research has explored normative aspects of SG research governance. As discussed in Chapter 3, several proposals have been made concerning high-level principles for SG governance (ASOC, 2010; Gardiner and Fragnière, 2018; Morrow et al., 2009; Rayner et al., 2013). Substantial attention also has been devoted to other fundamental governance concerns, such as how to define and categorize SG research for governance purposes (Bodle et al., 2014; SRMGI, 2011) and what possible objectives governance might serve (Bodansky, 2013; Dilling and Hauser, 2013; Nicholson et al., 2018; SRMGI, 2011).

Researchers have delved into specific design considerations as well, such as institutional options (Armeni and Redgwell, 2015; Nicholson et al., 2018; SRMGI, 2011); roles of governments, researchers, universities, funding agencies, publishers, and other nonstate actors in governance (Dilling and Hauser, 2013; Parker, 2014; Reynolds and Parson, 2020; Victor, 2008); and scales of governance (Jinnah et al., 2019; Parker, 2014; Rayner et al., 2013). Numerous potential mechanisms of research governance have been considered, including research registries and other transparency mechanisms (Craik and Moore, 2014; Nicholson et al., 2018); codes of conduct (Hubert and Reichwein, 2015; Morgan et al., 2013); sharing and institutionalization of best practices (Dilling and Hauser, 2013); forums or advisory committees to build norms, engage publics, and advise governments (Nicholson et al., 2018; Parson, 2017; Winickoff and Brown, 2013); project-specific and programmatic impact assessments (Craik, 2015; Lin, 2016); moratoria on field experiments (Parker, 2014); and prohibition of large-scale SG activities involving significant transboundary risks (Bodle et al., 2014).

Some research has focused specifically on governance of SG deployment while acknowledging the potential overlap between such governance and governance of SG research. The *Harvard Project on Climate Agreements* published a volume of policy briefs addressing various aspects of SG deployment governance, including possible deployment scenarios, development of criteria for decision making on deployment, public perceptions of SG, and technology governance regimes that could be useful analogues for SG governance (Stavins and Stowe, 2019). Researchers have explored different approaches for establishing an international governance regime, whether through existing governance regimes developed in other contexts (Armeni and Redgwell, 2015; Bodansky, 2013; Bodle et al., 2014; Burns and Nicholson, 2016) or through a new regime that commences with limited membership and requirements but expands over time in membership and depth of commitment (Lloyd and Oppenheimer, 2014). Other aspects of SG deployment governance that have received consideration include liability and compensation (Hester, 2018; Horton, 2018), as well as the compatibility of SG deployment with democratic governance (Horton, 2018; Szerszynski and Galarraga, 2013).

2.4 SYNTHESIS OF RESEARCH ASSESSMENT

SG research to inform decision making will require coalescence of findings from diverse disciplines in the applied, natural, and social sciences, as well as in the humanities. Scholars will need to work collectively to understand processes of uncertainties in both societal and climate-system dimensions and under a range of hypothetical future implementations. In addition, SG research should strive to be transdisciplinary, meaning that research agendas are co-constructed between researchers and non-academic stakeholders and "publics," so that the resulting research can be as relevant as possible to societal decision making. Technologies, publics, political regimes, and climate targets are co-produced and co-evolve, multiplying the challenges of responsible SG research and necessitating an examination of how beliefs, judgments, and practices during the research process may have influenced the research (see, e.g., McLaren and Markusson, 2020).

The following are some examples of how SG bridges across areas of expertise, and why some research questions are best framed by co-construction with stakeholders beyond the research community:

- SG might be implemented under a range of socioeconomic, climate, environmental, and geopolitical background conditions. Assumptions about these conditions will influence outcomes; thus, SG research

about these conditions will influence outcomes; thus, SG research needs to consider the range of possible futures in which implementation might be considered. Researchers based in the *social sciences* may be best equipped to define and characterize these scenarios.
- People and organizations will govern SG by establishing norms, regulating institutions to deal with SG and its effects. All of these processes require investigation through the *social sciences*.
- Societal choices made about SG implementation plans (e.g., where/when to inject reflecting particles, with what goals, and using what technology) will both influence and be influenced by engineering of the technology required for implementation (e.g., design of airplanes, nozzles, precursor chemicals, and

logistical protocols). Deliberation over such questions will thus need to involve participation of *applied scientists and engineers*.
- The projected physical effects of SG will depend on these design decisions. The expertise of *chemists, physicists,* and *material scientists* will be needed to understand the processes that follow if reflective material is released into the environment, including radiative effects, lifetime, and decay.
- For intervention strategies such as SAI, these factors in turn will influence how the injected material scatters and absorbs incident radiation; changes in RF cause thermodynamic and dynamic changes in climate at a range of scales. This can affect other Earth systems, such as ice sheets and sea levels—processes that will require investigation of *climatologists* and other *earth scientists*.
- Climate and other Earth system changes will influence biological organisms and ecological systems, thus raising questions best addressed by experts in the *life sciences*.
- Changes to the environment can directly and indirectly affect human behavior and welfare—including large-scale changes in the socioeconomic trajectory of societies—and understanding such dynamics requires input of *health and psychology scientists, economists,* and other *social scientists*.
- Integrating knowledge and making decisions about the potential effects of geoengineering (climatic, ecological, social, and political) and the distribution of these effects involves ethical values, as well as considerations of justice and equity. Engagement by *natural and social scientists, ethicists, economists, policy makers,* and *diverse publics* can strengthen these knowledge-integration and decision-making processes.
- Any initial SG design and implementation may be adjusted over time in response to new goals or knowledge. Understanding how such goals and adjustments would be driven (by whom? with whose agreement? based on what criteria?) raises complex decision science problems that will require transdisciplinary expertise and collaboration.

Understanding the outcomes and uncertainties associated with any proposed SG implementation requires having a robust characterization of each of the many factors listed above. Note that there will also be feedbacks among this web of impacts, which represent essential lines of inquiry themselves. For instance, assumptions about social system outcomes of SG interventions often feed into the design and interpretation of natural science experiments, and, in turn, many aspects of social science and humanities inquiry are predicated on assumptions about the feasibility and outcomes of proposed SG technologies. These interdependencies of natural and social science research underscore the importance of pursuing an interdisciplinary research agenda.

A large fraction of the geoengineering research to date has occurred at the nexus of a relatively small number of disciplines and "stages of inquiry"—for instance, focused on the links between climate forcing and climate effects and between strategic behavior and governance. Important knowledge gaps remain in many areas; this dearth of knowledge is, in turn, impeding progress in other areas of inquiry.

There is not necessarily a neat intersection between disciplinary-focused questions that represent the biggest knowledge gaps and the questions that (if addressed) would provide the most valuable information to aid decision making. For some knowledge gaps, relatively modest investment in geoengineering-specific research could provide significant additional knowledge. For other topics, (e.g., understanding the response of regional precipitation to SG radiative forcing), even substantial program-level funding may not yield significant near-term advances in the field. These types of considerations are addressed further in the research agenda discussed in Chapter 6.

BOX 2.4
Science and Technology Studies Perspectives on the Disciplinary Integration Needed for SG Research

The SG enterprise,given its complex nature,will doubtless benefit from the incorporation and integration of different knowledges.[a] Heyward and Rayner (2013) suggest that the geoengineering discourse entails a complex set of relationships between techno-scientific and social scientific expertise. Huttunen and Hildén (2014) suggest that dialogue between various disciplines and researchers also allows stronger interaction between different frames and the development of new syntheses. However, this may require reconceptualizing the relationship among disciplines.

Szerszynski and Galarraga (2013) discuss the counterproductive notion of "subordination" in which certain disciplines are given the task of problem definition and others (typically the social sciences) are allocated the task of filling in gaps within that given frame, together with the problematic presumption that disciplines can be integrated in a straightforward manner through an "integrative imaginary." They suggest an alternative notion of a "reflexive imaginary" that draws upon the multiplicity and heterogeneity that different disciplines can offer.

More broadly, Stilgoe (2015) proposes an approach of "collective experimentation" that recognizes geoengineering not as a simple object of analysis but as a process. More concretely, the "responsible innovation" approach proposed by Stilgoe et al. (2013) outlines a framework involving *anticipation, reflexivity, inclusion,* and *responsiveness* that aims to address social and ethical concerns and provide a practical and systematic approach to governance of scientific and technical issues such as SG.

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[a] Of course, different knowledges include not only disciplinary diversity but also geographic and demographic diversity of researchers, as has been pointed out by analysts (see, e.g., Mathur and Roy, 2019; Rahman et al., 2018; Sugiyama et al., 2017; Winickoff et al., 2015).

Conclusion 2.1: Understanding of some important questions about SG has advanced as a result of research conducted to date, but at present this state of understanding is limited. The research to date is ad hoc and fragmented, with substantial knowledge gaps and uncertainties in many critical areas. There is in particular a need for greater transdisciplinary integration in research, especially linking the physical, social, and ethical dimensions and inclusive of robust public engagement, as well as a need for expanding diversity among the research community itself.

Conclusion 2.2: Research to understand the potential nature, magnitude, and distribution of SG impacts—on ecosystems, human health, political and economic systems, and other issues of social concern—is in a nascent state. Studies published to date do not provide a sufficient basis for supporting informed decisions.

2.5 CURRENT MECHANISMS FOR RESEARCH GOVERNANCE

This section assesses existing governance structures that are relevant to SG research, encompassing several dimensions of hard governance (i.e., derived from domestic and international laws, treaties, and regulations; customary international legal principles; and human rights, liability, and environmental law) as well as soft governance (i.e., the use of nonbinding norms that are expected to produce effects in practice). It is important to note that laws that may be applicable to SG research were not enacted with SG in mind, and their intent, scope, and purpose were not to address the challenges of governance in this space.

As discussed in Chapter 5, in the context of SG research, governance relates not only to the physical risks of the research but also to dimensions such as public transparency over what is being undertaken, procedural issues and control, who has input into decisions about whether research can go forward, liability for the consequences of research, and more general conflicts over the role of humans in the environment and the morality of specific types of research (Dilling and Hauser, 2013). See Section 2.3d for review of existing SG governance research.

2.5a Hard Governance

NRC (2015) offered a brief overview of U.S. laws and international treaties that might be relevant to SG research or deployment. The discussion below expands on that overview and focuses specifically on laws that might apply to SG research.

Domestic Law

Several bodies of U.S. law, including environmental statutes, tort law, and intellectual property law, may be relevant to SG research. Notably, existing law generally focuses on physical impacts; other concerns surrounding SG research, such as slippery slope and moral hazard concerns (discussed earlier in this chapter), largely lie outside present legal frameworks. In addition, as the environmental statutes were not written with SG research in mind, further elaboration through rulemaking or other means may be necessary to clarify their applicability to SG research.

For small-scale field experiments, the most relevant statutes—the National Environmental Policy Act (NEPA) and the Weather Modification Reporting Act (WMRA)—are procedural in nature.

NEPA and state analogues. SG research conducted, sponsored, or authorized by the federal government potentially would be subject to NEPA, which requires federal agencies to prepare an environmental impact statement (EIS) for "major Federal actions significantly affecting the quality of the human environment . . . ." (42 U.S.C. § 4332(C)). NEPA requires an agency to describe the environmental impacts of such an action, identify alternatives to it, and make the EIS available for public comment (42 U.S.C. § 4332(C); 40 C.F.R. § 1503.1). However, the statute does not require the agency to obtain any sort of permit, nor does it bar an agency from proceeding with a proposed action once it satisfies its procedural obligations under the statute.

In determining whether an action has significant environmental impacts, an agency considers beneficial and adverse impacts that are reasonably foreseeable (40 C.F.R. § 1508.27 (pre-2020); 40 C.F.R. § 1508.1(g) (2020 revision)). If an agency determines that an action will not have significant environmental impacts, it may issue an environmental assessment and "finding of no significant impact" instead of preparing an EIS (40 C.F.R. § 1508.13 (pre-2020); 40 C.F.R. § 1501.6 (2020 revision)).

Small-scale field experiments with minimal physical effects are not likely to trigger the obligation to prepare an EIS and may not even require preparation of an environmental assessment if they fall within a "categorical exclusion," which refers to categories of actions that an agency has previously determined not to have significant impacts (40 C.F.R. § 1508.4 (pre-2020); 40 C.F.R. § 1501.4 (2020 revision)). For example, field experiments conducted or sponsored by the U.S. Department of Energy may fall under the agency's categorical exclusion for "[s]iting, construction, modification, operation, and decommissioning of facilities for small-scale research and development projects; conventional laboratory operations . . . ; and small-scale pilot projects" (10 C.F.R. Pt. 1021, Subpt. D, App. B, § B3.6).

By contrast, field experiments sponsored by the National Science Foundation (NSF) may not qualify for that agency's categorical exclusion applicable to research. NSF's NEPA regulations establish a categorical exclusion applicable to most NSF-sponsored scientific research projects under the rationale that their long-term effects "are basically speculative and unknowable in advance . . ." (45 C.F.R. § 640.3(b)). However, those regulations require preparation of at least an environmental assessment for "field work affecting the natural environment" and research projects involving "weather modification, or other techniques that may alter a local environment" (45 C.F.R. § 640.3(b) (3), (4)).

NEPA's requirements may apply to agency programs as well as individual agency actions (40 C.F.R. § 1508.18(b)(3) (pre-2020); 40 C.F.R. § 1502.4(b) (2020 revision)). A programmatic EIS could address environmental issues relating to the establishment of an SG research program and consider the developmental trajectory of the entire program. However, a programmatic EIS would be required only if federal research activities constitute a single proposal or are systematically connected (Lin, 2018).

In sum, NEPA would be of limited applicability to small-scale SG field research (Lin, 2018). NEPA applies only to activities conducted, sponsored, or authorized by the federal government. SG field research funded by entities other than the federal government would not be subject to NEPA as long as the research does not require a federal permit or rely on significant federal support. While NEPA would apply to federally funded or federally authorized SG field research, any NEPA analysis would focus on physical impacts, which are likely to be insignificant for small-scale experiments. Other concerns, such as slippery slope and moral hazard, would not be subject to NEPA analysis.

Fifteen states and the District of Columbia have enacted state environmental policy acts that are analogous to NEPA (Mandelker, 2012, § 12:2). These laws, which apply to state government actions and in some instances to local government actions such as zoning and permitting decisions, may be relevant to private SG field experiments lacking any federal involvement. Although field experimentation per se is unlikely to require a state or local permit, state permitting requirements for weather modification operations (see below) may in turn trigger state environmental policy act review.

WMRA and state analogues. SG field experiments may be subject to the reporting requirements of the federal WMRA (Hester, 2011). The WMRA requires any person engaging in weather modification activity in the United States to submit a report of such activity to the National Oceanic and Atmospheric Administration. Reports filed to date largely concern efforts to modify precipitation patterns over relatively

limited temporal and geographic scales[12] (Hester, 2013). However, the term "weather modification" encompasses "any activity performed with the intention of producing artificial changes in the composition, behavior, or dynamics of the atmosphere" (15 U.S.C. § 330(3)). Notably, this definition focuses on the intent of the actor undertaking the activity, as opposed to the nature of the activity or its effects. Activities specifically identified as subject to reporting include "[s]eeding or dispersing of any substance into clouds or fog, to alter drop size distribution, produce ice crystals or coagulation of droplets . . . or influence in any way the natural development cycle of clouds or their environment" and "[m]odifying the solar radiation exchange of the earth or clouds, through the release of gases, dusts, liquids, or aerosols into the atmosphere" (15 C.F.R. § 908.3).

Under the WMRA's definition of weather modification, the statute would be applicable to many—but not all—SG field experiments within the United States. For example, controlled release experiments in the atmosphere with even minor regional impacts would be subject to the WMRA if they are performed with the intent of changing the composition, behavior, or dynamics of the atmosphere. In contrast, outdoor experiments aimed solely at evaluating the size of droplets generated by a particular spray nozzle design may lack the requisite intent. SG research in the form of observational studies, indoor experiments, and modeling studies likewise lack such intent.

The WMRA aside, some states have their own weather modification laws that require permitting of weather modification activities and licensing of persons engaging in weather modification (Lin, 2018). These requirements are aimed at preventing weather modification activities from having detrimental effects on precipitation patterns. Although the broad definitions of weather modification under state weather modification laws may encompass SG field experiments, these laws may not apply to field experiments with limited effects. Some jurisdictions explicitly exempt research activities from permit and license requirements.

Regulatory statutes. Various regulatory statutes also could come into play, especially as the scale of SG field experimentation expands. The design and details of individual experiments will determine the applicability of specific statutes.

Several sections of the Clean Air Act (CAA) may be relevant to research in the United States involving the release of substances into the atmosphere (Hester, 2011). Under Title I of the CAA, the U.S. Environmental Protection Agency (EPA) has established ambient standards for SO_2 and particulate matter, both of which could be generated by SAI (Lin, 2018). However, the ambient standards themselves do not apply to indi-

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[12] See https://library.noaa.gov/Collections/Digital-Collections/Weather-Modification-Project-Reports.

vidual sources; rather, limits on pollution from individual stationary sources generally are established by state implementation plans designed to achieve the ambient standards. These plans focus on stationary sources, as opposed to mobile sources, and none of them explicitly addresses potential emissions from SG. SAI efforts involving aircraft may be subject to Title II of the CAA, which authorizes EPA to regulate pollution emitted from aircraft engines (42 U.S.C. § 7571). However, the release of aerosols from an aircraft by some other mechanism, such as a dedicated sprayer, would lie outside EPA's Title II authority (Hester, 2011). Similarly, EPA regulates pollution emitted from ship engines but not air emissions from ships by other mechanisms (CRS, 2009). Finally, because certain aerosols (including sulfur) can catalyze chemical reactions that deplete stratospheric ozone, Title VI of the CAA may also be relevant. Under Title VI, EPA must regulate certain ozone-depleting substances and phase out their use (42 U.S.C. § 7671a). None of the substances being considered for SAI is currently regulated under Title VI, however (Reynolds, 2019).

Research involving the discharge of substances into the ocean or U.S. waterways could trigger Ocean Dumping Act (ODA) or Clean Water Act (CWA) permitting requirements. The ODA requires a permit for the transport of material from the United States or on a U.S.-registered vessel for the purpose of dumping it into ocean waters (33 U.S.C. § 1411(a)). A permit is also required for the dumping of material transported from outside the United States into the U.S. territorial sea or into the contiguous zone to the extent that it may affect the territorial sea or the territory of the United States (33 U.S.C. § 1411(b)). Although SG field experiments might result in the release of material into ocean waters, ODA permitting requirements would not apply unless the material is transported for the purpose of ocean disposal. Existing regulations authorize the issuance of ODA dumping permits for research purposes (40 C.F.R. § 228.4(d)).

The CWA requires a permit for pollutant discharges from vessels or other point sources into "waters of the United States," including those portions of the ocean found within 3 miles of the coast (33 U.S.C. §§ 1311, 1342; Lin, 2018). Whether a CWA permit might be required for SG experiments that initially discharge materials into the air presents a close question (Hester, 2011). If these materials eventually wind up in U.S. waters, they arguably would constitute pollutant discharges subject to a permit. In a somewhat analogous context, EPA historically took the position that the otherwise legal spraying of pesticides does not require a CWA permit even if the pesticide eventually pollutes a waterbody. However, after a federal court rejected EPA's position, EPA issued a general permit to cover most pesticide applications (EPA, 2016).

SAI field experiments involving airplanes, balloons, or rockets would implicate oversight by the Federal Aviation Administration (FAA), which has jurisdiction over U.S.

airspace (49 U.S.C. § 40103; Lin, 2018). The testing of new aircraft design concepts or new aircraft equipment, for example, would require researchers to submit an application for an experimental certificate describing the purpose of the experiment, the estimated time or number of flights involved, and the areas over which the experiment would be conducted (14 C.F.R. § 21.191). Aircraft operations would be subject to air traffic control and to rules governing the location and manner of flights (Lin, 2018). In light of FAA's mission and expertise, its oversight of SAI activity would likely focus on safety rather than environmental impacts (Lin, 2018).

Tort liability. Field experiments that harm persons or property could lead to liability under several tort law theories, including negligence, strict liability, and nuisance (Hester, 2018). These causes of action are based primarily on state common law.

To prove negligence, a plaintiff must show that the defendant breached a duty of reasonable care and that the breach proximately caused harm to the plaintiff (Hester, 2018). Although most activities are judged under a negligence standard, abnormally dangerous activities are evaluated under a strict liability standard, which imposes liability on a defendant regardless of fault (Hester, 2018). It is unclear whether a negligence or strict liability standard would apply to SG field research. As a novel technology, SG might be subject to a strict liability standard. However, courts might apply a negligence standard to individual research activities that pose little hazard or that resemble research efforts outside the SG context. Under either negligence or strict liability, plaintiffs would have to demonstrate that defendants' conduct caused their harms, a task that may require distinguishing SG-related impacts from background climate variability.

Private nuisance requires demonstration of a substantial and unreasonable interference with use and enjoyment of real property. Whether an interference is unreasonable depends on the utility of the activity and the reasonable expectations of the landowner (Dobbs, 2008). Public nuisance, a claim usually limited to government plaintiffs, involves substantial and unreasonable interference with the enjoyment of a public right or public property. Many courts require plaintiffs to demonstrate that the social costs of defendants' activity outweigh its benefits (Hester, 2018; Kysar, 2012). Conceivable ways in which SG field research might interfere with the enjoyment of property or public rights include altering precipitation, reducing sunlight, or generating pollution. Nonetheless, plaintiffs asserting nuisance claims may face difficulties in proving that the SG field research activity caused their harms or in demonstrating that the costs outweigh the benefits.

Intellectual property law. Intellectual property law could influence the pace and direction of SG research (Burger and Gundlach, 2018). The patent system incentivizes in-

novation and investment in innovation by granting inventors exclusive rights over an invention for 20 years (35 U.S.C. § 154). During that time, the patent owner may use the invention, license it to others, or exclude others from using it (Chavez, 2015). However, a patent owner's exclusive control can block or limit society's access to the invention, and the existence of numerous patents in a field can increase the cost and difficulty of technology development (Chavez, 2015; Shapiro, 2001). At present, however, levels of patenting activity relating to SG appear relatively low (Reynolds et al., 2017). And under existing law, governments often possess a range of options for ensuring access to critical technologies (Reynolds et al., 2017).

International Environmental Law

Treaty Law

At present, no international agreements impose legally binding restrictions on SG research. However, various components of international law define the space in which such research might occur and express norms relevant to such research. Two treaty regimes—the United Nations (UN) Convention on Biological Diversity (CBD) and the London Convention and London Protocol (LC/LP)—have taken positions specific to geoengineering and geoengineering research.

UN Convention on Biological Diversity. The CBD's objectives are to conserve biological diversity, facilitate sustainable use of the components of biological diversity, and promote equitable sharing of the benefits arising from such use (CBD art.1). The CBD has been widely ratified, with the United States being a notable exception. Although the treaty makes no mention of SG or climate change, its governing body has issued nonbinding "decisions," or resolutions, that address geoengineering. The most pertinent resolution, issued in 2010,"[i]nvites Parties and other Governments . . . to *consider* the guidance" that includes the following measure specific to geoengineering:

> Ensure . . . in the absence of science based, global, transparent and effective control and regulatory mechanisms for geo-engineering, and in accordance with the precautionary approach and Article 14 of the Convention, that no climate-related geoengineering activities that may affect biodiversity take place, until there is an adequate scientific basis on which to justify such activities and appropriate consideration of the associated risks for the environment and biodiversity and associated social, economic and cultural impacts, with the exception of small scale scientific research studies that would be conducted in a controlled setting in accordance with Article 3 of the Convention, and only if they are justified by the need to gather specific scientific

> data and are subject to a thorough prior assessment of the potential impacts on the environment.
>
> (Report of the Tenth Meeting of the Conference of the Parties to the Convention on Biological Diversity, *Decision X/33: Biodiversity and Climate Change*, § 8(w), UNEP/CBD/ COP/10/27 (2011)).

While this provision is nonbinding, the language does suggest principles for governing outdoor SG research—and could in fact be interpreted by some parties as calling for, although not yet establishing, a moratorium on outdoor experiments. Namely, such research should be justified by the need to gather specific scientific data and subject to prior environmental assessment; furthermore, any field research beyond a limited scale should be subject to effective regulatory oversight. A subsequent resolution further "note[d] that more transdisciplinary research and sharing of knowledge among appropriate institutions is needed in order to better understand the impacts of climate-related geoengineering on biodiversity and ecosystem functions and services, socio-economic, cultural and ethical issues and regulatory options" (UNEP/CBD/COP/ DEC/XIII/14 (2016)).

London Convention/London Protocol. One other treaty regime has specifically addressed geoengineering, the London Convention and London Protocol. These agreements aim to protect the marine environment from the ocean dumping of wastes. The parties to the London Protocol have approved treaty amendments governing "marine geoengineering," although these amendments will not enter into force until they are ratified by two-thirds of the parties to the Protocol. As of October 2019, the amendments had been accepted by only 5 of the minimum of 35 states that would be needed for the amendments to enter into force (Brent et al., 2019). The amendments define marine geoengineering as "a deliberate intervention in the marine environment to manipulate natural processes, including to counteract anthropogenic climate change and/or its impacts, and that has the potential to result in deleterious effects, especially where those effects may be widespread, long lasting or severe" (Resolution LP.4(8) on the Amendment to the London Protocol to Regulate the Placement of Matter for Ocean Fertilization and Other Marine Geoengineering Activities [2013]).

The amendments forbid "the placement of matter into the sea from vessels, aircraft, platforms or other man-made structures at sea for marine geoengineering activities listed in Annex 4, unless the listing provides that the activity or the sub-category of an activity may be authorized under a permit" (Resolution LP.4(8), art. 6bis). At present, ocean fertilization is the only type of marine geoengineering listed in Annex 4. Unlisted marine geoengineering activities are implicitly allowed but could be added to Annex 4 upon a two-thirds vote of the parties to the London Protocol. Once listed,

a technique would be either prohibited or subject to a permitting regime. Parties may issue permits pursuant to an assessment framework designed to ensure that potential effects are analyzed and that health and environmental risks are avoided or minimized. MCB field research (or deployment) arguably falls within the definition of marine geoengineering and thus might be added to Annex 4, though there is some disagreement regarding whether the extraction of sea water for MCB would constitute "placement of matter into the sea" (Brent et al., 2019; Ginzky and Frost, 2014).

Below we discuss several other international agreements that are potentially relevant to SG research—including the UN Framework Convention on Climate Change (UNFCCC), the Vienna Convention for the Protection of the Ozone Layer ("Vienna Convention") and Montreal Protocol, the Convention on Long-Range Transboundary Air Pollution (CLRTAP), the Convention on the Prohibition of Military or Any Other Hostile Use of Environmental Modification Techniques (ENMOD), and the UN Convention on the Law of the Sea (UNCLOS).

UN Framework Convention on Climate Change. The UNFCCC and subsequent agreements negotiated under its auspices, including the 2015 Paris Agreement, are specifically oriented toward protecting the climate system. The UNFCCC, which boasts near-universal membership among nations, aims to "stabiliz[e] greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system" (UNFCCC, art. 2). The Paris Agreement articulates specific objectives of limiting global temperature rise "well below 2°C" and promising "efforts to limit the temperature increase to 1.5°C" (Paris, art. 2.1(a)). Neither the UNFCCC nor the Paris Agreement explicitly mentions SG. Rather, the agreements focus on reducing GHG emissions, enhancing GHG sinks, and promoting adaptation. Under the Paris Agreement, each party must "prepare, communicate, and maintain successive nationally determined contributions (NDCs)" and "pursue domestic mitigation measures with the aim of achieving the objectives of such contributions" (Paris, art. 4.2). While SG would not appear to fit the goals of reducing GHG emissions and enhancing GHG sinks, SG could contribute to limiting temperature increases, and nothing would prevent a party from reporting on SG activities in their NDCs.

Nonetheless, individual treaty provisions could be interpreted as relevant to SG research (Craik and Burns, 2019). For example, UNFCCC Article 4.1(g) requires parties to "[p]romote and cooperate in scientific, technological, technical, socio-economic and other research . . . related to the climate system and intended to further the understanding . . . regarding the causes, effects, magnitude and timing of climate change and the economic and social consequences of various response strategies."

And paragraph 49 of the "Decision Text" of the Paris Agreement calls on the Executive Committee of the Warsaw International Mechanism for Loss and Damage to "develop recommendations for integrated approaches to avert, minimize and address displacement related to the adverse impacts of climate change" (Decision 1/CP.21 Adoption of the Paris Agreement (2015)). Whether SG research would be consistent with such provisions is open to debate (Craik and Burns, 2019).

Vienna Convention and Montreal Protocol. The Vienna Convention and Montreal Protocol, which almost all nations have ratified, aim to avoid adverse modification of the stratospheric ozone layer. The Vienna Convention requires parties to "take appropriate measures . . . to protect human health and the environment against adverse effects resulting or likely to result from human activities which modify or are likely to modify the ozone layer"(Vienna Convention for the Protection of the Ozone Layer, art. 2.1 (1985)). The convention also obligates parties to undertake research on human activities and physical and chemical processes that may affect the ozone layer (Vienna, arts. 2.2, 3.1). The Montreal Protocol restricts the consumption and production of specifically listed ozone-depleting substances (Montreal Protocol on Substances that Deplete the Ozone Layer (1987)). Additional substances may be listed and subjected to control measures upon a supermajority vote (Vienna, art. 9). Injection of sulfate aerosols into the stratosphere could be subject to oversight under these treaties because they could exacerbate the ozone-depleting effect of chlorine gases already present (Tilmes et al., 2008). Parties to the Vienna Convention would have a duty to research the effects of SAI on the ozone layer and human health. To regulate substances used in SAI, the parties to the Montreal Protocol would have to add such substances to the list of regulated substances (Montreal Annex A–Annex C; Reynolds, 2018).

Convention on Long-Range Transboundary Air Pollution. The CLRTAP is a regional agreement aimed at addressing long-range transboundary air pollution, particularly as such pollution contributes to acid rain. The 51 parties to the CLRTAP include the United States, Canada, and various nations in Europe and the former Soviet Union. The agreement defines air pollution as "the introduction by man . . . of substances or energy into the air resulting in deleterious effects of such a nature as to endanger human health, harm living resources and ecosystems and material property . . . ." (CLRTAP, art. 1(a)). Under the CLRTAP, each party must report its pollution emissions and "endeavour to limit and, as far as possible, gradually reduce and prevent air pollution including long-range transboundary air pollution" (CLRTAP, arts. 2, 8). The CLRTAP also requires each party, upon request, to consult with other parties that "are actually affected by or exposed to a significant risk of long-range transboundary air pollution" originating in significant part from that party (CLRTAP, art. 5).

Several protocols to the CLRTAP establish binding obligations governing sulfate emissions.[13] The CLRTAP regime may be relevant to SAI field research involving sulfur, depending on the amount of sulfur injected into the stratosphere and its contribution to transboundary air pollution. CLRTAP nonetheless has been described as a "mismatch for climate engineering research governance" in light of its objectives and the unlikelihood that SG field tests would cause its thresholds to be exceeded (Burger and Gundlach, 2018).

Convention on the Prohibition of Military or Any Other Hostile Use of Environmental Modification Techniques. Developed in response to attempts to use weather modification as a weapon during the Vietnam War, ENMOD prohibits parties from "engag[ing] in military or any other hostile use of environmental modification techniques having widespread, long-lasting or severe effects as the means of destruction, damage or injury to any other State Party" (ENMOD, art. 1.1). The treaty defines "environmental modification techniques" as "any technique for changing—through the deliberate manipulation of natural processes—the dynamics, composition or structure of the Earth, including its biota, lithosphere, hydrosphere and atmosphere, or of outer space" (ENMOD, art. 2). Although SG falls squarely within this definition, the treaty is of limited applicability to the SG research assessed in this report in its current form. The treaty bars only "military or . . . hostile use of environmental modification techniques" and explicitly states that it "shall not hinder the use of environmental modification techniques for peaceful purposes and shall be without prejudice to the generally recognized principles and applicable rules of international law concerning such use" (ENMOD, arts. 1.1, 3.1). While ENMOD affirms parties'"right to participate in the fullest possible exchange of scientific and technological information on the use of environmental modification techniques for peaceful purposes" (ENMOD, art. 3.2), it holds minimal promise as a locus for future governance of SG research. The ENMOD parties have held only two meetings since its entry into force in 1978 (Reynolds, 2019). Moreover, unlike many of the other international agreements discussed in this chapter, ENMOD establishes no governing body or institution for implementing or expanding upon the agreement (Reynolds, 2019).

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[13] Protocol to the 1979 Convention on Long-Range Transboundary Air Pollution on the Reduction of Sulphur Emissions or Their Transboundary Fluxes by at Least 30 Per Cent, art. 3, July 8, 1985; Protocol to the 1979 Convention on Long-Range Transboundary Air Pollution on Further Reduction of Sulphur Emissions, art. 2.1, June 14, 1994; Gothenburg Protocol to Abate Acidification, Eutrophication, and Ground-Level Ozone, art. 3, Nov. 30, 1999. Specifically, the 1985 protocol mandates that parties achieve a 30 percent reduction in sulfate emissions from pre-existing levels; the 1994 protocol requires parties to "control and reduce their sulphur emissions in order to protect human health and the environment from adverse effects, in particular acidifying effects," in accordance with specified emissions limits; and the 1999 protocol sets emission limits for sulfur and other pollutants that contribute to acidification, eutrophication, and ground-level ozone. The United States is a party to the 1999 protocol, but not the 1985 and 1994 protocols.

UN Convention on the Law of the Sea. UNCLOS establishes a governance regime for the oceans that largely codifies customary international law. Ratified by more than 160 nations, but not the United States, the treaty establishes various obligations potentially relevant to marine-based SG. States have a general obligation to "protect and preserve the marine environment" (UNCLOS, art. 192). In furtherance of this obligation, states must "take . . . all measures . . . necessary to prevent, reduce and control pollution of the marine environment," including pollution "resulting from the use of technologies under their jurisdiction or control," as well as pollution "from or through the atmosphere"(UNCLOS, arts. 194.1, 196.1, 212.1). Such measures "include those necessary to protect and preserve rare or fragile ecosystems as well as the habitat of depleted, threatened or endangered species and other forms of marine life" (UNCLOS, art. 194.5). States also must monitor the risks or effects of pollution of the marine environment (UNCLOS, art. 204.1)."When [s]tates have reasonable grounds for believing that planned activities under their jurisdiction or control may cause substantial pollution of or significant and harmful changes to the marine environment," they must assess and disclose potential effects (UNCLOS, art. 206).

In addition to the foregoing, UNCLOS contains provisions specifically addressing marine scientific research. As a general matter,"[a]ll States . . . have the right to conduct marine scientific research subject to the rights and duties of other States" and "shall promote and facilitate" such research (UNCLOS, arts. 238, 239). Marine scientific research is to be "conducted exclusively for peaceful purposes,""with appropriate scientific methods and means" and in a manner consistent with relevant regulations and other legitimate uses of the oceans (UNCLOS, art. 240). Additional provisions affirm the exclusive right of coastal states to regulate, authorize, and conduct marine scientific research in their territorial sea, as well as a right to regulate, authorize, and conduct such research in their exclusive economic zone and continental shelf (UNCLOS, arts. 3, 245, 246). On the high seas, states may exercise the freedom to conduct scientific research, with due regard for the interests of other states (UNCLOS, art. 87).

UNCLOS' provisions could inform SG research in various ways (Reynolds, 2019). Its provisions on research presumably would allow legitimate and appropriate SG research. The obligation to protect the marine environment could support SG research because of its potential to protect ocean ecosystems, whether such research aims to reduce temperature globally or offer regional benefits (e.g., protecting the Great Barrier Reef). Research to assess and monitor SG's effects on the marine environment would also be encouraged. However, UNCLOS' provisions also may constrain SG research, depending on research design and effects. States' duty to ensure that activities under their jurisdiction do not harm the marine environment may limit SG research that pollutes or otherwise harms the marine environment. In addition, the fact that SG does not directly counter ocean acidification would weaken claims that SG research advances UNCLOS' objective of protecting the marine environment.

Customary International Environmental Law and General Principles

In addition to treaties, customary law also serves as a source of international environmental law. Under the conventional view, customary international law arises when there exists (i) a relatively uniform and consistent state practice regarding a particular matter and (ii) a belief among states that such practice is legally compelled (Murphy, 2006). Demonstrating these two elements can be challenging, which leads to some uncertainty regarding the precise obligations of customary international law (Bodansky, 2010). Indeed, customary international law has been described as a set of general principles whose primary significance is in influencing treaty negotiations rather than in regulating state behavior (Bodansky, 2010). Several general principles, including the obligation to prevent transboundary harm, the principle of intergenerational equity, and the precautionary principle, are potentially relevant to SG research (Flegal et al., 2019).

Under the *prevention of transboundary harm principle*, states have a responsibility not to cause significant harm to the persons, property, or environment in the territory or under the jurisdiction of other states (International Law Commission, 2001 arts. 2, 3; Trail Smelter Arbitration [U.S. v. Can.]; Weiss et al., 2016, 3 R.I.A.A. [1941]). This central obligation of customary international law does not establish an absolute duty to avoid transboundary harm, however (Hunter et al., 2015). Rather, states must act with due diligence, which may include not only substantive obligations to avoid or reduce such harm but also procedural obligations to assess the environmental impacts of planned actions on other states, provide prior and timely notification to affected states, and consult with affected states on measures to minimize or prevent significant harm (International Law Commission, 2001). SG research that could have significant transboundary impacts presumably would trigger these duties (Flegal et al., 2019).

Under the *principle of intergenerational equity*, present generations must ensure that the needs and interests of future generations are considered and safeguarded (Hunter et al., 2015). Intergenerational equity has been described in terms of each generation's duty to (i) conserve options for future generations by conserving the diversity of the natural and cultural resource base, (ii) conserve the quality of the environment by maintaining the quality of the planet so that it is passed on in no worse condition than that in which it was received, and (iii) conserve access to the use and benefit of planetary resources (United Nations, 2013; Weiss, 2019). Scientific research and development can advance intergenerational equity when it is undertaken to analyze and manage long-term threats to environmental quality (United Nations, 2013).

Climate change and SG are intergenerational in nature and raise questions about obligations to future generations. Applying the principle of intergenerational equity to SG may require a complex weighing of different risks, costs, and benefits. One could contend that preservation of the planet for future generations calls for immediate reductions in GHG emissions so that SG deployment (and research) would be unnecessary (Gardiner, 2010; Weiss, 2019). However, one could also contend that conducting SG research advances intergenerational equity by making SG potentially available to future generations and enabling the assessment of risks associated with SG deployment (Cicerone, 2006; Weiss, 2019).

The *precautionary principle*, another relevant but less well-established principle, provides that if there are threats of serious or irreversible environmental damage, lack of full scientific certainty does not excuse states from acting to prevent such damage (Rio Declaration, 1992, Principle 15; UNFCCC, art. 3.3). How the precautionary principle might apply to SG research is open to debate. In the context of climate change, the precautionary principle has typically been cited in support of action to reduce GHG emissions notwithstanding assertions of uncertainty surrounding the existence, cause, or extent of climate change (Farber, 2010). SG would not address the root causes of climate change, and the risks and uncertainties presently surrounding SG suggest that its deployment hardly represents a precautionary option. However, because SG might ameliorate the adverse effects of climate change, a precautionary approach might include SG research (Burger and Gundlach, 2018). In the context of new technologies, one commentator has proposed a "principle of reasonableness" that would complement the precautionary principle by allowing research and development to better understand the detailed implications of such technologies (Weiss, 2003).

Related to the principle of intergenerational equity is the concept of *sustainable development*, which calls for "development that meets the needs of the present without compromising the ability of future generations to meet their own needs." The concept seeks to maintain economic advancement that satisfies human needs and aspirations while protecting the natural systems that support life on Earth (United Nations World Commission on Environment and Development, 1987). The *Sustainable Development Goals* (SDGs), adopted in 2015 by the UN General Assembly, may also serve as norms for SG research. The SDGs are a core component of the 2030 Agenda for Sustainable Development, which sets forth a plan of action to end poverty, protect the planet, and promote prosperity. Several of the SDGs are potentially relevant to SG. SDG 13 calls for "urgent action to combat climate change and its impacts," including strengthening resilience and adaptive capacity to climate-related hazards and natural disasters. However, SDG 13 does not mention SG, and it acknowledges that the UNFCCC is the primary intergovernmental forum for negotiating the global response to climate change. SDG 14 calls for the conservation and sustainable use of the oceans, seas, and marine resources for sustainable development, and SDG 15 calls for the protection, restoration, and sustainable use of terrestrial ecosystems. SDG 17 seeks to "revitalize the global partnership for sustainable development," including enhancing cooperation on and access to science, technology, and innovation, and promoting the development and diffusion of environmentally sound technologies. SG research, particularly regarding its risks and impacts on human-natural systems, may be compatible with each of these SDGs. According to one analysis, however, SG deployment "could create risks for the successful delivery of more than half of all SDGs" (Honegger et al., 2018).

Damage and Liability

Liability under international law, like tort liability under domestic law, can serve as a form of governance. However, current mechanisms and principles of liability under international law are not likely to play a significant role in SG research governance.

In theory, states are generally responsible for breaches of international law, and a state may be held strictly liable for transboundary harm caused by activities within its jurisdiction or control (Sands and Peel, 2012). However, international law on liability for environmental damage is not extensively developed, and claims by one state that another state should be held liable for transboundary environmental harm are relatively rare (Hunter et al., 2015; Sands and Peel, 2012). States may be unwilling to consent to a forum for adjudicating claims, and establishing causation may prove challenging, particularly in the context of SG research (Hester, 2018).

States can incur liability under treaties or customary international law. However, relatively few international environmental agreements contain liability provisions. Under the climate change regime, the parties to the UNFCCC established the Warsaw International Mechanism for Loss and Damage to address harms associated with impacts of climate change in vulnerable developing countries (UNFCCC COP Decision 2/ CP.19; Paris, art. 8). The Warsaw Mechanism promotes cooperation and facilitation with respect to early warning systems, risk assessment, risk insurance, and the like but "does not involve or provide a basis for any liability or compensation" (Paris, art. 8; UNFCCC, COP Decision 1/CP.21 para. 51). In contrast, UNCLOS explicitly addresses liability. The agreement declares states "liable in accordance with international law" for damage caused by pollution of the marine environment (UNCLOS, art. 235). Furthermore, states are "responsible and liable . . . for damage caused by pollution of the marine environment arising out of marine scientific research undertaken by them or on their behalf" (UNCLOS, art. 263). Although customary international law recognizes that victims should be compensated for transboundary damage, there is a lack of consensus regarding state liability for such damage (Sands and Peel, 2012).

State liability aside, private parties may be civilly liable for environmental damages beyond national borders. A number of international liability regimes, implemented through domestic law and domestic courts, govern specific types of commercial activities with transboundary hazardous effects (Horton et al., 2015). However, none of these regimes applies to SG or SG research. Plaintiffs might rely instead on domestic tort law (discussed above) to impose liability and then attempt to enforce a favorable judgment in the nation where a defendant operates (Hester, 2018).

Human Rights and Environmental Law

Finally, international law on human rights also may be relevant to SG research. The existence of a human right may impose a duty on states not only to avoid actions that infringe upon those rights but also to protect and fulfill those rights (Burns, 2016). Substantive rights to life, health, and food, as well as procedural rights to information and political participation, are among the human rights recognized in the International Covenant on Economic, Social and Cultural Rights; the nonbinding Universal Declaration on Human Rights; and other international legal instruments. While environmental degradation undeniably can interfere with the enjoyment of such rights, it is not clear that such degradation necessarily constitutes a violation of human rights (United Nations, 2009).

Human rights treaties historically have not included a specific right to a safe, clean, and healthy environment (Hunter et al., 2015). Upon a request from the UN Human Rights Council to clarify human rights obligations relating to the environment, a special rapporteur proposed "Framework Principles on Human Rights and the Environment" in 2018. The framework principles, which "set out basic obligations of States under human rights law as they relate to the environment," include a declaration that states "should ensure a safe, clean, healthy and sustainable environment in order to respect, protect and fulfil human rights" and the affirmation of procedural norms regarding access to information, environmental impact assessment, participation in decision making, and access to justice (United Nations Human Rights Council, 2018).

There is increasing international recognition that climate change and responses to climate change could impact human rights (Svoboda et al., 2018b; United Nations, 2009). The preamble to the Paris Agreement encourages parties to "respect, promote and consider their respective obligations to human rights" when taking actions to address climate change, but neither it nor the main text of the agreement specifies how to implement this direction (Paris preamble recital 11). SG could adversely impact rights to food, health, water, and life (Burns, 2016). At the same time, it has been suggested that SG also could ease threats to human rights by ameliorating temperature increases (Svoboda et al., 2018b). Research that advances understanding of the potential impacts of SG on human rights could be consistent with the protection of such rights. Human rights law with respect to research generally affirms a right to enjoy the benefits of scientific research as well as protection of research subjects (Hubert, 2020).

2.5b Soft Governance

"Soft governance" refers to nonbinding norms found in codes of conduct, declarations, guidelines, and the like (Bodansky, 2010). Soft governance does not necessarily require state approval or involvement, and it can develop and adapt more rapidly than binding legal requirements (Hunter et al., 2015).

The SG research community has participated in some efforts to develop soft governance mechanisms. The 2010 Asilomar meeting, which involved physical scientists, social scientists, and experts from other disciplines, generated a report proposing five principles to guide geoengineering research (ASOC, 2010). Those principles overlap substantially with the Oxford Principles, which a small group of academics had developed to guide the research, development, and potential deployment of geoengineering (Rayner et al., 2013). While both sets of principles (discussed in Chapter 3) have remained important, they are "high-level and abstract" principles "to be interpreted and implemented in different ways, appropriate to the technology under consideration and the stage of its development, as well as the wider social context of the research" (Rayner et al., 2013). The Code of Conduct for Responsible Geoengineering Research (Hubert and Reichwein, 2015) (see Chapter 3) was developed subsequently to propose a more specific set of rules that could be followed by researchers and others.

The few explorations of SG field experiments have each adopted their own governance structures that generally reflect the principles outlined above. For example, the Stratospheric Particle Injection for Climate Engineering (SPICE) project stated an objective of helping researchers understand the wider opportunities and uncertainties of emerging technologies under the umbrella of Responsible Innovation, which looks to engage the public and stakeholders in the research and development process for emerging technologies. The governance structure took the form of a stage-gate process that presented progress to stakeholders and addressed different criteria until the issue was resolved. Ultimately, the field-trial aspect of the SPICE project was suspended, mainly due to concerns regarding patents on the technology that would have been used to disperse water droplets into the atmosphere.

Another experiment currently under development is also incorporating an ad hoc governance mechanism. The Stratospheric Controlled Perturbation Experiment (SCoPEx), at Harvard University, is not governed by a stage-gate process involving several stakeholders; instead, it appointed a search committee to evaluate the need for an advisory committee, and the search committee ultimately recommended the formation of an advisory committee. The advisory committee, working as this report is being written, is to advise the research team and Harvard administration on the following[14]:"(a) The scientific quality and importance of the proposed experiments, including scientific review and processes and standards for transparency; (b) Risks associated with the proposed research program, including environmental and social risks; (c) Effectiveness of risk management including regulatory compliance management of environmental health and safety; (d) The need, objectives and possible formats for stakeholder engagement; and (e) Other issues as deemed necessary by the Advisory Committee."

Finally, Australian governments are currently funding MCB experiments aimed at protecting the Great Barrier Reef (McDonald et al., 2019). Although participants in the project are involved in stakeholder engagement, commentators have raised questions regarding the ability of existing regulations to adequately govern these experiments (Fidelman et al., 2019; McDonald et al., 2019).

Conclusion 2.3: There is currently no coordinated or systematic governance of SG research. Although various legal mechanisms, developed primarily with other contexts in mind, could apply to some aspects of this research, these mechanisms focus primarily on concerns about physical impacts.

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[14] See https://projects.iq.harvard.edu/keutschgroup/scopex-governance. Information on the composition and work of the SCoPEx advisory committee is available at https://scopexac.com.

2.5c Lessons from Governance in Other Areas of Research

Research governance can be achieved either through arrangements with the force of law or through other less formal methods. Mandatory mechanisms, whether adopted by treaty or other kinds of international agreements, have the advantage of legal force but disadvantages such as a decreased likelihood of adoption; a greater length of time to achieve adoption; a likely absence of unanimity; and a high risk of unenforced, vague, or weak measures. Informal approaches, while easier to initiate, are disadvantaged by a lack of mandatory force (Bodansky, 2010). The following examples of efforts to govern research at the international level illustrate some of the problems with a legal approach.

- The *Treaty on Non-Proliferation of Nuclear Weapons*, negotiated from 1965 to 1968, is, in some ways, an immensely successful treaty, with 191 signatory states. Nevertheless, at least four states that were not party to the treaty produced nuclear weapons, and at least three other nations maintained, at some point, nuclear weapons development programs. The treaty's requirement that the parties seek complete nuclear disarmament has not been actively pursued by the largest nuclear powers.
- The *Biological Weapons Convention*, completed in 1972, has 183 state parties. Its effectiveness has been questioned because the Convention does not contain strong verification measures. During the 1990s a verification protocol was proposed, but, in 2001, the United States declined to sign on to a protocol and progress on a protocol ceased.
- The Council of Europe produced a *Convention for the Protection of Human Rights and Dignity of the Human Being with regard to the Application of Biology and Medicine* (the "Oviedo Convention") in 1997. It has been ratified by 29 member states, but the parties do not include some nations with advanced biological research capabilities. The Convention can only be enforced in the courts of the individual countries that have ratified it. The announcement of the birth of a cloned sheep in 1998 led to the rapid drafting and adoption of a protocol to the Oviedo convention that bans cloning of human beings, which has been ratified by 24 members of the Council of Europe.

Efforts have also been made to govern research domestically and across national lines independent of international law. Four examples of this approach are discussed below.

- Most countries that participate substantially in human subjects research follow similar laws and regulations, stemming in part from international codes from nongovernmental organizations, including the 1964 *Helsinki Declaration of the World Medical Association* (as amended over the decades) and the *International Ethical Guidelines for Health-related Research Involving Humans*, developed by the Council for International Organizations of Medical Sciences in collaboration with the World Health Organization. In addition, in 1990 the United States, the European Union, and Japan joined together in the International Council for Harmonisation of Technical Requirements for Registration of Pharmaceuticals for Human Use (ICH) to harmonize research and ethical requirements so that clinical trials in one jurisdiction will be acceptable in the others. Clinical trials conducted in other countries often follow the ICH guidelines in order to maximize the trials' international value.

- The Asilomar Conference on Recombinant DNA Molecules—hosted in 1975 by the U.S. National Academy of Sciences to convene scientists conducting or planning recombinant DNA research—adopted a set of recommendations that called for some precautions and identified different levels of risk and types of experiments (including suggestions for some experiments that should not be done). This quickly gave rise to U.S. regulations as well as a "Recombinant DNA Advisory Committee" of the National Institutes of Health (NIH). By the mid-1990s this committee had legal authority over any NIH-funded human trials of gene therapy. It is notable that committee guidance and approval have been sought even for trials not funded by NIH.
- Human embryonic stem cell research is another area in which non-legislative governance has played an important role. In 2003, the U.S. National Academies appointed a committee to propose ethical guidelines for human embryonic stem cell research. The resulting report, *Guidelines for Human Embryonic Stem Cell Research* (IOM, 2005), concluded that such research could be done ethically and offered numerous recommendations at varying levels of specificity. These guidelines have been followed almost everywhere in the world. Importantly, the International Society for Stem Cell Research (ISSCR) adopted guidelines that largely parallel the National Academies' recommendations. While ISSCR has no legal authority to regulate stem cell research, a large percentage of stem cell researchers are members of the society, and this has contributed to the guidelines' wide adoption. Discussions about the need for governance of the genomic editing of human embryos began in earnest in early 2015. These discussions led to the convening of the First International Summit on Human Genome Editing in December 2015. Reports on the topic were issued by the U.S. National Academies (February 2017), the UK's Nuffield Council (July 2018), and the German Ethics Council (May 2019). In November 2018, a Chinese scientist announced that he had edited human embryos, which were subsequently implanted and led to the birth of twin girls. This violated the National Academies and the Nuffield Council guidelines on heritable human genome editing. This failure of the scientific community to self-regulate led to redoubled efforts to prevent premature or inappropriate use of genome editing technologies, including an international commission created by the U.S. National Academies and the Royal Society and an international committee created by the World Health Organization. Both bodies were tasked with developing recommendations for additional oversight of efforts to edit the human genome.

Timely creation of a legally binding international governance regime for SG seems unlikely, except perhaps in the context of a perceived crisis stemming from the lack of such a governance regime. Customary international law also seems highly unlikely to evolve, and to be accepted, to include any nuanced governance rules. However, as is clear from the discussion above, international non-legal (i.e., informal) methods have sometimes succeeded in bringing some degree of governance to research. While it is true that most scientific research has not had the kind of direct cross-border effects of SG, in many cases, international non-legal activities were backed up by domestic law—as in human subjects research, recombinant DNA, and, to some extent, human germline genome editing. Furthermore, domestic governance efforts can be informative to policy makers developing international governance mechanisms.

Next: *3 The Decision Space: Context and Key Considerations for Solar Geoengineering Research and Research Gover...*

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