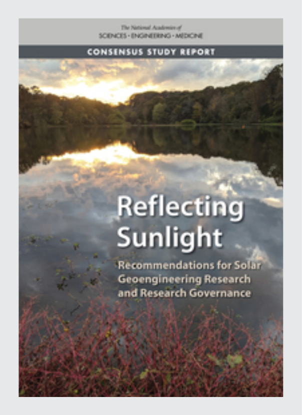

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Reflecting Sunlight

Recommendations for Solar Geoengineering Research and Research Governance

Committee on Developing a Research Agenda and Research Governance Approaches for Climate Intervention Strategies that Reflect Sunlight to Cool Earth

Board on Atmospheric Sciences and Climate

Division on Earth and Life Studies

Committee on Science, Technology, and Law

Policy and Global Affairs

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Although the reviewers listed above provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations of this report nor did they see the final draft before its release. The review of this report was overseen by **Antonio J. Busalacchi (NAE),** University Corporation for Atmospheric Research, and **Andrew R. Solow,** Woods Hole Oceanographic Institution. They were responsible for making certain that an independent examination of this report was carried out in accordance with the standards of the National Academies and that all

review comments were carefully considered. Responsibility for the final content rests entirely with the authoring committee and the National Academies.

Preface

In 2015, the National Research Council published a two-volume report that provided a technical evaluation and discussion of the impacts of geoengineering climate. One volume addressed technologies for removing carbon dioxide from the atmosphere. The other explored prospects for cooling the planet by albedo modification—increasing the reflection of solar radiation. A central conclusion from the 2015 study is that the two families of approaches for geoengineering climate differ greatly in terms of scientific understanding, technical feasibility, risks, and societal implications. In particular, understanding of prospects for and issues with albedo modification is nascent. This led that committee to recommend that "albedo modification at scales sufficient to alter climate should not be deployed at this time " (NRC, 2015, p. 9). Noting that the urgency of the climate crisis underscores the importance of understanding the full range of options, however, the committee also recommended a program of further research on albedo modification and the development of a framework for governing that research.

Since 2015, the motivation for understanding the full range of options for dealing with the climate crisis has gotten even stronger. Globally, 2015–2019 were the 5 warmest years in the instrumental record. Understanding of the link between warming and extreme heat, wildfires, drought, hurricanes, and diverse socioeconomic impacts is stronger than ever. As I write this in September 2020, my home in California's Bay Area is experiencing record-breaking temperatures and has been blanketed with wildfire smoke for more than 3 weeks. But despite overwhelming evidence that the climate crisis is real and pressing, emissions of greenhouse gases continue to increase, with global emissions of fossil carbon dioxide rising 10.8 percent from 2010 through 2019. The total for 2020 is on track to decrease in response to decreased economic activity related to the COVID-19 pandemic. The pandemic is thus providing frustrating confirmation of the fact that the world has made little progress in separating economic activity from carbon dioxide emissions.

The creation of this study committee is one response to the need for understanding the full range of options for dealing with the climate crisis. Its mandate flows directly from the recommendations of the 2015 report but with an urgency reinforced by the world's slow progress on climate. The undertaking of this report should not, however, be interpreted as an indication of giving up on decarbonization. Rapidly reducing emissions of carbon dioxide and other greenhouse gases remains a top priority, as explicitly recommended in the 2015 report. Throughout the committee's discussions, the focus was always on evaluating whether and how, in the context of a global emphasis on emissions reductions and carbon dioxide removal, other approaches might be explored.

The committee that carried out this study was remarkably diverse. With expertise ranging from atmospheric chemistry to philosophy and experiences ranging from space-based and airborne measurement campaigns to global climate negotiations, all of us needed to make real investments in stepping outside our communities and learning the language and perspectives of colleagues from very different backgrounds. Committee members arrived with a wide array of thoughts not only about the topic but also about the best path forward for building knowledge. Often, there was as much discussion about who needs to be in the conversation as there was about the design and oversight of a research program. I greatly admire the willingness of every member of the committee to explain and defend but also challenge their own perspectives.

Chris Field, *Chair*

Dedication

This report is dedicated to Paul J. Crutzen (1933-2021) and Steve Rayner (1953–2020).

Paul Crutzen and Steve Rayner were pioneering researchers, widely recognized for diverse contributions. Both made foundational contributions to solar geoengineering scholarship.

Paul Crutzen was, more than anything, a student of human impacts on Earth. He was a meteorologist best known for his research on stratospheric ozone depletion, work that earned him the 1995 Nobel Prize in Chemistry. Crutzen's coining of the term "Anthropocene" underscores the focus of his scholarship on impacts. His 2006 essay on solar geoengineering set the stage for future discussions in stark, memorable terms, laying out the risks from climate disruption, the challenges of decarbonization, and the pros and cons of solar geoengineering.

Steve Rayner, who called himself an "undisciplined" scholar, made major contributions to the understanding of how science and technology shape the relationship between societies and nature. Much of his focus was on the social science of addressing climate change. Deeply interested in the role of science in governance and the governance of science, Rayner was a strong proponent of ambitious action on climate but a harsh critic of the Kyoto Protocol. He established much of the framework for thinking about governance of solar geoengineering, especially through his role as lead author of the Oxford Principles for Geoengineering Governance.

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Summary

Anthropogenic climate change is creating impacts that are widespread and severe—and in many cases irreversible—for individuals, communities, economies, and ecosystems around the world. Without decisive action and rapid stabilization of global temperature, risks from a changing climate will increase in the future, with potentially catastrophic consequences. Limiting future warming to substantially less than 2°C above preindustrial levels requires dramatic decreases in the emissions of all greenhouse gases (GHGs) from human activity, with net emissions of carbon dioxide (CO_2) falling to zero in the second half of the 21st century. The potential to rapidly decrease GHG emissions is real, but progress in realizing that potential is insufficient, and global GHG emissions continue at very high levels. In light of these urgent concerns and limited progress with solutions, it is important to have a comprehensive understanding of the feasibility and potential risks and benefits—and consequences for diverse stakeholders—of the wide range of possible policy responses to climate change.

Meeting the challenge of climate change requires a portfolio of options. The centerpiece of this portfolio should be reducing GHG emissions, removing and reliably sequestering carbon from the atmosphere, and pursuing adaptation to climate change impacts that have already occurred or will occur in the future. Concerns that these three options together are not being pursued at the level or pace needed to avoid the worst consequences of climate change—or that even if vigorously pursued will not be sufficient to avoid the worst consequences—have led some to suggest the value of exploring additional response strategies. This includes solar geoengineering (SG),[1] which refers to attempts to moderate warming by increasing the amount of sunlight that the atmosphere reflects back to space or by reducing the trapping of outgoing thermal radiation (see Box S.1 and Figure S.1). To be effective, these SG strategies (like all climate change response efforts) would need to be continuously maintained for very long periods of time.

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[1] See Box 1.1 for a discussion of the committee's consideration of terminology and rationale for using the term "solar geoengineering" for this report. Many other types of climate intervention strategies have been proposed by investigators around the world—including numerous ways to alter the reflectivity (albedo) of Earth's land, ocean, and ice surfaces. This particular study focuses specifically on atmospheric-based interventions—both because these strategies are a source of growing research interest and because they pose particularly large governance challenges, given the inherently transboundary, global nature of such interventions.

BOX S.1
Solar Geoengineering Strategies Considered in This Study[a]

Stratospheric Aerosol Injection (SAI) is a strategy for increasing the number of small reflective particles (aerosols) in the stratosphere in order to increase the reflection of incoming sunlight.

Marine Cloud Brightening (MCB) is a strategy for adding particles to the lower atmosphere (near the surface) in order to increase the reflectivity of low-lying clouds over particular regions of the oceans.

Cirrus Cloud Thinning (CCT) is a strategy for modifying the properties of high-altitude ice clouds, increasing the atmosphere's transparency to outgoing thermal radiation.[b]

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[a] A wide variety of proposed intervention strategies can be labeled as "geoengineering" (including, for instance, strategies to place reflective material above Earth's atmosphere, strategies to directly alter the reflectivity of Earth's land, sea, and ice surfaces, and strategies to remove CO_2 from the atmosphere [also referred to as "negative emission strategies"]). This study was designed to focus specifically on the set of atmospheric-based strategies described below.

[b] Because CCT modifies thermal (infrared) radiation, it is technically not "solar" geoengineering.

The available research indicates that SG could reduce surface temperatures and potentially ameliorate some risks posed by climate change (e.g., to avoid crossing critical climate "tipping points"; to reduce harmful impacts of weather extremes). Yet these interventions could also introduce an array of potential new risks, for instance, related to critical atmospheric processes (e.g., loss of stratospheric ozone); important aspects of regional climate (e.g., behavior of the Indian monsoon); or numerous interacting environmental, social, political, and economic factors that can interact in complex, potentially unknowable ways. Predicting and attributing some types of risks, such as the occurrence of and impacts from extreme weather events, will be particularly challenging in the face of significant natural variability. In addition to the concerns about specific harmful impacts, some objections to SG are based on more general ethical concerns, such as the controllability and ownership of the technologies, the lack of agency by those who may be affected by these technologies, and path dependencies that may shape the overall climate change research portfolio.

SG could potentially offer an additional strategy for responding to climate change but is not a substitute for reducing GHG emissions. This is in part because SG

- does not address the underlying driver of climate change (increasing GHG concentrations in the atmosphere) or the key impacts of rising atmospheric CO_2 such as ocean acidification;

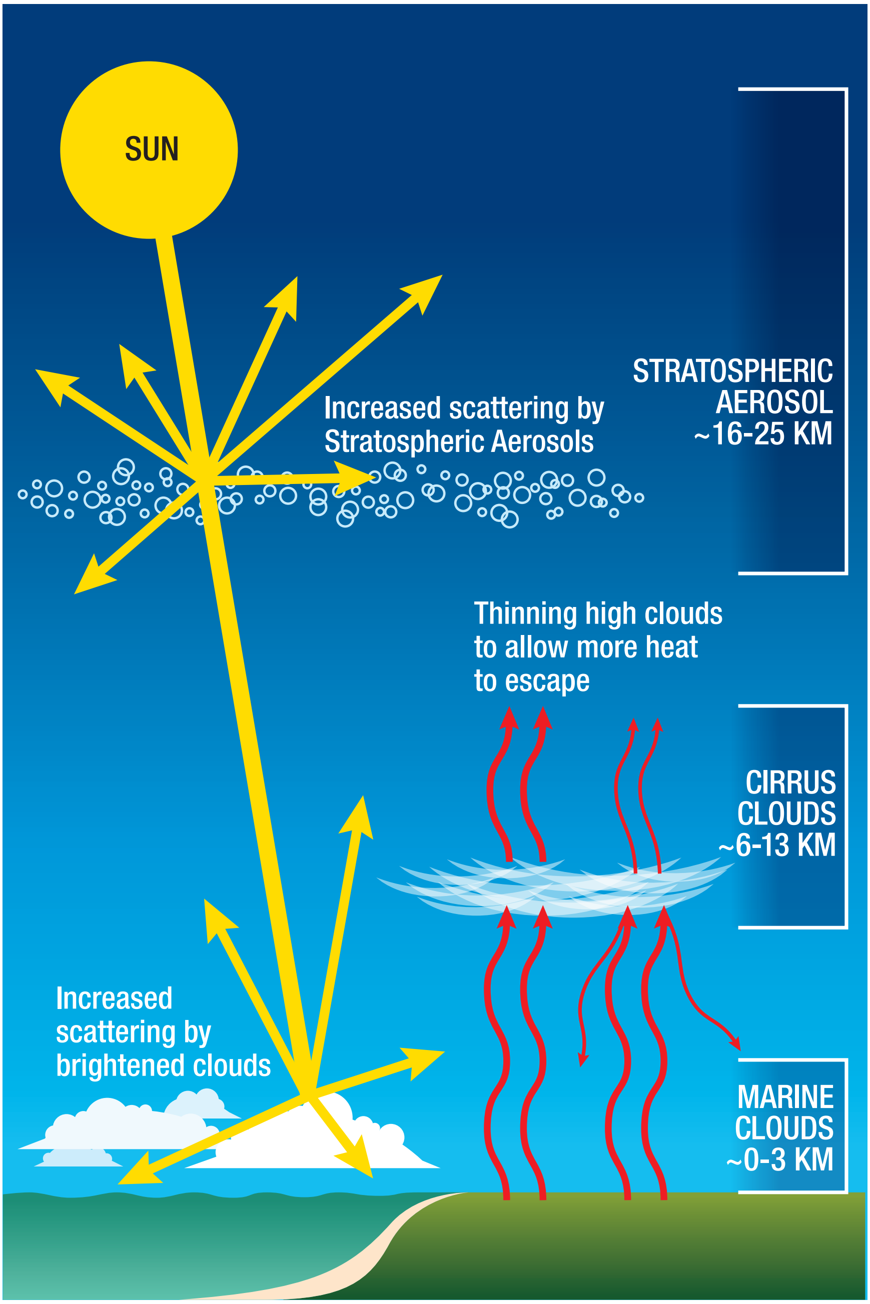

FIGURE S.1 Illustration of the basic mechanisms involved in Stratospheric Aerosol Injection (SAI), Marine Cloud Brightening (MCB), and Cirrus Cloud Thinning (CCT).

- raises concerns about new risks, uncertainties, and unintended impacts on natural ecosystems, agriculture, human health, and other critical areas of concern for society;
- cannot provide a reliable means to restore global or regional climate to some desired prior state; and
- entails unacceptable risk of catastrophically rapid warming if the intervention were ever terminated (if it were used to offset a large amount of warming without simultaneously deploying measures to reduce GHG emissions).

The National Research Council report *Climate Intervention: Reflecting Sunlight to Cool Earth* (NRC, 2015) reviewed the state of the science and provided high-level findings and recommendations regarding SG methods. This current study was tasked to update the 2015 assessment of the state of understanding and to provide recommendations for how to establish a research program, what to encompass in the research agenda, and what mechanisms to employ for governing this research (see Appendix A for the full Statement of Task). This report draws upon input from numerous experts and stakeholders invited to participate in committee meetings, workshops, and webinars (see Appendix B), as well as a review of the literature and extensive deliberations among the authoring committee.

CURRENT LANDSCAPE FOR SOLAR GEOENGINEERING RESEARCH AND RESEARCH GOVERNANCE

Understanding of some important questions about SG has advanced as a result of research conducted to date, but, at present, this state of understanding remains limited. For instance, with regard to our understanding of the efficacy and impacts of the different SG strategies considered herein, existing physical science research suggests the following:

- **SAI.** There is substantial modeling and empirical evidence (using volcanic eruptions as a natural analog) that SAI can induce cooling at a global scale, but large uncertainties remain regarding the cooling potential with injection amount, location, and type and regarding the effects of an increased aerosol burden on atmospheric chemistry, transport, and resulting regional and local effects on climate; these contribute to uncertainty in climate response and resulting impacts around the world.
- **MCB.** Research to date has made clear that adding aerosols to marine clouds can increase cloud reflectivity in some circumstances, and this phenomenon is commonly observed in studies of ship tracks. However, our limited under-

standing of aerosol/cloud interactions leads to large uncertainty regarding where and by how much cloud albedo can be modified and whether feedback processes will mask or amplify some of the effects. The key processes occur at scales too small to include directly in global climate models, and these process uncertainties will need to be reduced in order to develop reliable large-scale climate impact projections.

- **CCT.** The efficacy of CCT is currently unknown due to very limited understanding of cirrus cloud properties and the microphysical processes determining how cirrus may be altered. The few existing climate model simulations of CCT have yielded contradictory results because of these uncertainties.

SG research to date is ad hoc and fragmented, with substantial knowledge gaps and uncertainties in many critical areas. There is a need for greater transdisciplinary integration in research, linking physical, social, and ethical dimensions, and inclusion of robust public engagement. There is also a need to expand demographic diversity and inclusiveness among the research community itself.

Research to understand the potential magnitude and distribution of SG impacts—on ecosystems, human health, political and economic systems, and other issues of societal concern—is in a particularly nascent state. Studies published to date do not provide a sufficient basis for supporting informed decisions. The vast majority of research in the natural sciences has focused on climate modeling studies, with large uncertainties in how well climate models can represent some key processes. Social sciences research has been a mix of theoretical and empirical studies, with limited diversity in the participants engaged.

There is currently no coordinated or systematic governance of SG research. Various legal mechanisms developed primarily with other contexts in mind could apply to some aspects of this research, but these mechanisms focus only on concerns about physical impacts. The fragmented state of this research and research governance landscape is a barrier to the effective advancement of knowledge and the associated reduction of uncertainties.

THE CONTEXT AND KEY CONSIDERATION FOR SOLAR GEOENGINEERING RESEARCH

A range of intertwined scientific, societal, and governance issues makes the SG decision space particularly complex, similar in some respects to other emerging technologies (e.g., nanotechnology, synthetic biology, artificial intelligence, robotics, or autonomous vehicles). Factors such as uncertainty in the scope and magnitude of the approaches under consideration; the lack of social consensus around whether and how to pursue SG research; the relationship with other climate response strategies; and the global, intergenerational dimensions of SG make these emerging technologies challenging to consider.

Knowledge gained from a transdisciplinary SG research program will be critical for informing climate change response strategies, and evidence either in favor or disfavor of SG deployment could have profound value. Such knowledge could be time-critical for policy makers especially if there were intense public or political pressure for a dramatic climate action, or if SG were deployed in the absence of broad international cooperation and safeguards. The pursuit of an SG research program also brings potential risks—for instance, a program could be used as a rationale to undermine efforts to reduce GHG emissions, to legitimize SG as a response to climate change, or to create a community invested in moving toward deployment.

In designing a research program, it is important to take into consideration that research, technology development, and governance are often path dependent. Early decisions about how to structure and govern SG research may create momentum that shapes future research, development, and governance. Commitments to transparency, justice, and broad engagement in the design and implementation of research will facilitate institutionalization of these values and practices going forward.

A principal goal of any research program should be to better characterize and reduce scientific and societal uncertainties concerning the benefits and risks of SG deployment (relative to global warming in the absence of SG). However, there are limits on the level of uncertainty reduction that can be expected, and it is possible that additional research may expand particular uncertainties or reveal new uncertainties, especially for complex interacting factors such as high-resolution spatial patterns of impacts, indirect effects, socioeconomic and political or institutional responses over multidecadal timescales, and attribution for climate- and weather-related extremes. It is also important to recognize that research cannot resolve differences in fundamental values or worldviews among individuals or countries (e.g., regarding what level of certainty is sufficient for making decisions) and that most decision-making processes incorporate many considerations beyond just scientific research results.

Earlier analyses converge on several salient principles for SG research, notably, calling for research and research governance approaches that are

- in the interest of advancing the public good;
- aimed at advancing knowledge while taking into account societal norms and perspectives;
- coordinated and cooperative;

- adaptive and subject to ongoing assessment, check-points, and, if needed, exit ramps;
- inclusive and responsive, including engagement by diverse publics, stakeholders, and governments; and
- fair, equitable, and transparent.

In order to advance these principles, it is important to have a research program that is transdisciplinary, international, and diverse with respect to disciplines and methods, researchers, countries, and perspectives represented and to have research governance strategies that aim to build trust and legitimacy.

PROPOSED FRAMEWORK AND APPROACH FOR SOLAR GEOENGINEERING RESEARCH AND RESEARCH GOVERNANCE

An organized research program can help build the foundation of scientific insights and information that will help decision makers and stakeholders faced with choices about possible future implementation of SG. It is important, however, that such a program ensures that the information developed is as robust as possible, with significant attention to meaningful inclusivity and strong governance strategies. To this end, the committee envisions an integrated framework, illustrated in Figure S.2, that would enable research governance and research activities to evolve hand-in-hand, with ongoing mechanisms for stakeholder engagement and input. This engagement, combined with periodic programmatic assessments, could allow a research program to be responsive to new findings and developments that arise as the program and the knowledge base evolve.

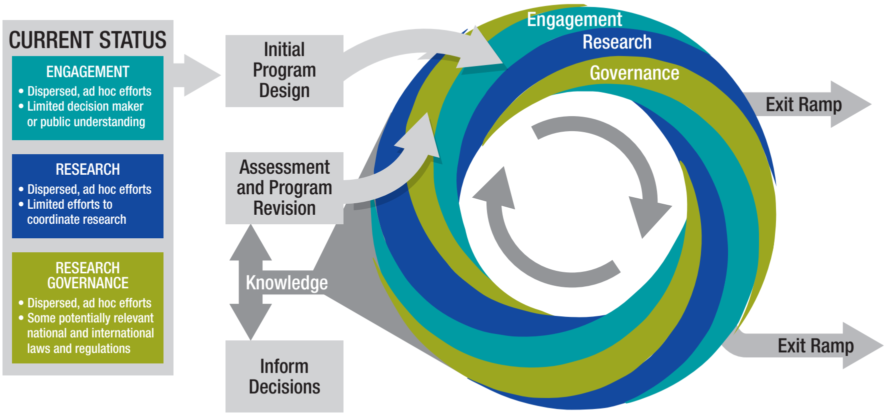

FIGURE S.2 Schematic of SG research and research governance environment.

The stepwise, iterative nature of this framework is paramount. Given the many complex features of SG, business-as-usual pathways for establishing a research program will not suffice. Understanding of how to design a robust program that meets all the principles and goals recommended herein is in a nascent state; thus, a research program needs to be sufficiently flexible to allow for improvements and adjustments as understanding grows. The committee offers suggestions for the rough contours of a program but at the same time suggests that expanding engagement with stakeholders around the world will help fill gaps in understanding and perspective.

The committee approached SG research design and coordination from the starting point of efforts within the United States, a choice based largely on practical considerations. Operationally, research agencies of the U.S. federal government already have extensive experience supporting global change research and coordinating that research across agencies; many (although not all) features of SG research can fit into the framework for existing global change research.

Recommendation 4.1:[a] The United States should implement a robust portfolio of climate mitigation and adaptation. In addition, given the urgency of climate change concerns and the need for a full understanding of possible response options, the U.S. federal government should establish—in coordination with other countries—a transdisciplinary, solar geoengineering research program. This program should be a minor part of the overall U.S. research program related to responding to climate change. The program should focus on developing policy-relevant knowledge, rather than advancing a path for deployment, and should be subject to robust governance. The program should

- **advance knowledge relevant to decision making, including design of future research efforts;**
- **ensure transparency, disciplinary balance, and public and stakeholder engagement;**
- **coordinate research across federal agencies and with research outside the U.S. federal government; and**
- **limit research on technology with direct applicability for deployment to early-phase, fundamental research.**

The program should, from the outset, prioritize development of international coordination and co-development of research with other countries, in line with the governance recommendations in Chapter 5 (especially Recommendations 5.1q, 5.1r, and 5.1s).[b]

The program should establish robust mechanisms for inputs from civil society and other key stakeholders in the design of the research program, as well as promote their engagement in relevant program components. Key stakeholders include climate-vulnerable communities and underrepresented groups, including from indigenous populations and the Global South.[c]

The program and its outcomes should be regularly reviewed and assessed by a diverse, inclusive panel of experts and stakeholders (including consultation with international counterparts) to determine whether continued research is justified and, if so, how goals and priorities should be updated.

"Exit ramps" (i.e., criteria and protocols for terminating research programs or areas) should be an explicit part of the program, with mechanisms to terminate a research activity, for example, if it is deemed to pose unacceptable physical, social, geopolitical, or environmental risks or if research indicates clearly that a particular SG technique is not likely to work.

[a] The first digit in a recommendation number refers to the report chapter in which it is presented.

[b] This refers to the Chapter 5 recommendations on (q) promotion of international cooperation and co-development on research teams, (r) promotion of international cooperation among national scientific agencies, and (s) voluntary coordination and cooperation by countries and non-state actors.

[c] In this report, the term Global South refers to populations from countries that have been historically underrepresented in global decision making.

SG research and research governance efforts to date have been ad hoc and dispersed. There would be significant value in pursuing more active integration across key research areas—such as modeling, observations, process studies, social and economic studies, and scenario designs—to ensure that research being conducted informs and is informed by other research as efficiently as possible. The United States does not currently have a coordinated federal approach to SG research. Building an effective, transdisciplinary research program will require coordination across multiple agencies, national laboratories, and cooperative institutes. The U.S. Global Change Research Program (USGCRP), charged with coordinating federal global change research across the federal science agencies, is the most logical entity for orchestrating an SG research program.

Recommendation 4.2: USGCRP should be tasked to provide coordination and transparent oversight of the research program, addressing roles including but not limited to the following:

- **Guiding the development and coordination of complementary research activities across the relevant federal agencies and advancing the research elements that are best aligned with each agency's mission and capabilities;**
- **Integrating existing agency assets, coordinating and tracking budget allocations, and harmonizing future budget requests;**
- **Overseeing coordinated research solicitations that foster interdisciplinary and transdisciplinary knowledge, relationships, and solutions, across all relevant disciplines, including the humanities, social sciences, and natural sciences;**
- **Maintaining an active database of all solar geoengineering research activities, in particular activities related to outdoor experimentation, and ensuring that this information is made publicly available;**
- **Ensuring rigorous peer review of all research proposed under the program;**
- **Periodically assessing progress and refining program goals and research priorities;**
- **Ensuring that all of the results from (and data sources developed through) federally supported research are publicly available, preferably at zero cost;**
- **Advancing opportunities for meaningful public engagement within and beyond the United States and pathways for this engagement to help inform and shape the research program;**
- **Connecting to and coordinating with relevant SG programs and activities outside the U.S. federal government; and**
- **Ensuring systematic support for the full range of research topics that are critical for advancing understanding of SG (see Chapter 6).**

ROBUST GOVERNANCE FOR SOLAR GEOENGINEERING RESEARCH

The goals of research governance include advancing and coordinating appropriate research, facilitating inclusive and equitable public and stakeholder engagement, and addressing physical risks together with social, ethical, and legal concerns. Table S.1 provides an overview of the governance mechanisms discussed in Chapter 5 of this report, goals and/or principles that they foster, and actors for the chapter's governance recommendations.

TABLE S.1 Governance Mechanisms Discussed in This Report

Governance Mechanism	Goals/Principles Served by This Mechanism	Relevant Recommendations	Actor(s) Discussed in the Report
code of conduct	responsible science, effective practices	5.1a, 5.1b, 5.1c	researchers, funders of research, national institutions
registry	transparency, information sharing	5.1d, 5.1e, 5.1p	nations, researchers, funders of research, scientific publishers, appropriate international body
data sharing	transparency, information sharing	5.1j, 51.k	researchers, funders of research, publishers
assessments and reviews	risk assessment, impact assessment, strengthen science, transparency, public engagement	5.1f, 5.1g, 5.1h, 5.1o	nations, funders of research, appropriate UN body or bodies
permitting	transparency, oversight	5.1i	nations
intellectual property	information sharing	5.1l	researchers
participation and stakeholder engagement	inclusivity, public engagement, transparency	5.1m, 5.1n, 5.1t, 5.1u	individuals, institutions, nations, researchers, funders of research, appropriate international and regional governance bodies
international cooperation and co-development on research teams	coordination of research, joint research projects/programs	5.1q	funders of research, researchers
international cooperation among national scientific agencies	coordination of research, information sharing, joint research projects/programs	5.1r	science agencies
international information sharing and cooperation on SG research and research governance	coordination of research, information sharing, transparency, participation, and public engagement	5.1s	coalition of state and non-state actors
international anticipatory governance expert committee	risk assessment, effective practices, conflict resolution	5.1v	UN body or other international institution

Existing U.S. laws and regulations are potentially relevant to SG research but were not crafted with SG research in mind. Laboratory and modeling studies generally would not trigger the application of existing environmental laws. The application of environmental statutes to SG field research would depend on the nature of the research, its location, and the materials used and released. Tort law serves as another potential mechanism for governance of research. For any of these mechanisms, the focus is on physical impacts, not broader social or ethical concerns that frequently surround SG research. Current international law provides a general framework, but it does not explicitly promote, prohibit, or significantly limit SG research; nor does it provide a system of required or recommended research transparency or reporting mechanisms. Some existing international conventions and agreements have explicitly attempted to address geoengineering or could in principle form part of a global system of international SG governance.

This report provides recommendations related to the governance mechanisms identified in Table S.1, many of which could be adopted at both national and international levels. However, it is arguably the case that international governance should not begin with current treaty bodies. With a few important exceptions, global agreements have tended to evolve out of domestic laws and regulations, which currently do not exist for SG. Additionally, attempts at international governance, especially on emerging issues, must confront the reality that achieving multilateral consensus is difficult and that initial multilateral agreements are often weak. At the same time, however, international cooperation among researchers in different countries can still develop in the absence of formal global research governance, providing valuable conduits for information sharing and cooperation.

Simultaneous domestic and international efforts may increase the effectiveness and likelihood of achieving meaningful governance. Governance mechanisms and principles developed domestically can help inform policy makers developing international architectures; in turn, international governance can help reinforce domestic efforts and create expectations of stronger domestic enforcement. Unless and until robust international research governance emerges, it is incumbent on any country where SG research is being conducted to create mechanisms and institutions to govern this work. While international governance practices and institutions ideally should be created as soon as possible, in reality, such mechanisms may emerge only after responsibility has been embraced at the national level and there is commitment by more countries to engage with research, deter unsafe research activities, and regulate activities with potentially significant transboundary impacts.

Recommendation 5.1: A U.S. national solar geoengineering research program should operate under robust research governance and support the development or designation of an international governance mechanism. Important elements of research governance include a research code of conduct, a public registry for research, regular program assessment and review processes, permitting systems for outdoor experiments, guidance on intellectual property, inclusive public and stakeholder engagement processes, mechanisms for advancing international information sharing and collaboration (within research teams and among national scientific agencies), and establishment of an expert committee to advance discussions about international governance needs and strategies.

AN INTEGRATED AGENDA FOR SOLAR GEOENGINEERING RESEARCH

SG research encompasses a diverse array of topics, each involving multiple avenues of investigation. The boundaries between these different research "clusters" are often blurred, with many questions that cut across different types of research. The committee found it useful to organize these research needs under three broad categories:

- **Context and Goals for SG Research.** This category encompasses studies that help better characterize the context for SG research, development, and possible deployment—with the aim of better understanding the evolving "decision space" for these activities. It includes efforts to clarify the range of possible goals for an SG program, to understand how these goals shape research priorities, to guide development of modeling scenarios, and to identify key considerations for decision making. This area of research will advance exploration of whether and how SG can be developed to generate broadly beneficial outcomes and how to build the capacity needed for countries to engage meaningfully in SG research and research governance.
- **Impacts and Technical Dimensions.** This category encompasses research to understand the technical feasibility of using different SG strategies to achieve regional-to-global-scale cooling, including chemistry and microphysics research to understand the properties of injected reflective particles and their interactions with clouds and other atmospheric processes; and it

includes research to understand the possible outcomes for other key climatic variables (e.g., precipitation or wind patterns) and subsequent impacts on human health and numerous ecological and societal systems. It also includes engineering studies of the technical requirements for different SG technologies and research to advance critical monitoring and attribution capabilities.

- **Social Dimensions.** This category encompasses a wide array of research exploring how to better understand public perceptions of SG research and its possible future deployment; how to fairly govern and effectively engage various publics and stakeholders in SG research, development, and deployment decisions; how to approach domestic and international conflict and cooperation in the SG arena; and how to integrate justice, ethics, and equity considerations.

These diverse research areas need to be investigated in an integrated and interactive manner (see Figure S.3). The proposed research needs vary considerably among the different clusters, reflecting the fact that some research topics are more nascent than others and that there are inherent variations in how different types of research are conducted. The research priorities range from computer modeling and laboratory and field studies to quantitative and qualitative social science investigations—and thus the nature of the steps forward differ accordingly.

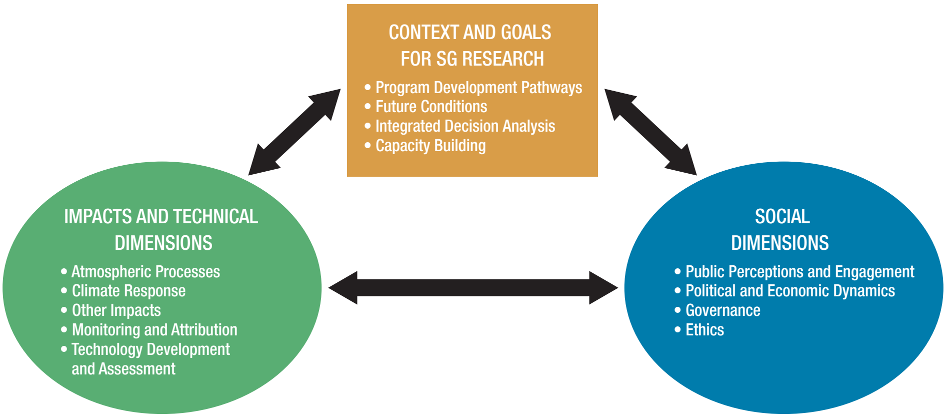

FIGURE S.3 Three broad categories and 13 research clusters in the proposed research agenda.

Recommendation 6.1: The agenda for the SG research program should encompass three broad, interconnected areas that address: (i) the context and goals for SG research, (ii) the impacts and technical dimensions, and (iii) the social dimensions. Under these broad categories, the following are recommended as key research clusters to pursue:

Context and Goals for SG Research

- **Program Development Pathways.** Designing an SG research program to maximize the prospects for broadly beneficial outcomes.
- **Future Conditions.** Exploring the range of future conditions under which SG-related decisions will be made.
- **Integrated Decision Analysis.** Understanding implications of, and strategies to address, persistent uncertainties that affect decision making related to SG.
- **Capacity Building.** Developing the capacities needed for all countries to engage meaningfully with SG research and research governance activities.

Impacts and Technical Dimensions

- **Atmospheric Processes.** Understanding chemical and physical mechanisms that determine how addition of materials to the atmosphere alters the reflection and transmission of atmospheric radiation.
- **Climate Response.** Assessing how different SG approaches would affect key climate outcomes.
- **Other Impacts.** Assessing the potential environmental and societal impacts of SG intervention strategies.
- **Monitoring and Attribution.** Designing an observational system (and understanding its limitations) for detection, monitoring, and attribution of SG deployment and impacts.
- **Technology Development and Assessment.** Addressing the science and engineering issues related to hardware, materials, and infrastructure underlying SG research.

Social Dimensions

- **Public Perceptions and Engagement.** Understanding public perceptions of SG and strategies for inclusive, meaningful societal engagement, and how to incorporate these insights into a broader research program.
- **Political and Economic Dynamics.** Exploring the implications of SG for national and international relations and related incentive structures.
- **Governance.** Developing effective, adaptive processes and institutions to govern SG activities.
- **Ethics.** Incorporating ethics and justice considerations for current and future generations into SG research and research governance.

CONSIDERATIONS FOR DELIBERATE OUTDOOR EXPERIMENTS

Limited outdoor experimentation could help advance the study of certain core atmospheric processes that are critical for understanding SG. Such activities, however, are controversial, posing significant potential for public concerns and objections. It is the committee's judgment that, subject to appropriate governance and oversight, outdoor experimentation could feasibly be pursued in a balanced manner that is sufficient in scale to acquire critical observations not available by other means but that is small enough in scale to limit impacts.

The committee considered how to set outdoor experimentation thresholds that address both the impacts of the potential perturbation on the climate and the impacts of the test materials on the environment. The recommended thresholds are intended to err on the conservative side—for instance, limiting the amount of material emitted per experiment to significantly less than other commonly accepted anthropogenic emissions to the atmosphere (e.g., from fireworks or commercial aircraft). Experiments that meet the proposed limitations would be considered on a case-by-case basis, in light of relevance to open questions, expected benefits of the study outcomes, and timing relative to other steps—and subject to approval based on the governance guidelines adopted by the larger SG program.

Recommendation 6.2: Deliberate outdoor experiments that involve releasing substances into the atmosphere should be considered only when they can provide critical observations not already available and not likely to become available through laboratory studies, modeling, and experiments of opportunity (e.g., observing volcanic eruptions, rocket plumes, or ship tracks). All outdoor experiments involving the release of substances into the atmosphere should be subject to the governance established pursuant to the Chapter 5 recommendations, including a permitting system (5.1i) and impact assessment (5.1h).

In addition, any outdoor substance releases should be limited to a quantity of material at least two orders of magnitude smaller than the quantity that could cause detectable changes in global mean temperature or adverse environmental effects (see Recommendations 6.2a and 6.2b for details of what these limitations mean in practice). These limitations should apply for at least the next 5 years and then be revisited and revised if needed, based on program review guidance from a diverse and inclusive panel of experts and stakeholders, as discussed in Recommentation 4.1.

FUNDING CONSIDERATIONS FOR SOLAR GEOENGINEERING RESEARCH

Implementing the recommended research and research governance will require dedicated resources. To help inform planning for a national SG research program, the committee offers a set of general guidelines for shaping the budget:

- Funding for SG research should not shift the focus from other important global change research, and it should recognize the risk of exacerbating concerns about a slippery slope toward deployment. These guidelines imply that the near-term budget for SG research should be small relative to the overall investment in global change research.
- The research program should support equitably all of the research clusters discussed in this chapter from the outset.
- The budget should be able to accommodate major field campaigns, should proposals for such campaigns meet other requirements outlined in **Recommendation 6.2.**
- A substantial fraction of the research program should be dynamically allocated in order to allow the research program to flexibly adapt as learning proceeds.
- Research funding should be accompanied by support for implementing research governance and public engagement.

The committee suggests that a reasonable initial investment in SG research is in the range of $100–200 million total over 5 years. A research program of this size would be sufficient to advance all the research topics identified in **Recommendation 6.1** but would still represent a small fraction of the national budget for climate change research. The budget for this research program would start small and increase over time, allowing for a thoughtful process of building capacity, adapting plans based on new information, and developing a research community over time.

In addition to funding research itself, support is needed for implementing robust research governance at national and international scales and for public engagement. The committee suggests as a general rule of thumb that these governance and engagement efforts be supported at approximately 20 percent of the level of the total research program support—an investment that would scale with the overall size of the research program.

CONCLUDING THOUGHTS

Based on the evidence available to date, there are indications that SG has the potential to lower Earth's surface temperature. But there are also indications from research to date that SG could have unintended negative consequences, for example, providing a rationale to alter GHG mitigation commitments, or consequences for society and ecosystems that arise from unfavorable changes in rainfall or temperature extremes. Much of the discomfort about an SG research program relates to the concern that even early results of the research might serve as a rationale to narrow the range of options going forward and that promising findings could increase pressure for deployment.

For an SG research program to be truly effective, it will need to be structured to minimize the risk that findings from a single discipline, a few studies, or a small slice of the research agenda will drive pressure for or against deployment. In particular, this will require a research program that, from the outset, examines not only the atmospheric effects of SG but also the ecosystem, and economic, political, and ethical implications. It will require a research program and culture without bias or advocacy for any particular outcome, with equal consideration of the factors that make SG either an unattractive or an attractive option. Designing such a program will require a deep commitment to exploring the full range of possible effects, avoiding the temptation to classify indirect effects as secondary or unimportant, and managing adaptively so that the program is shaped by ongoing discoveries.

CHAPTER ONE

Introduction

Climate change is a defining challenge of the 21st century. Since the beginning of the industrial revolution, Earth's average surface temperature has warmed by more than 1°C. This warming has already resulted in impacts on every continent and in the oceans. Observed impacts range from more frequent heat waves to increased coastal flooding associated with rising sea level (Herring et al., 2019; IPCC, 2014b). Warming temperatures are changing the distribution and composition of ecosystems, shifting cropping seasons and cultivars, and causing intensified conflicts over water resources. In the oceans, the warming and increased acidification caused by rising carbon dioxide (CO_2) levels is damaging coral reefs, with Australia's Great Barrier Reef experiencing its third major bleaching event in the past 5 years. Powerful new analytical techniques are revealing impacts of warming that has already occurred on crop yields, wildfires, and economic inequality (Abatzoglou and Williams, 2016; Diffenbaugh and Burke, 2019; Duffy et al., 2019).

The impacts depend on the amount of warming that occurs, with risks that are widespread, severe, and irreversible (IPCC, 2014b). If the global mean surface temperature rise were limited to 1.5°C, many risks would be substantially moderated (IPCC, 2018). Risks rise rapidly based upon further warming, and some risks may reach high levels even if warming is limited to 2°C. Stabilizing global temperature requires decreasing net emissions of CO_2 to zero. Because the warming effects of CO_2 persist for thousands of years, every ton emitted pushes the temperature higher, and the resulting temperature is a nearly linear function of cumulative CO_2 emissions since the beginning of the industrial revolution (IPCC, 2013).

The main lever one has for limiting warming is to constrain net emissions of CO_2 and other greenhouse gases (GHGs). Dedicated efforts to remove CO_2 from the atmosphere through natural or industrial processes can offset GHG emissions. These "negative emissions" strategies have the potential to be important parts of the climate solutions portfolio, and their development is advancing rapidly (Davis et al., 2018; IPCC, 2014a), but there remain many unanswered questions about capacity, cost, and unintended consequences (NASEM, 2019a). The challenge of decarbonization is also complicated by the long lifetimes and the high retirement costs of fossil infrastructure (Davis et al., 2010).

Meanwhile global anthropogenic (human-caused) GHG emissions are continuing to increase. In 2019, global CO_2 emissions were projected to reach an all-time high of ~37 gigatons (GT) of CO_2 from fossil sources and 6 GT from land-use change (GCP, 2020). Emissions of other GHGs add to the forcing of climate change, amplifying the warming effect by about one-third over that of CO_2 alone. The Intergovernmental Panel on Climate Change (IPCC) analyses suggest that total allowable emissions cannot exceed 420 GT CO_2 (post-2017) in order to have a substantial probability (66 percent chance) of stabilizing warming at 1.5°C or less. Based on 2019 emission rates, this emission total will be exceeded in less than a decade (IPCC, 2018). The emissions limit for stabilizing at 2°C is somewhat larger (allowing an additional 800 GT CO_2); reaching either target requires rapid and sustained emissions reductions, on the order of halving emissions every decade (Rockström et al., 2017).

Meeting the challenge of climate change requires a portfolio of options. This portfolio must involve reducing GHG emissions to the atmosphere (mitigation), and removing carbon from the atmosphere and reliably sequestering it. In addition, it must involve adaptation to climate change impacts that have already occurred or will occur in the future. But given the possibility that these three options will not be pursued swiftly or broadly enough to provide sufficient protection against unacceptable climate change impacts, some suggest there may be value in exploring additional response strategies—including possible strategies to moderate warming by altering the abundance or properties of small reflective particles (aerosols) or droplets in the atmosphere or by modifying cloud properties. In 2015, the National Academies released *Climate Intervention: Reflecting Sunlight to Cool Earth* (NRC, 2015), which reviewed the state of the science and provided high-level findings and recommendations on this set of possible strategies.

Two of the main conceptual approaches for reflecting sunlight involve increasing the reflection of solar radiation away from Earth. Stratospheric aerosol injection (SAI) proposes to accomplish this through increasing the number of small reflective particles in the stratosphere. Marine cloud brightening (MCB) focuses on increasing the abundance or reflectivity of clouds over particular parts of the oceans. Cirrus cloud thinning (CCT), the third approach, aims to modify the properties of high-altitude clouds, increasing the atmosphere's transparency to outgoing thermal radiation.[1]

The available research indicates that such approaches have the potential to reduce temperature and ameliorate some risks of climate change, but they also might introduce an array of potential risks. Such risks could be related to processes in the atmosphere (e.g., ozone loss from SAI); important aspects of regional climate (e.g., behavior of the Indian monsoon); or numerous environmental, ethical, social, political, and

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[1] While CCT is not truly a "reflecting sunlight" strategy like SAI and MCB, it is sufficiently related to these other methods to be included in the study scope.

BOX 1.1
Terminology Considerations

Apart from reducing GHG emissions, many other strategies for responding to climate change have been proposed, including mechanisms to remove CO_2 from the atmosphere and mechanisms to alter Earth's balance of shortwave and longwave radiation[a]—in particular to increase the amount of sunlight reflected away from Earth in order to lower global temperatures. The overall suite of approaches is often referred to as *geoengineering*. NRC (2015) recommended, however, that the term *climate intervention* be adopted in place of geoengineering, because the term geoengineering has other meanings in the context of geological engineering and because (the report argues) "the term engineering implies a more precisely tailored and controllable process than might be the case for these climate interventions."

While *climate intervention* reasonably describes the full collection of possible climate response options, the focus of this study is on a particular subset of intervention strategies that involve modifying particle concentrations or cloud properties in the atmosphere—marine cloud brightening, stratospheric aerosol injection, and cirrus cloud thinning. NRC (2015) used the term *albedo modification*[b] to describe strategies of this type, but that definition also encompassed mechanisms to increase sunlight reflection at Earth's surface—strategies that are not considered in the current study. In light of the terminology used in the 2015 report, the current study committee considered the alternative *solar climate intervention*; however, some feel that this phrase might cause semantic confusion (e.g., by implying that the aim is to intervene in the climate of the sun).

Solar geoengineering is commonly used by the scientific community, the media, and the public at large to describe methods designed to reflect sunlight back into space. As this terminology reasonably (albeit not perfectly[c]) encompasses the strategies discussed in this report, this study committee has adopted this terminology (abbreviated herein as SG).

We recognize, however, that other groups will use and suggest different labels (e.g., some publications use *solar radiation management*, and the IPCC has both used *solar radiation modification* and suggested referring only to the individual strategies and avoiding crosscutting labels [IPCC, 2012]). These terminology issues are worthy of ongoing consideration as they represent more than a semantic debate; in fact, terminology can affect public perceptions and opinions of the various response strategies proposed and can help frame the discourse moving forward.

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[a] *Shortwave* radiation refers to radiation of solar origin, which is primarily in the visible, ultraviolet, and near-infrared wavelengths. *Longwave* refers to radiation of terrestrial origin, which is typically in the infrared and longer wavelengths and is radiated by Earth, clouds, and the atmosphere.

[b] NRC (2015) defined albedo modification as approaches that seek "to offset climate warming by greenhouse gases by increasing the amount of sunlight reflected back to space."

[c] CCT, for example, is designed to affect infrared radiation rather than solar radiation.

economic factors that can interact in complex, potentially unknowable ways. The NRC (2015) study committee highlighted two potential risks in particular. First is the concern that with a heavy concentration of physical climate modeling research (relative to a focus on broader solar geoengineering [SG] impacts), enthusiasm for SG deployment might get ahead of the research. Second is the concern that SG deployment might be inexpensive enough that it could potentially be undertaken by a single nation or other actor, thus pointing to needs for rapid detection and attribution methods.

These different types of risks are highly diverse and likely to be perceived very differently across nations, communities, and individuals. Moreover, one does not (and, indeed, cannot) know the future climatic and sociopolitical conditions under which expanded SG research or potential deployment might be considered, and how the differing types of risks will be perceived by future decision makers and society at large. Very little research to date has attempted to address the full cascade of potentially interacting processes.

1.1 ORIGINS OF THIS STUDY

NRC (2015) made six recommendations. *Recommendation 1* discusses strategies that should be the core of the climate solutions portfolio—emissions reduction and adaptation. *Recommendation 2* speaks to the importance of additional research and development on technologies for CO_2 removal. *Recommendation 3* states that albedo modification at scales sufficient to alter climate should not be deployed at this time. *Recommendation 4* argues for a research program on albedo modification, pointing to the potential for research targeted at advancing fundamental knowledge as well as evaluating potential applications. *Recommendation 5* emphasizes the importance of improving monitoring of the atmospheric radiation budget as a strategy for detecting secret deployments. *Recommendation 6* points to the need for a serious deliberative process to explore and develop appropriate mechanisms for governing SG research.

As a follow on to NRC (2015), the National Academies of Sciences, Engineering, and Medicine launched the present study to develop a research agenda and recommend research governance approaches for SG intervention strategies, focusing on SAI, MCB, and CCT. The study was deliberately designed to address research needs and research governance in tandem, such that the understanding and thinking on each informs the other. This study considers transdisciplinary research[2] that integrates understanding across factors such as the baseline chemistry, radiative balance, and other characteristics of the atmosphere; potential impacts (both positive and nega-

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[2] As described in Toomey et al. (2015), whereas multidisciplinary research draws on knowledge from different disciplines, and interdisciplinary research synthesizes and harmonizes links between disciplines, transdisciplinary work moves beyond this bridging of divides within academia to also engage directly with the production and use of knowledge outside of the academy. Societal impact is a central aim of the research.

tive) of SG interventions on the atmosphere, climate system, natural and managed ecosystems, and human systems; the technological feasibility of these interventions; detection and monitoring of such impacts; ethical implications and public perceptions of SG research and possible deployment; and optimal strategies for governing such activities. The study explores and recommends appropriate research governance mechanisms at international, national, and sub-national scales, as well as self-governance by the research community. It considers the research governance that already exists and lessons from research governance mechanisms currently being used or considered for other areas of scientific inquiry (see full Statement of Task in Appendix A).

This report is intended for the broadest range of audiences interested in SG. The committee's focus was on research to support the information needs of those who may be involved in decisions about the scale, scope, direction, and organization of the SG research enterprise—including the appropriateness of certain kinds of studies, especially field experiments. Ultimately, SG research should help support decisions about whether or not to include these strategies in the portfolio of climate responses and even to understand who should be involved in these decision-making processes. As decision-making priorities evolve over time, this points to the need for a research portfolio that is iterative and adaptive in nature. Some of the information most relevant for policy decisions in this space can contribute to increasing our understanding of basic functions of Earth and its atmosphere, ecosystems, oceans, and societies; however, advancing "basic knowledge" was not the primary driver for the current study.

Funding for this study came from three very different types of entities. Reflecting its assessment of the importance of the topic, some funding came from the Arthur L. Day fund of the National Academy of Sciences. Four private foundations—the BAND Foundation, the Christopher Reynolds Foundation, the John D. and Catherine T. MacArthur Foundation, and the V. Kann Rasmussen Foundation—provided support. Three federal agencies also provided support for the study: the U.S. Department of Energy, the National Aeronautics and Space Administration, and the National Oceanic and Atmospheric Administration.

1.2 SCOPE AND MOTIVATION OF THIS REPORT

Available information is inadequate to provide the needed input to decisions about whether, when, and how SG should be included in the portfolio of climate response strategies, and a detailed agenda to define the relevant scientific research has thus far not been developed or implemented. A well-designed and well-governed research program could provide a great deal of critical information, but such a research program entails risks if its focus is too narrow, if stakeholders are not appropriately engaged, or if research decision making is not sufficiently transparent or inclusive. There are inherent limits to the questions that a research program can resolve for decision makers—including values-based questions about whether or not society should use SG as an option in the future, how to balance trade-offs in the potential impacts of SG, and how much uncertainty in outcomes is tolerable for decision makers or broader society—but research can provide useful insights that help inform these difficult questions.

The components of an SG research program and the interactions among them depend upon the contexts (i.e., social, economic, cultural, technological, and ethical) in which the research unfolds. While some questions that must be addressed are purely technical (e.g., Could a particular technology, under ideal circumstances, change radiative forcing by some desired amount?), other questions involve complex interactions between physical and social dimensions (e.g., Is it possible to manage the risk of an unintended damaging change in regional rainfall?), or they involve ethical considerations (e.g., How should trade-offs be evaluated when SG might improve the welfare of many but erode the welfare of others?).

Defining a research framework broadly perceived as fair, especially for stakeholders who lack political power or financial resources, is a major challenge. An important element to consider is the approach used for evaluating benefits and risks. For instance, one possible approach, a risk-risk framework, sets the objective of evaluating the benefits and risks of a given action in comparison to the benefits and risks of alternative actions, or compared to no action. An underlying challenge of such evaluations is the landscape of deep uncertainties surrounding climate change and SG.

An SG research program can encompass elements as diverse as scenario development; modeling; laboratory studies; field studies; and socioeconomic, political, governance, ethical, and public perception studies. Data sources will range widely—from stakeholder interviews, to laboratory experiments, to observations collected from satellites, aircraft, and ships. Of all the possible lines of research, field experiments with controlled dispersal of particles raise especially challenging issues. Some researchers have proposed that small-scale field studies are already the logical next step to advance understanding, and a few research teams in the United States and elsewhere are moving forward with planning for field experiments. But there is scientific debate about whether small-scale field experiments can provide useful insights about large-scale deployment; the need for caution in pursuing such proposals has been raised by many. For instance, NRC (2015) recommended that field experiments designed to inject material into the atmosphere should not proceed until key governance issues are addressed and appropriate structures are in place. Several nongovernmental organizations (NGOs) are on record as being strongly opposed to field experiments, while others accept them under highly specified conditions. Other perspectives point to the importance of suitable public engagement to explore whether there is "social license" to proceed with field experiments.

The committee's recommendations are grounded in the conviction that in order to maximize scientific value and prospects for social acceptance, an SG research program needs to be highly interdisciplinary, open to broad participation, as transparent as possible, and structured to actively foster coordination and knowledge sharing across nations.

Several existing reports and organizations address aspects of SG governance. For example, groups of scholars have proposed principles and best practice guidelines for operating norms. The Carnegie Climate Governance Initiative is focused on catalyzing policy discussions with governments and in international bodies to expand understanding of SG risks and benefits, and to prevent deployment of these technologies without having effective governance in place. The Solar Radiation Management Governance Initiative is a partnership among several NGOs convening conversations about SG in countries around the world, with an emphasis on engaging developing country researchers. Yet despite these many efforts, and progress being made in expanding the community of scholars, policy makers, and NGOs engaged in this topic, discussions are still mostly in the early stages, and no consensus has yet been reached about protocols for research governance.

Governance of SG research will also need to deal with the opportunities and challenges associated with engagement of the private sector. Private-sector involvement in research and development can spur innovation, attract capital investment, and accelerate the development of effective and lower cost technologies. At the same time, however, there are concerns that for-profit efforts may neglect social, economic, and environmental risks, that research transparency will be compromised by data that are not open and accessible, and that some companies may develop financial interests in moving from research to deployment and seeking private ownership of globally relevant technologies.

1.3 SOLAR GEOENGINEERING IS NOT A SUBSTITUTE FOR MITIGATION

The starting position of the committee is that SG is not a substitute for mitigation, nor does it lessen the urgency for pursuing mitigation actions. Four main lines of evidence

BOX 1.2
Context in 2020

During the period in which this report was developed and written, the unfolding of the COVID-19 pandemic has challenged many conventional notions about the relationships between scientific knowledge and policy making, as well as about international cooperation to address major societal challenges.

In many settings, the pandemic has vividly illustrated the value of forward-looking research, a strong capacity for science-based decision making, and careful attention to risk analysis. In other settings, responses to the pandemic have laid bare fractures at the science-policy interface, shined a spotlight on highly unequal impacts of policies on marginalized individuals and communities, and underscored challenges in international cooperation in a time of global crisis. When embraced, proactive efforts to build a foundation of scientific understanding and link it to decision making have strengthened resilience. In contrast, the selective marshaling of knowledge has strained the integration of science into policy and constrained the development of informed and equitable societal responses.

Any discussion of SG technologies has both global and intergenerational aspects. Even "short-term" applications of SG technologies may require sustained interventions lasting a half-century or more, highlighting the importance of understanding issues related to the prospects for consistent governance, resilient institutions, and evidence-based decision making.

Lessons from the pandemic might very well be salient for important elements of SG research and research governance. Research and research governance aim to reduce uncertainties about the risks and potential of SG, but they will not in and of themselves ensure that future social and geopolitical conditions will be conducive to the effective and equitable deployment of these technologies. This concern provides motivation for ensuring that discussion of SG research and research governance is grounded in caution and humility; pays close attention to changing social, political, economic, ecological, and institutional conditions; and appreciates the importance of diverse, equitable, and global cooperation. These elements were threaded throughout this report from the outset, and they became even more central as the committee concluded its work.

underscore this position. The first is that SG does not address some of the key impacts of elevated CO_2 concentrations, including impacts on ocean acidification (with ramifications for the structure and function of ocean ecosystems) and impacts on terrestrial plants (altering growth rates, competitive interactions, and crop nutritional values). Second, there is abundant evidence that SG cannot restore the climate with high fidelity to any specific prior state but rather leads to outcomes that differ from prior states in terms of spatial and temporal temperature and precipitation patterns, as well as extreme events, which introduce a new set of challenges all their own. Third, SG may lead to a variety of unintended consequences and impacts. Fourth, offsetting a large amount of warming through SG (something that might be advocated in the absence of stronger future mitigation) requires that the intervention be sustained for very long periods of time and entails unacceptable risks of catastrophically rapid warming if the intervention were ever terminated.

This is a critical framing point for all discussion of SG research and research governance, stemming from not only technical calculations but also considerations about social acceptability, ethics and justice, and the other social dimensions discussed in this report. No matter what the research concludes, climate change mitigation must be a central element of society's future. The goal for research is to determine whether SG can be a complement to mitigation, not a substitute, and whether and under what conditions it could be part of the portfolio of climate response strategies.

Conclusion 1.1: Anthropogenic climate change is creating impacts that are widespread and severe—and in many cases irreversible—for individuals, communities, economies, and ecosystems around the world. Unless emissions of CO_2 and other long-lived GHGs are driven to net zero, and emissions of short-lived GHGs are stabilized, risks from a changing climate will increase in the future, with potentially catastrophic consequences. There is real potential to rapidly decrease GHG emissions, but at present global-scale GHG emissions continue at very high levels. In light of these urgent and growing concerns, it is important to have a comprehensive understanding of the feasibility, risks, benefits, and unknowns—and consequences for diverse stakeholders—of the wide range of possible policy responses to climate change.

Conclusion 1.2: The most commonly considered responses to climate change include reducing GHG emissions, removing and sequestering carbon from the atmosphere, and adapting to climate change impacts. SG could potentially offer an additional strategy for responding to climate change but is not a substitute for reducing GHG emissions. This is in part because SG

- **does not address the root cause of climate change and does not address all of the impacts of rising atmospheric CO_2, especially ocean acidification;**
- **raises concerns about new risks, uncertainties, and unintended impacts on natural ecosystems, agriculture, human health, and other critical areas of concern for society;**

- **cannot provide a reliable means to restore global or regional climate to some desired prior state; and**
- **entails unacceptable risk of catastrophically rapid warming if the intervention were ever terminated (if it were used to offset a large amount of warming).**

1.4 THE STUDY PROCESS

The study was developed and overseen jointly by the National Academies' Board on Atmospheric Sciences and Climate and the Committee on Science, Technology, and Law. The members of the study committee had expertise in diverse areas such as atmospheric physics, chemistry, ecology, economics, policy studies, law, ethics, and international governance and negotiations. Several committee members have a long record of contributions to SG scholarship, while some were chosen to bring perspectives from other research domains.

The committee held five in-person meetings, during which (as per National Academies' rules and procedures) all of the information-gathering sessions were open to the public, while internal deliberations and report writing were held in closed session. These included the following:

- Meeting #1 (April/May 2019; Washington, DC) included presentations from leading researchers, overviews of existing efforts to explore SG governance, input from project sponsors regarding their motivation for requesting this study, and presentations from stakeholders representing civil society, governments, and NGOs.
- Meeting #2 (August 2019; Boulder, CO) included a workshop to gather insights about the current state of SG research. Invited experts addressed the current status of modeling studies, observational studies, research on impacts across many sectors, and work on engineering development for relevant technologies.
- Meeting #3 (September 2019; Stanford, CA) included a workshop on research governance issues. Invited experts discussed questions about ethics and scientific responsibility, engagement and representation, governing research for collective benefit, perspectives on existing frameworks for SG governance, and lessons learned from governance of research in other complex, ethically fraught fields (e.g., related to biotechnology).
- Meeting #4 (October 2019; Washington, DC) and Meeting #5 (January 2020; Vancouver, BC, Canada) were closed to the public as the committee debated

key report messages and supporting arguments and collaborated to develop text for this report.

The committee also held three virtual information-gathering sessions. One session focused on learning more about SG research activities being advanced in China and in Australia. Two other sessions were organized to seek insights from individuals who could offer "decision-maker" perspectives (based upon their experience as leaders in various national and international organizations) about the types of information they would need from the scientific community to help inform decisions related to SG research, research governance, and possible deployment. To aid these discussions, the committee developed a set of hypothetical scenarios about potential SG research and/or deployment for speaker consideration (see Appendix C).

The committee also received a wide variety of written input from interested organizations and individuals, which was reviewed and discussed among the group. These information-gathering steps were followed by several months of work (carried out by calls, emails, and other virtual means among subgroups and the full committee) to finish deliberations and to facilitate the process of completing its report. Following standard National Academies' procedures, the draft report then underwent a rigorous process of external peer review prior to publication.

1.5 THE REPORT ROADMAP

The rest of the report is organized as follows:

Chapter 2 reviews the "landscape" of SG-related research (i.e., the current state of understanding and key knowledge gaps that need to be addressed—across both natural and social science realms), as well as the landscape of existing governance and legal structures that could be relevant to this research.

Chapter 3 explores the complex "decision space" surrounding this issue, including the types of information needed by decision makers; the many societal considerations that shape research and research governance planning; and the principles for SG research that have been highlighted in past work.

Chapter 4 presents the committee's core recommendations for a national program of SG research and research governance, considering how such a program could be organized, managed, and funded.

Chapter 5 recommends key mechanisms to pursue, at national and international levels, for governance of SG research that help assure robust research oversight and regulation and adherence to critical goals such as legitimacy, transparency, and stakeholder engagement.

Chapter 6 defines a broad transdisciplinary agenda for research to fill the key knowledge and information gaps identified in the earlier chapters and explores the special considerations related to outdoor experimentation.

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.

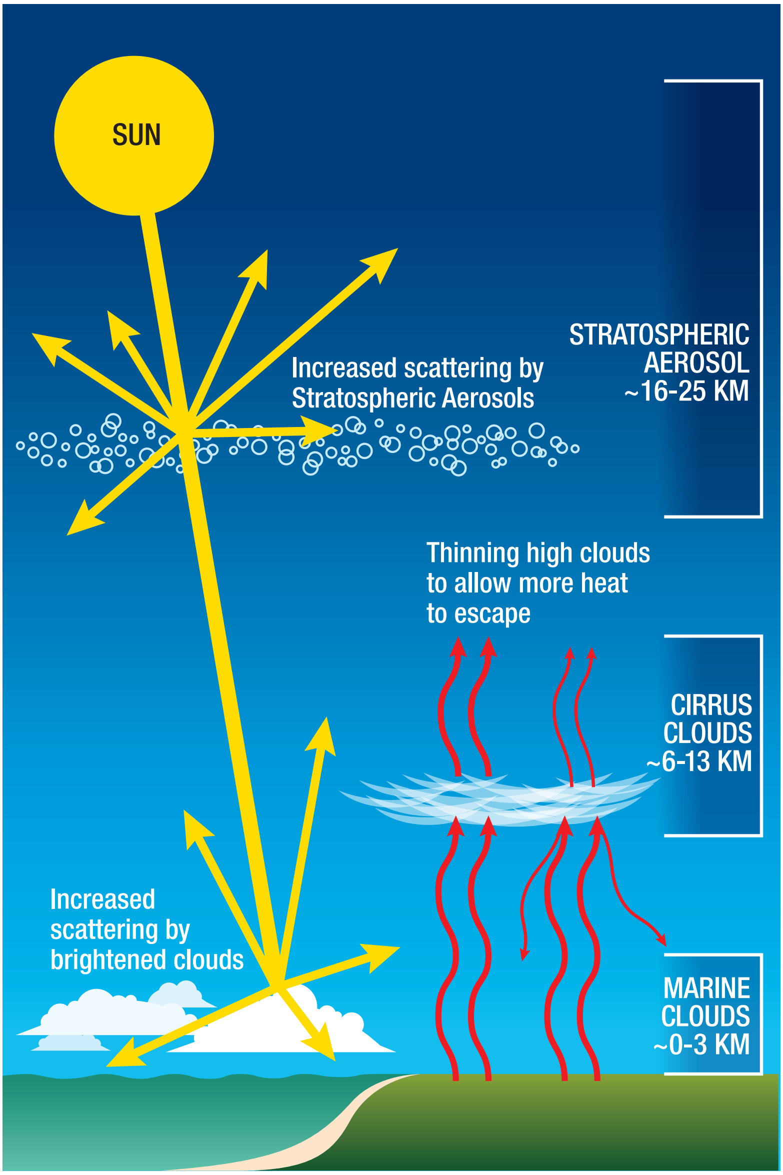

FIGURE 2.1a Illustration of the basic mechanisms involved in Stratospheric Aerosol Injection (SAI), Marine Cloud Brightening (MCB), and Cirrus Cloud Thinning (CCT).

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 vessels; 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 primarily 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).

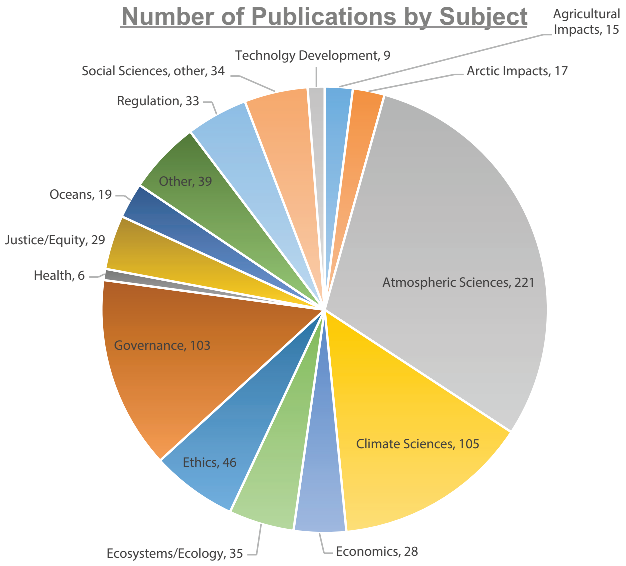

FIGURE 2.2 Distribution of subject matter for geoengineering publications (specific to SAI, MCB, and CCT) for the period 1983 to 2020. Data from Scopus literature search for the period 1950 to 2020.

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. Under-

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.

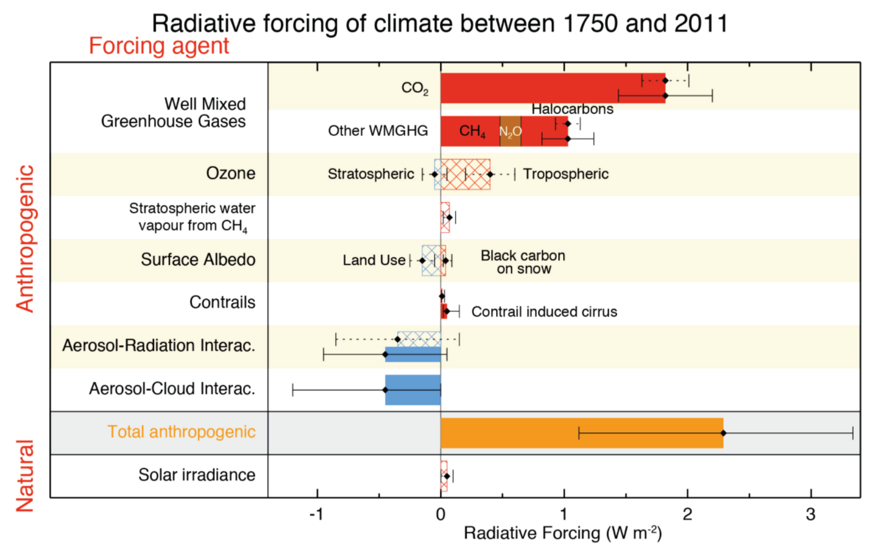

FIGURE 2.2.1 Global, annual mean RF (W/m^{-2}) due to key climate forcing agents, for the period from pre-industrial to 2011. Note that some of these effects remain poorly understood and even the sign of forcing (positive/negative) is uncertain. SOURCE: IPCC (2018).

standing 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.

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

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

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).

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.

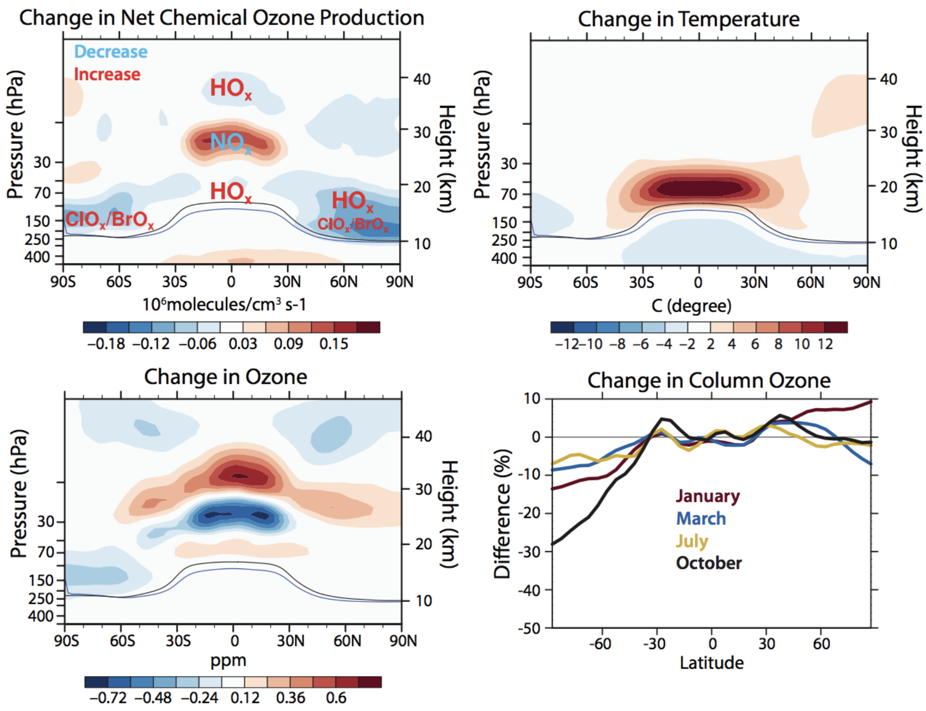

FIGURE 2.3 Processes impacting stratospheric ozone in 2042–2049 following RCP8.5 for 16 Tg S yr^{-1} injections at 15°N/15°S. Impact of enhanced sulfate aerosols on zonal and annual averaged net rate of chemical production of ozone (top left), temperature (top right), and ozone concentration (bottom 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 (TiO2) 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 cause a substantial reduction in reflectance. Alternatively, it

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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).

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.

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).

Thus, while there is 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 annual 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 processes 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 (Ghan 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 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 the cloud 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 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

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

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.

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 scenarios 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 both 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 regional 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 without either 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.

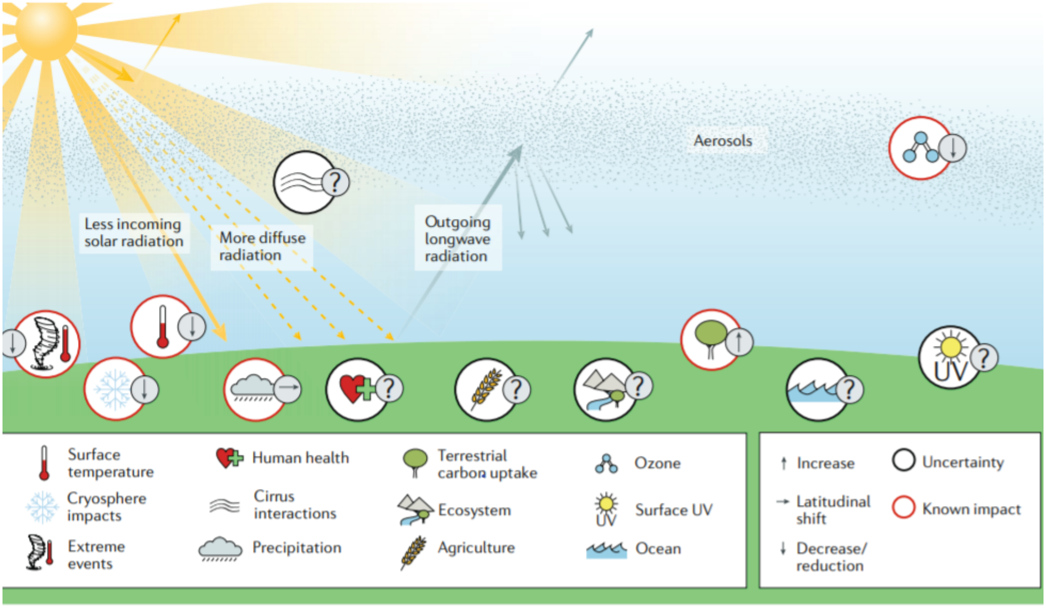

FIGURE 2.4 Illustration of some potential benefits from SAI along with some possible risks. SOURCE: Kravitz and MacMartin (2020).

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 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.

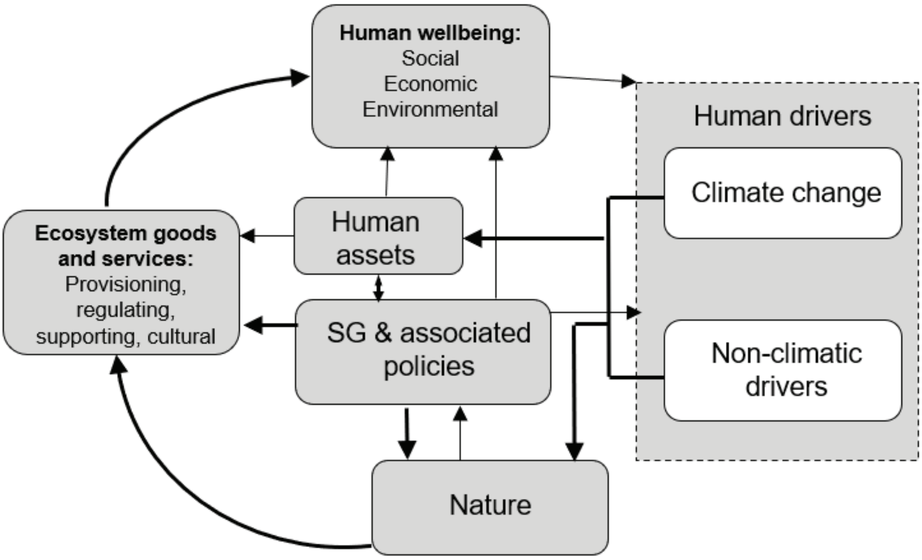

FIGURE 2.5 Illustration of the "impact pathways" of SG on linked social-ecological systems. SOURCE: Drawing upon the conceptual framework developed for the *Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services* (Díaz et al., 2015).

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.

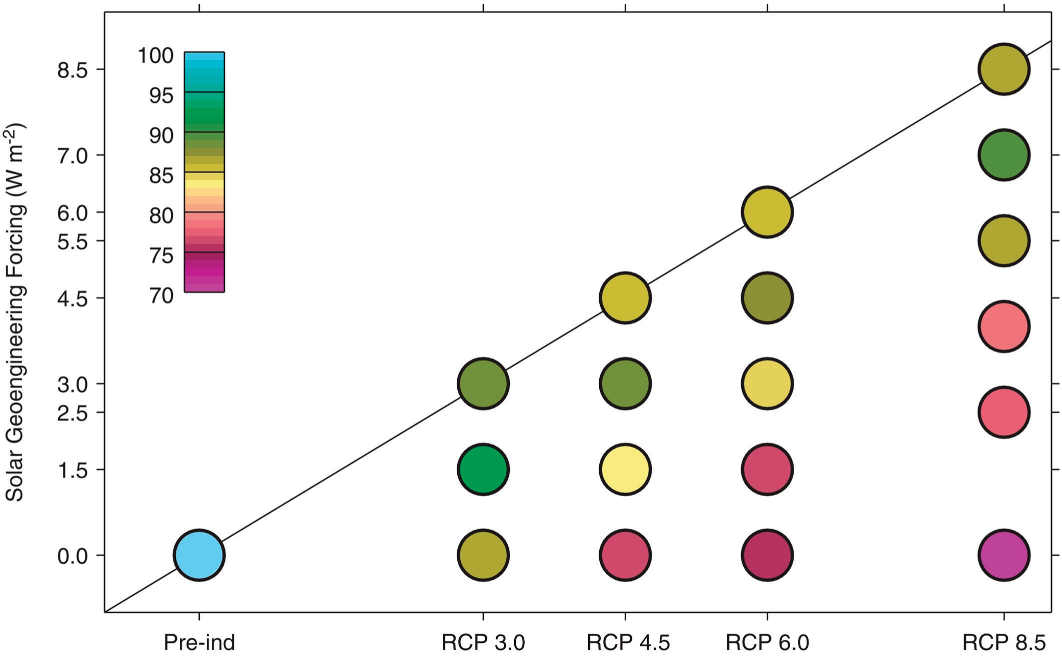

FIGURE 2.6 Shallow water tropical reef suitability in 2070 (plotted as a percentage relative to preindustrial) under four emission scenarios (x-axis) and different levels of solar engineering (y-axis). Habitat suitability is defined as the mean probability of a coral reef being present (as a single environmental 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 predicted 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 around 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 even 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. The good news is that 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—*Odin OSIRIS, ACE-FTS, MAESTRO, Aura MLS*—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 premise 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 existing 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 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).

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

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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.

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.

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 without 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; Frumhof 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 weight 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 socio-technical 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, 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 be better characterized as "deeply reluctant and highly conditional" (Carr and Yung, 2018). In a study of vulnerable populations in the South 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 engagement 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 brinks-manship" 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 questions, 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; SRMGI, 2011). 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 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 actions, and creating 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 interdependences 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 pertaining 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 such 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 innovation 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 geo-engineering activities that may affect biodiversity take place, until there is an adequate scientific basis on which to justify such activities and appropriate consideration of the associated risks 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

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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.

establishes no governing body or institution for implementing or expanding upon the agreement (Reynolds, 2019).

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 Declara-*

tion 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.

CHAPTER THREE

The Decision Space: Context and Key Considerations for Solar Geoengineering Research and Research Governance

The fragmented state of the SG research and research governance landscape is a barrier to the efficient and effective advancement of knowledge and the understanding of societal views on this issue. This chapter describes the "SG decision space" that spans a complex, interconnected terrain encompassing scientific research, societal values and perspectives, and governance mechanisms. Section 3.1 considers which decision makers might be primary consumers of information from a research program and discusses their potential information needs. Section 3.2 examines the societal contexts in which SG-related decisions may be made, and Section 3.3 considers the many intertwined scientific, societal, and governance issues that make this such a challenging area of exploration. Section 3.4 explores high-level principles that might guide research and research governance, as context for constructing a research program that is attentive to the many difficult social issues inherent to this topic.

3.1 ENABLING FUTURE DECISION MAKERS

Scientific research is typically conducted to support curiosity-driven knowledge expansion, predetermined objectives, or both. SG research could be viewed as seeking a middle ground, where scientific knowledge is acquired to assess the feasibility and uncertainties of deployable, predictable, and controllable SG technologies, and to provide information that permits society to assess the value of SG as part of climate change response.

At the intersection of science and society are people who must make decisions about research activities, governance mechanisms, and potential deployment actions. Addressing the needs of these diverse decision makers is a primary goal of a research program. To assist with identifying these needs, the committee engaged several representative decision makers over the course of this study (discussed in Box 3.1).

BOX 3.1
Decision-Maker Webinars

The committee hosted two public webinars during which it asked individuals with significant environmental policy experience to consider several climate intervention scenarios and identify the questions that they would want answered before they could make an informed decision about pursuing an SG research program (inclusive of outdoor experiments with possible transboundary impacts) or actual deployment. Key points arising from these conversations included the following:

- Decision makers will need to integrate a wide variety of scientific, social, political, and legal considerations when making decisions about SG.
- Broad advisory input and governance frameworks are necessary for good decision making.
- Real-world decisions always involve uncertainties. Eliminating all uncertainties associated with SG is not realistic or expected. However, clear communication of confidence levels can support better decision making.
- Decisions about research and deployment will be made within a broader climate change context of research, responses, and impacts. The relative risks and benefits of an array of possible climate responses—inclusive of SG and absent SG—are important. Risk-risk frameworks are typical in this kind of decision analysis.
- An important element of risk-benefit assessment will be reversibility—if realized outcomes become unacceptable, what is the viability, cost, and time frame to reverse the decision?
- The decision space for SG will be shaped by political, social, and economic factors such as capacity, attribution and liability, public perception, potential responses from different nations, and relative "strength" of major parties who may resist international oversight or control of their sovereign research activities.
- There are political risks associated with research, especially if research is perceived as unilateral and self-interested based on actors' past policy decisions. Focusing on information-oriented (rather than deployment-oriented) research, developing multilateral cooperation, prioritizing research that advances global understanding, addressing concerns about moral hazard, promoting transparency, and facilitating public engagement may help mitigate political risks.

See Appendix B for a list of the webinar speakers and Appendix C for the scenarios provided for speaker consideration.

3.1a Who Are the Decision Makers?

A decision maker is anyone with the authority to determine the course of future actions. SG decision makers may exist at all levels of society and include local community leaders, elected national representatives and civil servants, academics, corporate and nongovernmental organization (NGO) executives, and representatives within multinational bodies. Decision makers are geographically diverse, spanning the globe; economically diverse, spanning developed and developing nations; and politically diverse, spanning a spectrum of political viewpoints. Decisions relating to SG may arise for decision makers at any level, whether it be reviewing a local permit for experimentation or pursuing a globally coordinated initiative to initiate or restrict deployment of a technology.

3.1b Decision-Maker Needs

What information will enable informed decisions about SG, and what research will best provide that information? Answering these questions is an exercise in prediction and anticipation, as there are currently few decision makers who are knowledgeable about and focused specifically on this issue.[1] If research activities expand beyond current modeling efforts, or if SG were to be considered for deployment, decision makers will be faced with a wide array of complex questions. This includes general questions such as the following:

- What are the different geoengineering action options available?
- How are these different options likely to be received or accepted by different stakeholders and publics?
- How might SG affect the broader portfolio of climate responses? How can SG research be governed so as to minimize risks of mitigation deterrence?
- What are the known costs and potential liabilities (e.g., fiscal, political, and social) of different SG actions?
- How might SG research or deployment affect international relations?
- What forms of governance are needed to manage research and development, and decisions about deployment?

and includes many questions specifically about the outcomes/impacts of SG deployment:

- What global- and regional-scale impacts might be expected over time?
- What will be the distribution of impacts (i.e., benefits and risks) across different parts of the world, and what are the equity/justice implications of such differences?
- What are the expected risks and benefits in terms of outcomes from different SG approaches, relative to expected outcomes without deployment?

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[1] One possible exception is the sponsors of Australia's experimental marine cloud brightening program for the Great Barrier Reef (which is part of a larger program on climate adaptation).

- Can SG actions be effectively managed to deliver the intended outcomes? What would be the (positive or negative) indicators of such outcomes, and on what timescale might these outcomes be known?
- What are the possible unintended consequences associated with different SG actions, and what could be done to mitigate against such consequences?
- If adverse impacts are experienced and are perceived to outweigh the benefits of deployment, can SG actions be reversed?

The purpose of designing an SG research and research governance program is to help address these questions as effectively and efficiently as possible, as a foundation for informing the choices that decision makers may face.

3.1c Scenario Context

Decisions about SG deployment would be made by a wide variety of actors with differing motivations and under differing climate, geopolitical, and societal conditions. It is important to consider a wide range of possible scenarios in order to identify the types of information that could be necessary for robust decision making. Below are a few scenarios that have been used to inform research to date[2] (noting that current knowledge is insufficient to ascertain whether SG is a viable option for addressing the challenges encapsulated within scenarios).

The "climate context" for SG decision making will depend in particular on the severity of climate impacts occurring and on the degree to which other climate change responses (e.g., mitigation, carbon dioxide removal [CDR], and adaptation) are being pursued. At least three types of scenarios have been commonly discussed in this regard:

- A common framing scenario is referred to as "peak shaving," in which mitigation efforts are having a positive effect, but are not sufficient to prevent an "overshoot" of goals for limiting global mean temperature increase. Large-scale CDR could potentially help reduce temperatures but only over time periods of decades to centuries. It has been suggested that, in the interim, SG might be considered for deployment in a temporary way to reduce peak temperatures (MacMartin et al., 2018a; Tilmes et al., 2016; Wigley, 2006). Here "temporary" implies a sustained deployment over multiple decades to a half-century or more, to limit peak temperatures during a period of globally

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[2] A better understanding of the range of future scenarios is itself a research question, discussed in Chapter 6.

sustained decarbonization. In this context, an important factor influencing SG research or deployment considerations will be the trajectory of continuing mitigation measures and what is known about the plausibility of large-scale CDR relative to the required time frame of a commitment to SG once begun.

- An alternative (also time-bound) scenario is one in which there are emission reduction efforts but no reliance on CDR, large-scale adaptation is under way, and SG deployment is considered to slow the rate of temperature rise, with the goal of securing more time for adaptation (Irvine et al., 2019; Keith and MacMartin, 2015; MacMartin et al., 2014a). Current projections of peak temperatures, expected impacts, and the timescale for adaptation would influence considerations of how or whether SG might be utilized.
- A third scenario is one in which efforts for meaningful mitigation, CDR, and adaptation have been inadequate, and SG is considered as an emergency response to blunt destruction caused by rapidly accelerating temperature rise. This scenario is characterized by the need for indefinite and ever-increasing levels of SG, with significant unmitigated direct harms from rising CO_2 concentrations (e.g., ocean acidification), and growing risk of unintended side effects from intensifying SG deployment.

Differing political contexts and scenarios will also affect decision making. For instance, a scenario involving deliberative action through a globally representative body or agreement might best address social and governance concerns and provide the most resilient foundation for research activities or sustained deployments. But there may also be scenarios in which regional coalitions or collections of individual state actors act autonomously but with shared views or even scenarios involving a lone actor, perhaps not even representing a sovereign nation, attempting unilateral deployment. In each of these cases, the actor(s)' record of pursuing climate change mitigation, and the associated inferences regarding underlying motivations and commitments to decarbonization, might be an important part of the decision-making context.

The specific details of a particular SG deployment could also significantly alter the context for decision making. For example, in a lone actor scenario, response to a localized marine cloud brightening (MCB) operation deployed by a small island nation is likely to differ from the response to a large nation experimenting or deploying stratospheric aerosol injection (SAI) at a scale with transboundary or global effects. If that island nation were part of a coalition of island nations mounting a coordinated deployment campaign that started to have measurable global effect, these differences might diminish. Similarly, an SAI deployment focused on Arctic sea ice preservation, while it would still have a global impact, would have different implications and potentially elicit different responses than efforts designed to change global temperature.

3.2 SOCIETAL CONTEXT FOR SOLAR GEOENGINEERING RESEARCH

The potential of SG activities to cross geo-political boundaries, the long timescales over which SG might be deployed, and the diversity of perceptions about potential SG benefits and risks all raise societal issues that could affect the course of SG research as much as scientific and technical considerations. The following discussion identifies issues that shaped the committee's exploration of SG research and considers how these issues factor into SG research and research governance program design.

3.2a Diverse views on Solar Geoengineering Research

SG research is controversial within and beyond the climate science community. Some view SG as a potentially critical tool for climate change response and thus argue for an acceleration of, and greater funding for, research. Others argue that without substantial societal demand for SG research, it is inappropriate to redirect funds away from other areas of climate science. There is no consensus, domestically or internationally, on whether and how research should be pursued. Section 2.3b reviews the "conditional" support for SG that is found in social science research studies. Environmental NGO positions are divided on the question of outdoor experiments—some silent, many strongly opposed,[3] and others in favor of caution with controls for outdoor experiments and greater engagement of global publics in decision making.[4]

These widely varying views illustrate why an SG research program needs to be multifaceted, encompassing not only natural science research to better understand the direct and indirect effects of different SG approaches, but also social science research to better understand societal views on risk tolerance and equity, as well as the most effective and appropriate methods to engage stakeholders and to build research and research governance capacity.

3.2b Issues Related to Risk and Uncertainty

Characterizing and Reducing Uncertainty

Risk assessment and uncertainty characterization will be critical for future SG decision making. Risks and uncertainties may be reduced, but not eliminated, by research.

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[3] See https://climatenetwork.org/resource/can-position-solar-radiation-modification-srm-september-2019/.

[4] See https://www.ucsusa.org/sites/default/files/attach/2019/gw-position-Solar-Geoengineering-022019.pdf.

Some degree of uncertainty will be a persistent feature of SG technologies, especially at regional scales, as a direct result of uncertainties in the underlying climate models. In fact, some SG research activities may result in increased characterization of uncertainties. For example, model projections of the climate response to SG currently use a relatively modest range of future climate, socioeconomic, and deployment scenarios. Research designed to improve understanding of the possible future conditions under which SG might be deployed may expand the range of scenarios assessed, and this in turn may expand our understanding of uncertainties about SG efficacy and risks. In other words, further research might (at least initially) help illuminate how little we know.

It is particularly important to understand the extent of uncertainty reduction that could be achieved through research activities versus through actual SG deployment (or at least testing at scales that would be tantamount to deployment). For example, decision makers may reasonably wish to know the likelihood of SG-induced changes in regional precipitation patterns and how such changes could affect agriculture, ecosystems, and public health. If risks are significant, they might further ask whether a consequential precipitation change that is observed following deployment could be attributable among natural climate variability, direct consequences of climate change, or the SG activity.

Many difficulties in reducing uncertainty are linked to challenges associated with performing field experiments on the spatial and temporal scales required to observe climate impacts. Given the backdrop of natural climate variability, a perturbation experiment large enough to produce a detectable change in secondary effects such as regional precipitation patterns would necessarily have to be large enough to affect radiative forcing at hemispheric or global scales for decades. That is, it would need to be carried out at a deployment scale. An SG research program may be able to reduce some current uncertainties, for instance, related to regional precipitation and precipitation-dependent systems; but with current technology, it is unlikely that models will be able to provide high confidence about secondary effects (see Chapter 2). Further characterizing and quantifying how much uncertainty can be reduced through research will be critical for decision makers, and this itself can be viewed as an important research question.

Assessment of Comparative Risk

Some argue that decisions about expanding research on (and considering potential deployment of) SG strategies should be based on efforts to weigh the risks of climate change against the risks of the particular form of SG in question. Risk-risk assessment (or risk trade-off analysis) provides a framework wherein the risks of one policy option are comparatively assessed in relation to the risks of others to identify options that maximize benefit. The relevant comparison would characterize the risks of climate change without SG versus the risks of climate change with SG—in both cases, looking across a range of greenhouse gas (GHG) concentration pathway scenarios and including an array of other climate response actions. This is a common methodology for assessing choices between complex and indeterminate options.

Comparative risk assessment, often quantified as the probability of an outcome times the magnitude of that outcome, requires probability and magnitude estimates for key risks associated with different policy choices. The robustness of any comparative risk assessment is dependent upon the accurate identification of the climate context (with its associated risks), the identification of the relevant SG options (with their associated risks), and interactions between these and other factors discussed in the following section. It is likely that, even with substantial further research, significant uncertainties will remain absent full deployment and decades-long observation. This is equally true for comparison to the impacts of climate change without SG, where uncertainties across the broad range of impacts are unlikely to be fully understood or quantifiable. In similar cases in which data-driven risk assessment is limited, other strategies such as assessment by expert judgment can be employed—though such methods increase subjectivity and risk of disagreement, especially if such risk assessments are highly contextualized.

Another particular challenge for comparative risk assessment is the diverse perception of risk across the global communities that may be affected by SG research or deployment. Climate change effects—with or without SG—will not be distributed equally across the globe, and risk perceptions and risk-related values vary significantly across nations and communities. Therefore, any risk-risk analysis should be contextualized to the specific decision maker, and the challenge of reaching consensus on risk assessments will scale to the breadth of impact for the activity under consideration.

For these reasons, operationalizing comparative risk analysis will be challenging and require specific focus in any research and research governance program. A primary implication is the need for research to better identify and understand the potential climate, health, and ecological risks (as well as the broader social, political, and economic risks) that could be associated with specific forms of SG.

The inherent challenges in quantifying risks, together with diversity in risk perception and priorities among different global stakeholders, support the notion that international participation and stakeholder engagement will be important for determining how to address risks and uncertainties in relation to the overall research enterprise. Any consideration of moving from research to deployment would increase the needed scale and breadth of such engagement. These challenges also support the assertion that an SG research agenda needs to include research on issues of risk and uncertainty, including the scientific, social, political, and ethical dimensions of this topic. New approaches may be necessary to understand, evaluate, manage, and communicate risk and uncertainty in this domain.

Risk Governance

In addition to characterizing risks and uncertainties, and attempting to compare a range of GHG concentration pathway scenarios and climate response portfolios, risk assessment can be embedded in a broader approach to risk, often described as risk governance. The risk governance approach evolved out of a framework that includes risk assessment, risk management, and risk communication. However, it involves a more integrated and iterative process of understanding, evaluating, and managing risks and uncertainties by engaging both experts and various publics throughout these ongoing processes (Klinke and Renn, 2019). As such, the risk governance approach is process oriented and addresses both the objective and subjective dimensions of risk and uncertainty.

If pursued for SG research, a risk governance approach might include engaging experts, stakeholders, and diverse publics in exploring risk and uncertainty in relation to various climate scenarios, including scenarios that involve one or more forms of SG. Risks and uncertainties may vary significantly depending on context, and both technical expertise and public and stakeholder engagement could play an important role in characterizing and evaluating risks under different scenarios.

Developing responses to climate change is a dynamic and ongoing process. There will be significant unknowns in any pathway taken, and decisions about SG research, as well as any future decisions about deployment, will be made in an environment of incomplete information. This is the case for all policy decisions but will be particularly acute for decisions (including but not limited to SG) that have global and intergenerational reach. Efforts to understand and characterize the climatic, ecological, and social risks and uncertainties associated with SG, as well as to understand their significance for various groups, will be an important component of any research program. A risk governance approach can incorporate comparative risk assessment into a broader frame that includes collaborative, participatory, and adaptive approaches to managing risk, uncertainty, and ignorance. As Klinke and Renn (2019) put it, “the goal of risk governance is to embrace uncertainty, complexity, and ambiguity as major characteristics of risk governing processes and deal with them upfront.”

Conclusion 3.1: A principal goal of any SG research program should be to better characterize and reduce scientific and societal uncertainties concerning the benefits and risks of SG deployment (relative to global warming in the absence of SG), to help inform future decision makers. There are, however, limits on the level of uncertainty reduction that can be expected, and it is possible that additional research may expand particular uncertainties or reveal new uncertainties, particularly with respect to complex, interacting factors such as high-resolution spatial patterns, indirect effects, socioeconomic and political/institutional responses over multidecadal timescales, and attribution for climate- and weather-related extremes.

3.2c Solar Geoengineering and Society

Societal concerns about climate change specifically, underlying economic and equity conditions more broadly, and perceptions about technological risk versus benefit, factor significantly into considerations of SG research. Such considerations encompass complex justice and equity concerns, discussed in Section 2.3a ("Ethics and Geoengineering"), as well as several other key issues highlighted below.

Failure to Meet Climate Mitigation Goals

SG research emerged largely in response to concerns over inadequate action to mitigate climate change by reducing GHG emissions. Rationales for considering SG as one element of a broader climate response include (i) broadening the array of tools with which to address climate impacts (sometimes justified by appeal to the need to develop "every tool in the toolbox" against climate impacts); (ii) reducing the impacts of a possible "climate emergency"; (iii) buying time for more ambitious mitigation and climate stabilization (the "peak-shaving" scenario); and (iv) reducing near-term impacts of climate change for vulnerable communities.

Philosopher Stephen Gardiner has argued that the failure to significantly reduce emissions represents an ongoing moral failure, which leaves us in an ethically compromised position: "It is mainly because we have failed—and continue to fail—to do what we should have done, ethically speaking…that geoengineering is being considered at all" (Gardiner, 2020). Gardiner questions whether an ethical geoengineering policy is likely in the context of this ongoing moral failure, noting that many of the same problems that plague climate policy (e.g., a tendency to focus on the short term, postpone action to mitigate, and displace risks onto others) may emerge in the context of SG research, development, and consideration of deployment.

Others suggest that research is important precisely because progress on mitigation has been so slow (Victor et al., 2013). According to this view, even if it would not be needed in an ideal world, research on SG may be important now, given that many parts of the world are already experiencing significant negative impacts of climate change. SG might be able to reduce the severity of some of these impacts (at least temporarily) while GHGs are being stabilized.

Moral Hazard/Mitigation Deterrence

As discussed in Chapter 2, 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. As mentioned previously, the idea that geoengineering might undermine mitigation efforts is commonly referred to as "moral hazard" (Keith, 2000; Lin, 2013; McLaren, 2016). The worry is that if geoengineering is viewed as a partial remedy for near-term climate impacts, it may reduce incentives to commit to and invest in mitigation and adaptation efforts.

Societal acceptability of expanded investments in SG research within the United States and internationally may be contingent, in part, on how moral hazard concerns are addressed. An expanded research program can be expected to have greater social acceptability if it is embedded within a portfolio of climate policies and research investments that include a firm policy commitment to decarbonization. In the absence of such a commitment, expanded funding for research risks exacerbating moral hazard concerns and reducing societal acceptability of both research and prospective deployment.

Slippery Slope Concerns

A commonly expressed concern about pursuing an SG research program is that such a program could create a "slippery slope," or an acceleration toward eventual deployment (should a viable technology emerge). There are various ways in which this acceleration scenario could occur:

- First, a research program could create political momentum toward deployment. Political support will generally be needed to start a state-sponsored, nationally coordinated program. One concern about political acceleration of SG is that those same actors who politically supported, defended, or sanctioned a research program may become invested in seeing it used.

- Second, research programs could create sociotechnical communities of interest, motivating further development of the technology. An SG research program could take several decades to produce the desired results. In that time, any number of structural, institutional, and even psychological factors could incline the research community toward a demonstration of the technology platforms under development. In a future in which climate change is increasingly getting worse, some SG researchers or research communities could become focused on advocating for deployment.
- A third line of argument is economic—that those developing the technology will seek an opportunity to monetize it, thus motivating a push for deployment.

An overarching concern is that any one of these pathways to acceleration could result in deployment. If motivated together, they could produce mutually reinforcing dynamics. There are, however, countervailing scenarios in which researched technologies are not deployed or in which governance could effectively mitigate acceleration:

- Research could dissuade deployment if it is found that it is very difficult to produce a technology that is deployable, predictable, and controllable. If it is demonstrated that SG is not an "easy" alternative to GHG mitigation or large-scale adaptation, then it could become less politically attractive.
- Moreover, if it were to take a long time to discern whether an SG intervention is working, it may attract less political support, since any positive outcome might not yield political capital for its proponents in their political lifetime.
- The idea of a "sociotechnical community" accelerating deployment could be counterbalanced by the active cultivation of transparency among the research community. Demonstrations of transparency with regard to risks unearthed by a research program or of an aversion to advocating for deployment in the face of lingering uncertainties about SG's secondary impacts could reduce an impetus toward deployment.
- The economic acceleration scenario is mitigated by the natural marketplace of capital allocation, as substantial economic forces are already pursuing more traditional climate mitigation measures. The current market for measures such as decarbonization of the energy sector is estimated in the tens of trillions of

> dollars over the next decade.[5] For SG deployment to represent a significant financial opportunity for its proponents, it will have to have sufficient supporting evidence to allow it to outcompete other investment streams. This could also counter-balance concerns about mitigation deterrence, as investors in these new energy systems will have little motivation to abandon these revenue streams in the face of relatively small research programs, which cannot be monetized in the near term.

Although the likelihood of a slippery slope from research to deployment is difficult to assess and may change over time, "one of the problems with slippery slopes is that it is not necessarily possible to recognize them until it is too late to implement policies to address them" (Parker, 2014). By designing research efforts that build in mechanisms to detect and prevent slippery slopes, this risk may be reduced. Such mechanisms include (i) stage-gate systems or checkpoints, in which approval is required to proceed in scaling-up research, or moving from laboratory-based to field-based experiments; and (ii) incorporating public engagement into decision processes (Callies, 2019a).

Geopolitics

Societal views about SG can be affected by the results of scientific research (i.e., by new insights about risks and benefits) and by the conduct of research itself (i.e., by the inclusivity and transparency of the enterprise); in turn, evolving societal views of climate change or risk management may steer the focus of SG research activities. This "co-evolution" of research (Jasanoff, 2004) and societal views necessarily has implications at the level of geopolitics, which refers to behavior between nation-states as shaped and mediated by geographical characteristics. Technology has long had a role in shaping geopolitics. Just as national security technologies developed during the Cold War shaped geopolitics and governance in that era (Dalby, 2015), geoengineering technologies could likewise influence geopolitics in the coming decades.

SG may have very different implications for different countries, and countries have widely varying interests in and political engagement with this technology (Heyen, 2015). Different national actors may have very different perceptions and opinions on

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[5] Global Commission on the Economy and Climate Change 2018; International Finance Corporation 2017.

the following questions: Is it appropriate to pursue a geoengineering research program? How does geoengineering relate to other actions seeking to address climate impacts? Under what conditions might it be appropriate to deploy geoengineering? What is the desirable climatic state resulting from geoengineering, and how will it be governed? (Humphreys, 2011). This has led to proposals such as geopolitically relevant ranking criteria to demarcate different geoengineering approaches (Boyd, 2016). Divergent interests among states also raise important questions about meaningful public participation with the geoengineering research enterprise (Jasanoff, 2019).

Research attention to issues such as how preferences about environmental futures are formulated by different people in different places, how conditions of substantial uncertainty influence decision making, and how model-based projections inform these processes might help improve our understanding of various dimensions of the regional and social disparities and related political implications of geoengineering (Heyen, 2015). Such research issues also highlight the importance of attention to the international governance of geoengineering and perhaps to a deeper exploration of "the more difficult, and more interesting question...what kind of planet is it that provides 'the future that we want'" (Dalby, 2014).

Urgency for Research

There exists no consensus on the particular timeline for various phases of SG research, development, and possible deployment. Time frames for research and development are often unstated or focus on the short term, such as the next 5–10 years. Geoengineering research is not, however, an open-ended, curiosity-driven enterprise, and the technologies being explored are generally envisioned as relevant to addressing climate impacts this century. Many researchers imagine that decisions about whether to proceed in further developing and possibly deploying SG would occur in the next 10–30 years, and some worry that a unilateral actor might try to deploy sooner than that. There is disagreement about the relative urgency of research, with some arguing that the risk of catastrophic unmitigated climate impacts is increasing and that, as this technology represents one of a few known responses that could relieve human suffering, it should be rapidly explored and developed. Others argue that such climate emergency framing is problematic because it has the potential to displace discussion of social and ethical issues critical to SG research and development. As climate change impacts progress, societal feedback on research urgency will change accordingly. The challenge is to design a research agenda and governance framework today that best positions the state of science to be responsive to this feedback, not lagging so far behind that options are foreclosed and not pushing so far ahead that risks are exacerbated.

Conclusion 3.2: Knowledge gained from a well-designed and well-governed SG research program will be useful for informing climate change response strategies, and evidence either in favor or disfavor of SG deployment could have profound value. Such knowledge could be time-critical for policy makers especially if there were intense public or political pressure for a dramatic climate action, or if SG were deployed in the absence of broad international cooperation and safeguards. The pursuit of an SG research program also brings potential risks—for instance, a program could be used as a rationale to undermine efforts to reduce GHG emissions, to legitimize SG as a response to climate change, and/or create a community invested in moving toward deployment. With careful attention, an SG research program can be designed to enhance these benefits and reduce these risks.

3.3 INTERSECTING DIMENSIONS OF RESEARCH, SOCIETY, AND RESEARCH GOVERNANCE

Science and technology do not exist in a vacuum; there are risks associated with the use of any technology, but risk can be moderated by governance. Take, for example, the concern that deployment would need to be indefinite—in other words, that once initiated it could never be stopped because it is necessary to maintain a target temperature range. While this objection may sound defeating given the risks associated with assuming indefinite maintenance of large-scale delivery and monitoring systems, anticipating this concern could lead to governance frameworks that ensure SG is considered only as part of a broader overall strategy for temperature stabilization. The following sections discuss how research, society, and governance interact in the context of SG.

3.3a Research Governance Considerations

A key near-term goal of SG research governance could be to foster a diverse, socially engaged, responsible, and accountable research program that provides clearer understanding of SG as one possible component of a broader climate response strategy, incorporating the complex and interdisciplinary perspectives inherent to the topic. With that goal in mind, some critical functions of research governance would include the following:

- Ensuring compliance with existing laws and respect for well-established ethical norms (e.g., informed consent) and values (e.g., transparency);
- Enabling responsible and legitimate SG activities to be executed efficiently;
- Promoting development and sharing of socially beneficial knowledge;
- Managing key technical concerns (e.g., unintentional secondary environmental or health impacts);
- Managing key societal concerns (e.g., moral hazard or slippery slope);
- Building trust and legitimacy across stakeholders;
- Aligning interpretation of the above and compliance across potential actors (national, international, and non-state); and
- Helping develop the capacity for future governance to effectively address decisions and responsibilities related to SG deployment.

There currently exists no clear legal framework or institutional locus for global decision making about SG research, development, or deployment. As noted in Chapter 2, some international laws and principles could be applied to certain aspects of research or deployment, but there exists no international governance regime designed specifically for research or development, and there is no one charged with making decisions about whether, how, and when SG should ever be used. Some researchers have argued that SAI would be "easy and cheap", raising concerns about unilateral geoengineering by an individual country, collection of parties, or independent actor, potentially before the consequences of SG were extensively studied. Even barring such unilateral scenarios, there are significant unanswered questions about international governance approaches and institutions for research, development, and decisions about any large-scale testing or use. As research governance extends to potential deployment governance, the institutional challenges increase dramatically.

Although research and decisions regarding whether to pursue SG further may happen over coming decades, the time frame for deployment to achieve and maintain a desired effect is typically envisioned as significantly longer, on the magnitude of decades to centuries. Thus, global-scale interventions could require multidecadal or multicentury coordination and monitoring. This poses a particular challenge for the development and sustainment of institutions that could manage SG over many generations and with transnational/global cooperation, with no clear historical success models to emulate.

3.3b Research and Research Governance Intersection

> "[Science] is intertwined with technology, innovation, and socio-economic change, facilitating the creation of new possibilities. It is this aspect—the role that science plays in creating new futures—that raises the most pressing questions for governance."
>
> – *Global Governance of Science: Report of the Expert Group on Global Governance of Science to the Science, Economy and Society Directorate, Directorate-General for Research, European Commission* (Ozoliņa et al., 2009)

SG research and research governance can be mutually supportive and co-evolve. SG technologies are not well developed or understood, and there is not agreement about whether and under what conditions it would be reasonable or prudent to use these technologies. This is a complex domain that involves scientific, social, political, legal, and ethical questions, and these questions interact. For example, to understand the feasibility and desirability of different approaches requires both scientific and social knowledge, and it involves both descriptive components (e.g., What would the climate effects of a certain SAI deployment be?) and normative ones (e.g., "How are different objectives with different spatial or temporal [effects] to be balanced?" [Tuana et al., 2012]). Research can generate knowledge important to answering these questions. Research governance can advance and coordinate appropriate research; facilitate inclusive and equitable public and stakeholder engagement; address physical risks and social, ethical, and legal concerns relating to research; and help to guide research toward socially beneficial ends.

Contemporary scientific research is governed to improve both research processes and research outcomes. In the United States, for example, abuses of human subjects as part of scientific research in the 20th century triggered governance to ensure stronger protections for research participants, particularly centered on the norm of informed consent. These governance changes required more thoughtful research design and provoked reflection on research priorities, arguably contributing to better processes and better outcomes for research.

Although governance is well integrated into many scientific research processes, traditional mechanisms focus primarily on protection of human and animal subjects, assessment of direct environmental risks of research, research integrity, transparency, and funding accountability. This research governance paradigm emphasizes the responsibilities of individual researchers and research groups to ensure that their research conforms to laws, guidelines, and effective practices, and tends to separate governance of research processes from governance of research products. This approach implicitly relies on a linear model of innovation, beginning with basic research, then moving to applied research, (technology) development, and (production and) diffusion (Godin, 2006). The linear model implicitly assumes that the main social and policy decisions regarding the use and regulation of particular technologies occur once a technology is fully formed.

A large body of scholarship in science and technology studies challenges the linear model, however, showing how "ethically significant decisions are often embedded in the scientific analysis itself" (Tuana et al., 2012) and that scientific ideas and beliefs are embedded in and evolve together with representations, social identities, discourses, and institutions (Jasanoff, 2004). Other research suggests that the changing relationship between science and society necessitates a transparent, participative, and context-sensitive scientific process in order for the generated knowledge to be socially robust (Gibbons, 1999; Nowotny et al., 2001). This is particularly true of issue-driven areas with high stakes, differing values, and difficulty in reducing uncertainty, in which a post-normal scientific approach involves broader communities in knowledge generation and validation (Ravetz and Funtowicz, 1999).

Innovation studies literature also indicates that successful innovation is based on interactions between the science and technology community and other actors (e.g., Kline and Rosenberg, 1986) with "user-producer" interactions being particularly important (Lundvall, 1992). Even framing research questions and setting a research agenda involves judgment and values (Jasanoff, 2019), and differences in frames may lead to policy controversies (Schön and Reid, 1994). In the case of SG, for example, one of the main motivations for research is concern about the human and ecological impacts of climate change and a desire to understand whether and how SG could mitigate these impacts and risks. However, other values are also at stake: some believe that large-scale SG would be a hubristic and morally problematic response to climate change (e.g., see Hamilton, 2013), while others worry that geoengineering cannot be democratically governed (Hulme, 2014; Owen, 2014; Szerszynski et al., 2013), and still others argue that geoengineering would be likely to reduce or increase global inequities (Horton and Keith, 2016; Preston, 2012; Svoboda et al., 2011).

Although some of the debate over SG focuses on whether it is "good" or "bad," a more nuanced approach is useful when considering the governance of research. SG includes a range of technologies that could be developed and utilized in a variety of ways, or not utilized at all, and a blanket assessment can obscure the diverse forms that geoengineering technologies might take (e.g., Flegal and Gupta, 2018; Stilgoe, 2015). Additionally, the research process itself will shape whether and how these technologies are developed, and normative questions can be explicitly discussed and explored as part of this process.

SG research is goal oriented, guided by the aim of exploring approaches that might temporarily alleviate some of the negative effects of global climate change. However, the precise mission for geoengineering research is not always clearly defined. Different rationales and purposes for SG have been offered, and the design of particular geoengineering strategies depends on the central purposes for which it is being developed, as well as on trade-offs between various objectives (offsetting effects of climate change on temperature versus offsetting effects on precipitation).

MacMartin and Kravitz (2019) argue that although SG research thus far has focused on modeling the impacts of particular geoengineering scenarios and identifying the uncertainties associated with those predictions, additional attention is needed to the design question, "How would one deploy to meet specified objectives?" Defining these objectives is a value-laden enterprise, and the particular objectives one identifies shapes the kinds of scenarios that are modeled and explored. International engagement as well as input from diverse publics can support the development of model scenarios that reflect various perspectives and objectives. In addition, stating explicitly the objectives underlying various SG model scenarios can clarify their strengths and limitations and reduce the likelihood that modeling will focus on an overly narrow range of scenarios.

SG research is often framed from the perspective of an unspecified deployer—for example, what kind of geoengineering do we want to consider, and what effects would it have? Given certain objectives, how might we design a geoengineering strategy that would achieve them? Should we focus on optimal strategies or robust ones (cf. Bellamy, 2015)? In each of these questions, the "we" is ambiguous (additionally, the "we" of the designers is not necessarily the same "we" as the decision makers), and there are other perspectives from which the mission of geoengineering research could be understood.

For example, some countries might be less interested in determining how to design an SG strategy than about how to detect and attribute any negative side effects of another country's intervention; other countries may be legitimately worried about existential threats from unabated climate change and therefore may be particularly interested in engaging with and supporting deployment-oriented research. Other nations might be interested in studying ways to counteract geoengineering efforts that they oppose, and if future generations were to inherit a geoengineered world, they might be more concerned about how to safely phase out geoengineering than how to start it.

Given the complexities of these interactions, research without continuous co-evolution of research governance striving to incorporate evolving objectives and objections seems certain to result in sub-optimal execution hindered by various forms of backlash.

3.3c Society-Research Governance Intersection

The substantial and growing body of literature on ethics, justice, and equity addresses a range of issues including whether and under what conditions geoengineering would be morally permissible; whether and how SG could be fair and equitable, considering multiple dimensions of justice (e.g., distributive, procedural, recognitional, and intergenerational); what principles might guide ethical governance; and how to evaluate SG in relation to other climate response options and address interactions with other climate responses. Such societal interests link governance of what and how SG research is conducted and its implications for influencing any subsequent consideration of SG deployment.

SAI is typically envisioned as a global-scale intervention, and the effects cannot be isolated to local or regional scales due to dispersion of aerosols throughout the stratosphere (although it could be designed to have relatively larger influence in the Arctic, for example). National-level research, governance, and stakeholder engagement may be starting points, but it should be remembered that stakeholders are global. Values and preferences surrounding research, governance, and whether and under what conditions SG could or should be used vary widely. In addition, SG may interact differently with social and ecological systems in different parts of the world, thus raising distinctive local or regional concerns. It is important not to generalize too widely from a narrow subset of stakeholders, research studies, or governance proposals.

Societally informed implications for research governance go beyond outdoor experimentation. Although some areas of SG research, such as modeling, have no direct climatic effects, the technologies being explored are typically envisioned as regional- to global-scale interventions that would potentially (for small-scale MCB) or necessarily (for global SAI) have transboundary effects. Therefore, the international and transboundary dimensions of SG deserve consideration throughout the full course of research. In addition, although current U.S. and international laws focus primarily on physical impacts, stakeholders and members of the public have shown much more wide-ranging concerns in relation to SG research. For example, concerns surrounding the Stratospheric Particle Injection for Climate Engineering experiment, which generated significant controversy, centered not on the experiment's minimal environmental effects but on the potential for the experiment to open the door to further development of SG and the private ownership of the technology.

These concerns also include the fact that the technologies under consideration could be used for decades or centuries; thus, future generations would inherit responsibilities for managing this deployment. Such responsibilities could be viewed as burdensome to future generations (especially if the use of SG were not accompanied by substantial climate mitigation efforts); at the same time, doing research now may benefit future generations by providing knowledge that can inform critical decisions and may provide an additional possible strategy to reduce some negative impacts of climate change.

3.3d The Nexus of Research, Society, and Research Governance

Because SG research and development are controversial and socially consequential, and the technologies themselves could have a range of regional- to global-scale impacts, building trust, legitimacy, accountability, and social responsiveness in both research and research governance are key. Even if some research and research governance initiatives begin within individual nations, the international dimensions of research and development are crucial, and inclusiveness, cooperation, coordination, and trust are critical in developing research and research governance from their earliest stages.

In this context, neither a "governance first" nor "research first" approach will work; rather, research and research governance need sustained interaction over time (see Box 3.2). At this early stage of research, there is an opportunity to co-develop research and research governance and programmatically facilitate their interaction over time. More specifically, one can co-develop governance approaches, governance research, governance capacity, and governance structures alongside research (with mutual learning between the research and research governance efforts), beginning in the early stages, in order to make thoughtful and legitimate decisions about whether or how research should proceed, what directions it should take, and whether and under what conditions SG should ever be used.

BOX 3.2
Responsible Research and Innovation Models

Emerging models of *responsible research and innovation* (RRI) hold significant promise in addressing the complex sociotechnical dimensions of technologies such as artificial intelligence, genetic engineering, nanotechnology, and geoengineering. RRI does not rely on a linear model of innovation; instead, it acknowledges the deep interconnections among science, technology, and society and provides frameworks for the development of socially responsive science. Owen et al. (2012) identify three important features of RRI:

- **Science *for* society: socially guided research goals.** Rather than focus on restricting or constraining inquiry, RRI focuses on guiding research "toward socially desirable ends," asking "how the targets for innovation can be identified in an ethical, inclusive, democratic, and equitable manner." To achieve this goal, RRI incorporates public and stakeholder engagement to help shape scientific agendas.
- **Science *with* society: engagement, deliberation, and responsive research.** Socially responsive science requires not only socially guided goal setting but also ongoing engagement in the process of science itself. This involves engaging publics and stakeholders throughout the research process to anticipate the potential environmental, social, political, economic, and other consequences of research and innovation; reflect on research aims in light of those potential consequences; and inclusively deliberate about and adapt research trajectories as learning proceeds.
- **Collective responsibility for science and innovation.** RRI adopts a broader vision of responsible science than traditional "research ethics" models that focus on the responsibilities of individual scientists. Rather than conceive of responsibility as resting exclusively with scientists, RRI takes a collective approach that involves funders as well as "actors and users who collectively translate ideas into application and value."

There are multiple rationales for RRI and for the greater social engagement it requires (Owen et al., 2012). The *instrumental* rationale is that RRI can smooth the pathways to innovation by creating stronger social support for research and preventing public backlash in response to concerns about emerging technologies. The *substantive* rationale is that RRI can generate better science and innovation, which is more attentive to social needs and attuned to issues, opportunities, and risks that might otherwise be overlooked. The *normative* rationale is that RRI provides a more democratic, just, and equitable approach to scientific research and technological development, enabling people to engage in processes that shape the futures that affect them and others.

RRI provides one model for greater integration between science and technological development and broader societal values and priorities. It is part of a broader set of approaches to science that facilitate greater societal engagement in the production of scientific knowledge.

Conclusion 3.3: Research, technology development, and governance are often path dependent. Early decisions about how to structure and govern SG research may create momentum that shapes future research, development, and governance. Commitments to transparency, justice, and broad engagement in the design and implementation of research will facilitate institutionalization of these values and practices going forward.

3.4 PRINCIPLES FOR SOLAR GEOENGINEERING RESEARCH AND RESEARCH GOVERNANCE

In order to integrate the breadth of the complexity of the intertwined research, social, and governance issues associated with SG, the committee explored higher-level principles to inform the design of a research agenda and associated governance mechanisms and to ensure completeness in addressing critical elements. The following section discusses principles of general governance, research governance, and international law that are relevant to SG, as well as some of the specific governance proposals that have been developed in relation to research, development, and any possible future consideration of deployment. Drawing on these examples, the concluding section identifies key guiding principles for research and research governance.

3.4a General Principles of Governance, Research Governance, and International Law

> "The governance of science needs to focus on the whole spectrum of scientific activity, from theory construction and basic research to technological development and innovation." – Ozoliņa et al., 2009

International governance principles have been proposed for many different domains, and there is often significant overlap among them. For instance, in 1997, the United Nations Development Program identified *participation, rule of law, transparency, responsiveness, consensus orientation, equity, effectiveness and efficiency, accountability,* and *strategic vision* as key principles of good governance.[6] In 2001, the European Commission identified *openness, participation, accountability, effectiveness,* and *coherence*

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[6] See https://web.archive.org/web/20080904004111/mirror.undp.org/magnet/policy/chapter1.htm.

as central. Woods (1999) focuses on three key principles for good governance in the international domain: *public participation, accountability,* and *fairness*—noting that public participation gives "affected parties access to decision making and power so that they have a meaningful stake"; accountability "requires clarity about for whom or on whose behalf the institution is making and implementing decisions"; and fairness applies both to the processes by which decisions are made and the outcomes of those decisions. Woods further notes that accountability depends on transparency, which provides information critical to holding institutions accountable.

Woods' principles were not developed specifically for global governance of science, but they overlap with science governance recommendations such as those of the 2009 Global Governance of Science report to the European Commission, which endorsed five principles: *openness, participation, accountability, effectiveness, and coherence* (Ozoliņa et al., 2009). The recommendations of *A Framework for Addressing Ethical Dimensions of Emerging and Innovative Biomedical Technologies* reflect many of these same principles, adapted for a biomedical context. These include principles focused on *advancing the general public good, protecting the interests of those more specifically affected, ensuring integrity of the research process, engaging relevant communities, and ensuring oversight and accountability* (NASEM, 2019b).

More directly applicable governance proposals may be found in the environmental arena. For instance, the Lisbon Principles for sustainable ocean management (Costanza et al., 1998) include *responsibility* (use resources in ways that are ecologically sustainable, efficient, and fair), *scale-matching* (consider and integrate across multiple scales), *precaution* (err on the side of caution, especially with respect to irreversible impacts), *adaptive management* (iteratively assess and adjust), *full cost allocation* (consider and include all social and ecological costs and benefits), and *participation* (engage stakeholders in decision making).

In the realm of natural resource management more broadly, Lockwood et al. (2010) drew on an expert panel, literature review, and work with Australian governance authorities to develop eight recommendations for governance. They argue that governance should be "*legitimate, transparent, accountable, inclusive, and fair* and… also exhibit *functional and structural integration, capability, and adaptability*." These environmental governance recommendations aim to be responsive to social values, as well as to cope with "complexity, uncertainty, interdependency, and deficiencies in resources, expertise, and knowledge" (Lockwood et al., 2010). The emphasis on inclusivity and participation, integration, capability, and iterative assessment and adaptability particularly speak to these features. As indicated below, these latter elements often require approaches to governance that include but extend beyond traditional mechanisms. In governance of science, this involves strengthening connections and facilitating greater communication between "science" and "society," through ongoing engagement with stakeholders, publics, and decision makers and increased attention to "usable science," developed in response to social values and needs.

3.4b Existing Proposals for Geoengineering Research Governance

Developed subsequent to the UK Royal Society report (Shepherd, 2009), the Oxford Principles (Rayner et al., 2009, 2013) were developed and presented to the British House of Commons, then later published in an academic journal. The Oxford Principles, which aimed to address "early research through deployment," are as follows:

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

In 2010, a conference at the Asilomar conference center in California brought together researchers to discuss geoengineering governance. The resulting report identified five principles as the basis for research governance, many of which overlap with the Oxford Principles:

- Promoting collective benefit;
- Establishing responsibility;
- Open and cooperative research;
- Iterative evaluation and assessment; and
- Public involvement and consent, with "consideration of the international; and intergenerational implications of climate engineering" (ASOC, 2010).

As described in Chapter 2, the Code of Conduct for Responsible Geoengineering Research (Hubert and Reichwein, 2015) was developed subsequently to provide a more specific set of rules that could be followed by researchers and others. Provisions relating to research discuss cooperation across jurisdictions, practices for responsible research, assessment of outdoor experiments, public participation, post-project monitoring of outdoor experiments, and open access to information.

More recently, Gardiner and Fragnière, 2018) extended and modified the Oxford Principles in their 10 Tollgate Principles for geoengineering governance:

- **Framing.** Geoengineering should be administered by or on behalf of the global, intergenerational, and ecological public, in light of their interests and other ethically relevant norms.
- **Authorization.** Geoengineering decision making (e.g., authorizing research programs, large-scale field trials, and deployment) should be done by bodies acting on behalf of (e.g., representing) the global, intergenerational, and ecological public, with appropriate authority and in accordance with suitably strong ethical norms (e.g., justice and political legitimacy).
- **Consultation.** Decisions about geoengineering research activities should be made only after proper notification and consultation of those materially affected and their appropriate representatives and after due consideration of their self-declared interests and values.
- **Trust.** Geoengineering policy should be organized so as to facilitate reliability, trust, and accountability across nations and generations.
- **Ethical Accountability.** Robust governance systems (including of authority, legitimacy, justification, and management) are increasingly needed and ethically necessary at each stage from advanced research to deployment.
- **Technical Availability.** For a geoengineering technique to be policy-relevant, *ethically defensible forms* of it must be technically feasible on the relevant time frame.
- **Predictability.** For a geoengineering technique to be policy-relevant, ethically defensible forms of it must be reasonably predictable on the relevant time frame and in relation to the threat being addressed.
- **Protection.** Climate policies that include geoengineering schemes should be socially and ecologically preferable to other available climate policies and focus on protecting basic ethical interests and concerns (e.g., human rights, capabilities, and fundamental ecological values).
- **Respecting General Ethical Norms.** Geoengineering policy should respect general ethical norms that are well founded and salient to global environmental policy (e.g., autonomy and justice).
- **Respecting Ecological Norms.** Geoengineering policy should respect well-founded ecological norms, including norms of environmental ethics and governance (e.g., sustainability, precaution, respect for nature, ecological accommodation).

Compared to the Oxford Principles, the Tollgate Principles provide more specificity regarding the interests that geoengineering research or deployment should serve: a "global, intergenerational, and ecological public." Additionally, compared to the Oxford Principles, the Tollgate Principles make reference to a number of more substantive ethical norms, including *sustainability, precaution, respect for nature, justice, and human rights*. The Tollgate Principles also more explicitly assert that forms of geoengineering should be *ethically defensible*, as well as *technically feasible* and *reasonably predictable*. Both the Oxford and Tollgate Principles share a commitment to trust and legitimacy, accountability, and engagement of affected publics or their representatives.

The Oxford Principles, Asilomar recommendations, and Tollgate Principles represent a subset of the proposals for principles of SG governance within a broader landscape of reports and proposals, plus a growing academic literature. Notably, there is significant convergence in certain basic requirements and desired features of research governance, especially in mainstream literature. However, there exists significant divergence in other areas, including regarding whether further research should be pursued.
At one end of the spectrum, some oppose further research (Cairns, in Hulme, 2014; Long and Cairns, 2020) or the application of stringent conditions before additional research is undertaken (Whyte, 2012). At the more permissive end, proposals call for de-exceptionalizing SG research and limiting governance below a certain threshold (see, e.g., Parson and Keith, 2013). Despite differences, there seems to be consensus among commentators on governance that clearly defined governance mechanisms are needed for any future expansion of research. Jinnah (2019) argued that "good governance" of SG should promote fair distribution of benefits, protect vulnerable populations, and amplify marginalized voices. This underscores the idea that research governance needs to promote research and development that is fair and equitable, including concern for substantive impacts and inclusive processes.

Across the writing on SG research and research governance, certain key ideas and principles repeatedly emerge:

- Transparency;
- International coordination and cooperation;
- International governance of any experiments with transboundary effects (and seeking to avoid transboundary harm);
- Public participation;
- Research in the public interest; and
- Legitimacy and accountability.

Also discussed repeatedly, but not explicit in all proposals, are the following:

- Fairness and inclusion;
- Intergenerational considerations; and
- Maximized benefits and minimized harms and risks.

Conclusion 3.4: Earlier analyses converge on several salient principles for SG research; notably, calling for research and research governance approaches that are

- **in the interest of advancing the public good;**
- **aimed at advancing knowledge while taking into account societal norms and perspectives;**
- **coordinated and cooperative;**
- **adaptive and subject to ongoing assessment, check-points, and, if needed, exit ramps;**
- **inclusive and responsive, including engagement by diverse publics, stakeholders, and governments; and**
- **fair, equitable, and transparent.**

In order to advance these principles, it is important to have a research program that is transdisciplinary, international, and diverse with respect to disciplines and methods, researchers, countries, and perspectives represented; and research governance strategies that aim to build trust and legitimacy.

Our subsequent research governance recommendations, discussed in Chapter 5, are informed by these principles.

CHAPTER FOUR

A Solar Geoengineering Research Program: Goals and Approach

4.1 INTRODUCTION

Solar geoengineering (SG) research will almost certainly evolve along several tracks. The kind of individual-investigator research that has been the foundation of most of the available information to date will continue. Increased interest in SG from philanthropies and individuals may lead to an increase in opportunities for building coordinated research programs and tackling diverse questions related to SG. The Harvard Solar Geoengineering Research Program, the Marine Cloud Brightening Project at the University of Washington, and the Marine Cloud Brightening Project for the Great Barrier Reef based in Australia are examples of existing programs that, while still modest in scale, have grown to include several researchers representing a range of disciplines. As national or international programs emerge, it will be important to recognize, build upon, and coordinate across efforts at every scale. Even in cases where lines of research are technically non-overlapping, participation in coordinated efforts can play a valuable role in building trust and transparency.

Design of an effective, coordinated SG research program, however, raises many questions that require careful consideration—for instance, should some kinds of research be funded through governmental sources and other research funded through non-governmental entities? Should the roles and responsibilities for research funding change as the scale of a research program passes particular thresholds of size and scope? Are there specific kinds of research that should be executed as coordinated, multi-investigator, multi-funder projects? How should the priorities for coordination evolve in response to political, social, economic, or climate dynamics?

We approach the general topic of research design and coordination from the starting point of efforts based in the United States. This is a choice based on practical considerations. Operationally, research agencies of the U.S. federal government already have extensive experience supporting global change research and coordinating that research across agencies. Many, though certainly not all, features of SG research will fit into the framework for existing global change research. The committee also considered the role of philanthropies in supporting national or international SG research, which introduces both advantages and disadvantages.

A central feature of a national SG research program and of U.S. input into international or other programs is that the goal of the program should be clearly and unequivocally to understand the prospects and limitations of SG options and not to drive toward eventual deployment. As discussed in more detail in Chapter 6, a national research program should be designed to explore the full range of issues relevant to possible future deployment. This should include not only issues related to technical feasibility and efficacy but also issues related to indirect effects, social implications, human perceptions, and judgments about equity. If these technologies are ever seriously considered for deployment, the perceived legitimacy of the research program will be as important as the specific findings. Thus, a key challenge is to develop and coordinate a research program that is informing decisions without committing to further development of that technology or creating research communities that are invested in its ultimate deployment. The next chapter identifies specific governance mechanisms to foster norms among researchers.

4.2 GOALS AND ATTRIBUTES OF A SOLAR GEOENGINEERING RESEARCH PROGRAM

The type of ongoing research and research governance framework that the committee envisions is illustrated in Figure 4.1. This framework would enable research governance and research activities to evolve hand-in-hand, with ongoing mechanisms for stakeholder engagement and input into both components. This engagement, combined with periodic programmatic assessments and revisions, could allow a research program to be responsive to new findings and developments that arise as the program and the knowledge base evolves.

Business-as-usual pathways for establishing a research program may not suffice given the many complex features of SG that are discussed in earlier chapters (e.g., that the issue is value-laden, involves deep uncertainties, and is highly dependent on social and political context). Understanding of how to design a robust program that meets all the principles and goals recommended herein is in a nascent state; thus, a research program needs to be sufficiently flexible to allow for improvements and adjustments as our understanding grows. The committee offers suggestions for the rough contours of a research program but, at the same time, suggests that expanding engagement

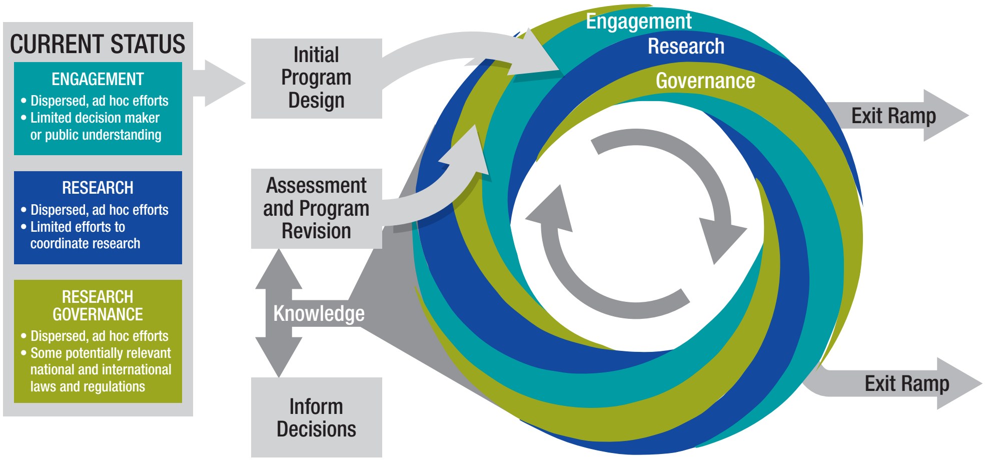

FIGURE 4.1 Schematic of SG research and research governance environment.

with stakeholders around the world will be needed to help fill gaps in understanding and perspective and will be useful for the initial program design.

The SG research and research governance framework needs to be stepwise and iterative in nature. Reflexivity, learning, and adaptiveness are essential in an interlinked system, in which evolution in any one domain will have implications for future activity both within that domain and in other parts of the system (e.g., new knowledge about potential impacts may influence understanding of deployment options and governance arrangements). The possibility of "exit ramps" together with periodic assessment and program revision (as illustrated in Figure 4.1) would build in opportunities to make adjustments as needed.

This possibility of exit ramps helps address the general problem of research funding for a specific project or a larger program becoming locked into place and renewed year after year even in the absence of meaningful progress. This problem occurs because expectations become set, among both the funded researchers and the funding agency, that can be difficult to overcome. In the context of SG research this dynamic can be particularly troubling. The goal of the research is not, fundamentally, to be a continuing investigation into some areas of science but rather to answer important questions about the feasibility, risks, and acceptability of different SG approaches. Thus, support should focus only on research that can provide information valuable (in the short term and mid-term) to those goals. Locking in of nonrelevant research in this context could waste resources and might lead to the continuation of research on approaches that have been rejected on social or political grounds.

No perfect solution exists, but some approaches can make it easier to terminate projects that are no longer worthwhile. One approach is to include fixed terms to the projects with pre-set milestones that must be met to justify continuation. A second approach is to mitigate the reliance interests of the researchers by providing a warning period—for example, a warning that funding will end in 1 year unless some objectives are reached. A third option might be to demand discontinuance of some existing projects every year, forcing the funding authority to make choices among their existing inventory. Any of these methods, of course, should be announced in advance to the funding applicants, and each would require disciplined review, preferably by a body that is overseeing more than one kind of research and so is positioned to make choices about more and less promising approaches.

A socially robust research and research governance environment should be integrative, as illustrated by the braided circle in Figure 4.1. The program will need to integrate insights across numerous disciplines, as diverse as climate dynamics, atmospheric physics and chemistry, terrestrial and oceanic ecology, agronomy, medicine, political science, sociology, law, philosophy, and engineering. This will be necessary for holistic assessments and to design possible solutions, with collaborators working toward a shared set of objectives along a common timeline. Research activities will also need to stretch across a lengthy "chain of inquiry." Pursuing ad hoc, isolated studies as is presently the case is not an effective pathway for rapidly advancing understanding.

Likewise, public engagement and transparency are mainstays of socially robust research and will be critical for the success of a research program. Diversity is needed in terms of the sites of production of knowledge and the expertise assembled to engage in research. A program will be most effective if it is ambitiously inclusive and systematically incorporates a diversity of stakeholder and disciplinary perspectives, especially those that are typically marginalized. The committee thus envisions public engagement being woven into both SG research and research governance, as shown in Figure 4.1.

It will be important to establish and utilize mechanisms for stakeholder input and decision-maker needs, beginning with the stage of program design. One way of ensuring that the program as a whole is responsive to decision-maker needs is to establish mechanisms to assess those needs and incentivize program leaders to take those needs into account. Relevant mechanisms could include convening a stakeholder advisory committee, conducting research on needs, or requiring co-production as a research approach for some portion of projects. Similarly, a program will need to be nimble and be able to adjust priorities as they emerge from both research findings and decision-maker needs.

BOX 4.1
Building Legitimacy in Knowledge Production

Social science research has highlighted that the production of knowledge cannot be decoupled from, and in fact is increasingly shaped by, the context in which it is produced, and this realization has important implications for the design of an SG research program. The following are some relevant insights in the literature about the challenge of ensuring a research program is effective and legitimate.

- Gibbons (1994) defines two different modes of production of knowledge: Mode 1, where problems are set and solved in a context governed by the academic interests of a specific community; and Mode 2, where knowledge is produced in a context of application, a diversity of sites, and a broader set of communities. The evolving relationship between science and society has increased the need for context-sensitive science that aligns more with Mode 2, to ensure that knowledge production is seen by society to be both transparent and participative (Gibbons, 1999; Nowotny et al., 2001). When knowledge is produced according to Mode 2, scientific ideas and beliefs are embedded in and evolve together with representations, social identities, discourses, and institutions. In effect, science and social order are co-produced (Jasanoff, 2004).
- When knowledge is produced in the context of a specific application, where "facts are uncertain, values in dispute, stakes high, and decisions urgent," knowledge generation and verification must occur through "extended peer communities" (Ravetz, 1990).
- Differences in framing of an issue may lead to policy controversies, especially in complex contexts involving multiple perspectives. Thus, engaging in careful reflection on framing could help improve the effectiveness of policy solutions (Schön and Reid, 1994).
- Nowotny (2003) suggests that ensuring that the design of an SG research program is "socially robust" entails three closely interrelated aspects: (i) Robustness is tested for validity, not only inside the laboratory. (ii) Social robustness is most likely to be achieved through involving an extended group of experts, real or symbolic users, and real or "imagined" lay persons. (iii) Since society is no longer only a "recipient" of science but an active partner participating in the production of social knowledge, the robustness of such knowledge results from having been repeatedly tested, expanded, and modified.
- Jasanoff (2003) suggests a related framework with four focal points (*framing, vulnerability, distribution,* and *learning)* that bring into focus questions such as "what is the purpose? who will be hurt? who benefits? and how can we know?" Such a framework requires attention to both substance and process and stresses deliberation as well as analysis.

Interactions and learning across various operational elements are critical for a successful SG research program. Specifically, coordination is essential for integrating perspectives from research, from those involved in supporting and guiding this research enterprise, and from those exploring governance strategies for any potential future deployment. An SG research program could employ numerous mechanisms to effectively coordinate research efforts among multidisciplinary investigators. While most research will likely advance through individual and group projects, there are numerous coordinating mechanisms—such as community-driven science plans, town hall meetings at scientific organization conferences, scientific steering groups, interagency program manager groups, joint requests for proposals, and annual principal investigator meetings—that could be employed to ensure that these individual efforts are coordinated and organized to communicate as research is planned and executed and that highest priority efforts are supported.

Finally, the SG research program should award funding in a manner that encourages creative thinking while avoiding commitments to further development of a specific technology or to the creation of research communities that are invested in its ultimate deployment. Awarding funding through a competitive process ensures that diverse researchers are able to apply for funding, and competition among research teams also ensures that the best ideas are generated and tested.

Funding for SG research from for-profit organizations raises special concerns. If any such organizations have taken successful research steps toward deployable SG technologies, they will likely have a financial interest in seeing actual deployment advance. For an issue as controversial and complex as this one, that kind of thumb-on-the-scale should be avoided if possible. One might try to discourage or even prohibit for-profit research (as has been done for other issues in some circumstances, such as with regard to nuclear weapons). But for SG research, some work might be best carried out by for-profit firms. For example, companies that build aircraft may be better placed than government or university researchers to assess the possibilities of high-altitude transport aircraft. Similarly, firms that build spraying nozzles may be better able to find improvements to them. Of course, even in the cases in which for-profit entities are best suited for carrying out the research, government agencies may still be the primary source of funding.

Some small-scale research on the technology needed for deployment is appropriate only to the extent that it is necessary either to assess basic feasibility or to support other key research needs (e.g., for small-scale experiments, or to understand boundaries of feasibility such as achievable altitudes for stratospheric aerosol injection [SAI]). Research aimed solely at developing the technology needed for deployment should be discouraged (whether funded by governments, foundations, or private firms) until decisions on deployment have been made. We recognize that it may be difficult in some cases to draw the line between feasibility-oriented research and deployment-related research. The best protection is likely to be a robust decision-making process for deployment that can minimize any inappropriate influence stemming from potential profits.

Recommendation 4.1: The United States should implement a robust portfolio of climate mitigation and adaptation. In addition, given the urgency of climate change concerns and the need for a full understanding of possible response options, the U.S. federal government should establish—in coordination with other countries—a transdisciplinary, SG research program. This program should be a minor part of the overall U.S. research program related to responding to climate change. The program should focus on developing policy-relevant knowledge, rather than advancing a path for deployment, and the program should be subject to robust governance. The program should

- **advance knowledge relevant to decision making, including design of future research efforts;**
- **ensure transparency, disciplinary balance, and public and stakeholder engagement;**
- **coordinate research across federal agencies and with research outside the U.S. federal government; and**
- **limit research on technology with direct applicability for deployment to early-phase, fundamental research.**

The program should, from the outset, prioritize development of international coordination and co-development of research with other countries, in line with the governance recommendations in Chapter 5 (especially Recommendations 5.1q, 5.1r, and 5.1s).[a]

The program should establish robust mechanisms for inputs from civil society and other key stakeholders in the design of the research program, as well as promote their engagement in relevant program components. Key stakeholders include climate-vulnerable communities and underrepresented groups, including from indigenous populations and the Global South.

The program and its outcomes should be regularly reviewed and assessed by a diverse, inclusive panel of experts and stakeholders (including consultation with international counterparts) to determine whether continued research is justified and, if so, how goals and priorities should be updated.

"Exit ramps" (i.e., criteria and protocols for terminating research programs or areas) should be an explicit part of the program, with mechanisms to terminate a research activity, for example, if it is deemed

to pose unacceptable physical, social, geopolitical, or environmental risks or if research indicates clearly that a particular SG technique is not likely to work.

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[a] This refers to the committee recommendations on (q) promotion of international cooperation and co-development on research teams, (r) promotion of international cooperation among national scientific agencies, and (s) voluntary coordination and cooperation by countries and non-state actors.

4.3 CAPACITY NEEDED TO ADVANCE SOLAR GEOENGINEERING RESEARCH AND RESEARCH GOVERNANCE

SG requires new knowledge in understanding both the physical phenomena relating to SG interventions and the potential ecological, economic, social, political, and human implications of such interventions. But these implications necessarily will vary across space and time and are context-dependent. Therefore, research capacity to understand the nature of these impacts in any specific location has to be cognizant of local context and draw upon local knowledge. This will require multiple kinds of expertise such as modeling and experimental natural science (e.g., atmospheric science and ecological sciences), social science, and the ability to engage in transdisciplinary research that brings to bear multiple disciplines on identifying the issues of local relevance and then engaging in the production of knowledge to address these issues. Furthermore, given the complexity of these endeavors, even the understanding of how to effectively govern and guide such research might be inadequate and therefore itself a subject of research. Lastly, there is a range of questions pertaining to the governance of SG interventions—for example, under what conditions and under whose oversight might a specific SG intervention be initiated and terminated, and how do these governance systems fit and interact with broader climate governance systems? Exploration of various options and their appropriateness in both a transnational and local context requires yet other forms of research capacity that draw on the humanities and social sciences as well as practical knowledge of the state and dynamics of the global climate policy domain.

The capacity to suitably govern SG research will require an understanding of the nature, needs, and concerns relating to this research such that it can be enabled and supported in a manner consonant with societal perspectives and objectives, while being mindful of, and minimizing, the risks that may result from such research. This will require close engagement with the research community as well as relevant stakeholders, while also being cognizant of approaches in other issue domains as well national contexts. The governance of deployment, on the other hand, probably would require some form of international engagement, given the transboundary nature of interventions and capabilities to jointly determine approaches and pathways that reflect both national priorities and the international landscape.

The transdisciplinary nature of SG, its linkage to other issue domains, and the wide breadth of stakeholders whose perspectives are of relevance necessitate a high level of coordination capacity to draw together different forms of expertise and knowledge to inform, shape, guide, and engage in research. Similarly, some aspects of the research governance will require coordination among relevant experts, stakeholders, and policy makers within and beyond national boundaries. Such capacity may particularly be in short supply in developing countries where policy makers and other actors are overstretched.

It is likely that much natural and social science research capacity will reside in academic and other research institutions (including government research laboratories). In some cases, international research actors (e.g., International Institute for Applied Systems Analysis and The World Academy of Sciences) may play a key role in undertaking or facilitating research, especially in cases in which individual countries do not have appropriate research institutions. A well-informed and active civil society can play a key role in bringing to bear a variety of perspectives into these efforts as well as helping ensure that marginalized groups also have a voice in the process. Government agencies will also necessarily play a key role in the funding and oversight of SG research efforts, but given the unusually complex nature of this issue and the need for transdisciplinary, sociotechnical, "Mode 2" science, these agencies may also need to develop the capacity to support and govern this research enterprise in an appropriate fashion.

On the other end, engaging with SG governance will require an altogether different kind of capacity that requires drawing upon and marshaling the full breadth of scientific and societal resources. Since interactions between different communities—such as between natural and social scientists, between researchers and policy makers, and between researchers and citizens—will play an important role in an effective SG enterprise, boundary organizations that can mediate communication across these interfaces are likely to play an important role in facilitating these interactions (McNie, 2007). Examples of such boundary organizations include the Intergovernmental Panel on Climate Change (IPCC), professional societies, and civil society groups. Networks may be seen as another form of capacity, which is characterized by flow of knowledge across community boundaries, thereby enabling transdisciplinarity. Some forms of networks may self-organize, as in the case of collaborating researchers, but in many cases the development and sustainment of networks may require efforts targeted specifically toward this end (Dilling et al., 2015).

Public funding can play a central role in developing local capacity that might be needed in order to support the kinds of activities (e.g., natural and social science research, boundary work, and knowledge network development) that might be required for any particular form of SG research enterprise—and indeed even a systematic exploration of the kind of research enterprise that might be societally desirable. While private funding such as from philanthropic organizations has been and can continue to play a role in supporting such work, it is not accountable to the public in the same way as a public agency and therefore cannot be seen as a substitute for public support. On the other hand, some coordination between public and private efforts may be useful in enhancing the efficiency of capacity development.

International support may be particularly useful for the development of local capacity in countries that have limited public funding to support SG research. This issue will require thoughtful engagement, though, both in terms of understanding what kinds of capacities are particularly needed in that context and how to develop such capac-

BOX 4.2
Why Start a Research Program Now?

Over the past several years, the world has seen continuing improvements in the scientific understanding of the why and how of anthropogenic climate change, a growing appreciation of the seriousness of the impacts of warming, and the widespread realization that we are experiencing serious, rapidly increasing damages from the warming that has already occurred. At the same time, progress in addressing the core causes of climate change through decreasing greenhouse gas (GHG) emissions and removing CO_2 from the atmosphere has been limited and has failed to turn the tide on the long-term trend of rising GHG emissions. In many ways, the substantial drop in global CO_2 emissions seen in 2020 (related to the COVID-19 pandemic) reveals the essence of the challenge—economic activity and CO_2 emissions are still strongly linked and tend to rise and fall in lockstep. Ultimately, solving the climate crisis will involve breaking that link.

The world has had scientific warnings about the risks of climate change for decades. From 1990 (when the first IPCC report was issued) to 2019, CO_2 emissions increased by 65 percent and the global average temperature increased by about 0.5°C. The need and potential for accelerating decarbonization is high (NASEM, 2021). But even rapidly accelerated decarbonization may not be sufficient, and further delay in understanding the options imposes real and growing constraints on the nature, cost, and ambition of possible responses. In considering next steps, it is critical to have the clearest possible picture of the full suite of options, including their technical feasibility, social context, possible risks, benefits, and costs.

At this time, understanding of SG is nascent. We lack the knowledge to make even preliminary recommendations about whether the technology should have a place in the portfolio of options ity, especially given limited success in capacity development efforts more generally. Support for international collaboration and coordination may also be particularly helpful.

4.4 FEDERAL AGENCY PARTICIPATION AND COORDINATION

SG research and research governance efforts to date have been ad hoc and dispersed (as discussed in Chapter 2). Most research has been carried out by individual investigators and teams under non-targeted sources of funding. Even the Geoengineering Model Intercomparison Project (Kravitz et al., 2011), an internationally coordinated project designated by a working group of the World Climate Research Programme (WCRP), is conducted on a voluntary basis by individual modeling centers, with no dedicated sources of funding. As with other Earth-science interdisciplinary programs, there would be significant value added by coordinating across modeling, observations, process studies, social and economic studies, scenario designs, and beyond—to

considered for future deployment. This report takes no position on that, since current knowledge is too incomplete to support any recommendation. But the committee believes that a well-designed research program can help provide the information needed to support balanced decisions about next steps and future prospects. Results from an SG research program might support the idea that deployment could be effective, affordable, safe, and publicly acceptable—but they might also reveal that such deployment would be ineffective, too costly, or would raise unacceptable technical or social risks. Without the research, there is no way to know. Without the research, we could be missing the opportunity to decrease unacceptable damages of climate change, or we could be wasting time and energy on concepts destined to go nowhere.

Some of the arguments against an SG research program involve concerns that even early-stage research might build constituencies and institutions that intrinsically point toward or away from deployment. But the holistic and inclusive research program proposed by the committee seeks to balance these path dependencies so that all options remain open, until there is sufficient knowledge for evidence-based decisions. Indeed, one motivation for starting an SG research program now is to help grow the community with relevant expertise, especially in areas where research to date, interdisciplinary integration, and public engagement have been limited.

SG is controversial. Strong positions abound, with voices from different parts of the spectrum emphasizing different aspects, perspectives, and audiences. In this complicated space, a well-designed, broad-based research program, with technical, social, and ethical elements, can play a central role in building the transparency and trust that are foundational for wide support of evidence-based decisions. And in an era when the pace of climate change is closing options, moving forward now with an SG research program can keep as many options open as possible.

help ensure that the research conducted informs (and is informed by) other research as efficiently as possible.

The United States does not currently have a coordinated federal SG research program, nor a coordinated approach for creating such a federal program. Several federal science agencies support global change research activities that advance observational science; climate analysis; detection and attribution research; and the development, evaluation, and application of Earth system models (see Table 4.1). Each agency has different technological and scientific strengths and different missions and cultures, but they could all provide valuable contributions to an SG research program. In fact, a significant fraction of the existing federal climate research enterprise could help advance understanding of SG approaches and impacts. This includes, for instance, ongoing federal research on atmospheric circulation and aerosol/cloud interactions, which is directly relevant for understanding the potential effectiveness and impacts of both SAI and MCB.

TABLE 4.1 Budget Crosscut for Funds Self-Identified by Agencies as Their Contributions to USGCRP Research Activities. Funding amounts are shown in millions of dollars.

Agency	FY2018 Enacted ($M)	FY2019 Enacted ($M)	FY2020 President's Budget ($M)
Department of Agriculture (USDA)	103	101	96
Department of Commerce (DOC)	320	293	194
Department of Energy (DOE)	239	259	117
Department of Health and Human Services (HHS)	10	11	10
Department of the Interior (DOI)	25	25	13
Department of Transportation (DOT)	0	0	0
Environmental Protection Agency (EPA)	18	19	0
National Aeronautics and Space Administration (NASA)	1,499	1,484	1,286
National Science Foundation (NSF)	254	237	219
Smithsonian Institute (SI)	8	8	8
Total (USGCRP)	2,477	2,436	1,943

SOURCE: USGCRP (2020).

The U.S. federal agencies with climate-related research programs[1] most relevant to SG research include the following:

- The U.S. Department of Energy (DOE), with a focus on the troposphere and Earth system modeling and a long history of ground-based atmospheric radiative measurements. DOE is also home to most of the R&D related to energy technologies and carbon capture and storage.
- The National Oceanic and Atmospheric Administration (NOAA), with weather, climate, atmospheric composition and chemistry, and oceanic observation and prediction responsibilities for the nation.
- The National Aeronautics and Space Administration (NASA), with stratospheric platforms, Earth system observations from satellite platforms and airborne facilities, and modeling of climate and atmospheric composition.
- The National Science Foundation (NSF), in fostering investigator-driven research across many disciplines, including human-dimensions aspects, as well as focused efforts at the National Center for Atmospheric Research (NCAR).
- The Defense Advanced Research Projects Agency, with expertise in mission programs.
- The U.S. Department of Agriculture (USDA), U.S. Environmental Protection Agency (EPA), and U.S. Geological Survey, for impacts research related to agriculture, forests, freshwater systems, and other ecosystems.
- The National Institutes of Health, Centers for Disease Control and Prevention, and EPA, for research related to impacts on human health.

Agencies such as DOE, NOAA, and NASA have considerable experience with mission-driven atmospheric monitoring (including aerosol research) and broader integrated assessment modeling. And several individuals within the national laboratories (e.g., DOE/Pacific Northwest National Laboratory, NOAA/Geophysical Fluid Dynamics Laboratory, and NOAA/Earth System Research Laboratories) are carrying out SG-focused research. NCAR is home to a "Community Climate Intervention Strategies" project[2] that coordinates webinars and workshops and has numerous scientists actively publishing SG-related research. None of the federal agencies, however, has resources or personnel dedicated specifically to working on SG issues, are positioned to launch a mission-

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[1] The Office of Naval Research has conducted research on the marine atmosphere in the past, including the 1994 Monterey Area Ship Tracks Experiment. Whether capacity will be available for future research is an open question.

[2] See https://www.ccis.ucar.edu/.

driven research program, or have a mandate to respond to policy makers or provide input to SG-related international assessments. Moreover, because there is no coordinated federal strategy for SG research activities (or even guidance defining what "SG research activities" encompass), it is challenging to identify and track federal funding related to this topic.

The small percentage of climate/global change funding focused on human dimensions research has been identified as a long-standing concern in numerous National Academies reports (e.g., NRC, 2004, 2009, 2012). Some agencies have made modest investments in human dimensions research; for example, NSF's Social, Behavioral and Economics division supports some fundamental research; NOAA, EPA, and DOE support some human dimensions research related to their decision-making needs. However, this is a tiny fraction of the federal investment in physical and natural science research relevant to climate change. Furthermore, federal agencies do not have a clear home for program-directed human dimensions research, resulting in a lack of relevant capacity, resources, and leadership within research coordination efforts. The limited investment in human dimensions research makes it challenging to address some of the questions of greatest relevance for SG research, in which public perception and social attitudes are likely to play an important role in future decisions.

An effective, transdisciplinary research program will require coordination across multiple agencies, national laboratories and cooperative institutes, and academic institutions. While the focus of this study is on a U.S. (national) research program, strong international engagement and open international collaboration will promote the strongest scientific and global policy outcomes.

Interagency Coordination

The importance of cross-agency coordination was emphasized in a U.S. Government Accountability Office (GAO) report about design of a federal geoengineering research program (GAO, 2010). This report noted that some key practices for enhancing collaboration across agencies include establishing a commonly accepted operational definition for relevant activities; emphasizing the importance of leveraging existing resources to support common outcomes and address identified needs; developing mechanisms to monitor, evaluate, and report on results; comprehensively assessing the costs, benefits, and risks of each technological option; and identifying potential overlap among proposed and existing programs. The report suggests that without coordinated efforts to identify relevant research and share information across agencies, policy makers and agency officials may lack key information needed to inform their decisions on SG research.

The U.S. Global Change Research Program (USGCRP) was established in 1990 under the U.S. Global Change Research Act to coordinate the efforts of federal agencies to "assist the Nation and the world to understand, assess, predict, and respond to human-induced and natural processes of global change" (P.L. 101-606). Today the program encompasses 13 agencies (those listed in Table 4.1 plus the U.S. Department of State, U.S. Department of Defense, and the U.S. Agency for International Development). USGCRP is under the purview of the National Science and Technology Council (NSTC) within the White House Office of Science and Technology Policy (OSTP). As such, it is the principal mechanism within the Executive Branch to coordinate global change research across the diverse entities that make up the federal research and development enterprise.

USGCRP is the most logical entity for orchestrating coordination of SG research at the federal level, as part of its larger mandate to manage climate change-related research more broadly. USGCRP has for more than three decades helped coordinate climate research across federal agencies. Coordination mechanisms used by USGCRP include developing strategic plans, organizing monthly meetings of agency representatives, and establishing interagency working groups that focus on specific program priorities. A recent National Academies' review of USGCRP's accomplishments (NASEM, 2017) noted that the *Adaptation Working Group* and the *Climate Change and Human Health Working Group* made important contributions to the third National Climate Assessment, and the *Carbon Cycle Working Group* has facilitated significant progress across multiple agencies.

Despite its successes, the ability of USGCRP to coordinate across participating agencies has at times been hindered by the program's inability to directly control relevant agency budgets or to shift funding to emerging research areas, by the lack of strong leadership, and by insufficient support for coordinating mechanisms (NASEM, 2016; NRC, 2004). Successful management of the national SG research program recommended herein will require a concerted effort by USGCRP, with strong support from NSTC and OSTP, to address these limitations.

Another limitation that must be addressed is that the scope of research currently supported by USGCRP agencies does not match the full breadth of research needs identified in this report. As discussed above, a particular concern is the relatively small investment in human dimensions research, which can be attributed in part to the lack of a strong agency home for such research and the inability of USGCRP to influence agency investments to address these gaps. On the physical science side, USGCRP does not have a strong history of supporting some issues that are critical to SG, such as stratospheric research.

International Engagement

A second report on climate engineering from GAO (2011) addressed the importance of international collaboration. The report highlighted the value of U.S. efforts to sponsor (or at least encourage) joint research with other nations (including developing/ emerging industrial nations); to facilitate rigorous and transparent evaluation of new technologies developed by others; to foster cooperation and norms for conducting research; and to study how deployment of SG technologies could impinge on geopolitical equity, human rights, and justice. GAO (2011) also suggested research on how to define climate emergencies and achieve international agreement on response strategies as well as exploration of issues concerning military engagement in climate engineering research.

USGCRP has a long history of facilitating international research coordination (as described on its website[3]) and this experience could be leveraged for a national SG research program. Much of USGCRP's current international coordination work focuses on WCRP and Future Earth. For example, the WCRP Climate and Ocean—Variability, Predictability, and Change (CLIVAR) project seeks to understand the dynamics, the interaction, and the predictability of the coupled ocean-atmosphere system. To enhance integration of relevant research priorities at international, national, and individual agency levels, the U.S. CLIVAR office is co-located with the USGCRP National Coordination Office.

Public Engagement

The 2011 GAO report also discussed how effective engagement can foster shared learning across national leadership, the general public, and the research community; help ensure transparency; build shared norms; help frame research agendas to reflect the concerns and needs of the public and decision makers; and bring an informed, democratic process to decisions that broadly affect society. USGCRP and its participating agencies have experience with various types of stakeholder engagement processes that could provide a foundation for the efforts needed in an SG research

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[3] See https://www.globalchange.gov/what-we-do/coordinate-internationally.

program. Examples include the engagement activities undertaken by USGCRP as part of the National Climate Assessments (in particular the development of NCAnet,[4] an ongoing effort to engage producers and users of assessment information across the United States), as well as centers established by individual agencies to support climate-related decision making (e.g., the NOAA Regional Integrated Science and Assessment centers, USDA Climate Hubs, and the U.S. Department of the Interior Climate Science Centers). While this experience provides a valuable foundation, the SG research program described herein will require additional mechanisms for engagement with civil society and other stakeholders, with particular attention given to climate-vulnerable communities and underrepresented groups including from indigenous populations and the Global South. While USGCRP itself is not likely well suited to lead international engagement processes, it can help assure that the United States actively supports and participates in efforts led by appropriate international organizations.

Recommendation 4.2: The U.S. Global Change Research Program should be tasked to provide coordination and transparent oversight of the research program, addressing roles including but not limited to the following:

- **Guiding the development and coordination of complementary research activities across the relevant federal agencies and advancing the research elements that are best aligned with each agency's mission and capabilities;**
- **Integrating existing agency assets, coordinating and tracking budget allocations, and harmonizing future budget requests;**
- **Overseeing coordinated research solicitations that foster interdisciplinary and transdisciplinary knowledge, relationships, and solutions, across all relevant disciplines, including the humanities, social sciences, and natural sciences;**
- **Maintaining an active database of all SG research activities, in particular activities related to outdoor experimentation, and ensuring that this information is made publicly available;**
- **Ensuring rigorous peer review of all research proposed under the program;**

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[4] See http://ncanet.usgcrp.gov/.

- **Periodically assessing progress and refining program goals and research priorities;**
- **Ensuring that all of the results from (and data sources developed through) federally supported research are publicly available, preferably at zero cost;**
- **Advancing opportunities for meaningful public engagement within and beyond the United States and pathways for this engagement to help inform and shape the research program;**
- **Connecting to and coordinating with relevant SG programs and activities outside the U.S. federal government; and**
- **Ensuring systematic support for the full range of research topics that are critical for advancing understanding of SG (see Chapter 6).**

4.5 ROLES FOR PHILANTHROPIC SUPPORT

At present, more than two-thirds of SG funding in the United States is coming from private sources, including from foundations and individuals (see Table 4.2). This funding has supported some research efforts, as well as efforts to explore governance of research. Support from philanthropic sources may be particularly valuable for advancing research and research governance activities that pose a difficult fit for traditional government funding. For instance, efforts related to international capacity building do not align easily with the mission or scope of existing federal agency programs and thus could be bolstered by alternative means of support.

Yet, there are many concerns about private philanthropy funding SG research. Private-sector funding lacks the level of accountability to the broader public typically associated with governmental support. These concerns are especially acute when it comes to private support for outdoor experiments. Other concerns relate to the ethical and

TABLE 4.2 Approximate Funding Amounts for SG Research and Governance-related Efforts, by Location and Funding Type between 2008 and 2018

Location	Government Funding	Private Funding	Mixed Funding
North America	$7,180,000	$18,090,000	$910,000
Europe	$20,350,000	$1,380,000	$0
Asia	$3,840,000	$300,000	$0
Other	$0	$150,000	$0

SOURCE: Necheles et al. (2018).

other implications of potentially having a small number of wealthy individuals and philanthropies setting research and policy agendas, and shaping the overall path forward, for the SG enterprise.

It is possible that research and research governance activities supported by philanthropy could be subject to the type of governance framework outlined in Chapter 5 (e.g., by mechanisms such as public registries of research, review and assessment efforts, and advisory committee oversight), although many questions remain regarding the degree to which these mechanisms would apply and be effective. The "code of conduct" recommendations in particular could provide a valuable basis for guiding the efforts of both governmental- and nongovernmental-funded research alike; in fact, prior to the creation of a coordinated government program, it may be private philanthropies that first socialize and require adherence to a code of conduct from those researchers that they support. Even in the absence of any legal or regulatory constraints, societal pressure may help motivate privately funded activities to adhere to common standards for transparency, public engagement, safety precautions, etc.—especially if there is public backlash in the face of activities that fail to adhere to such standards.

As a general approach, philanthropic support for SG research and research governance (and related activities such as capacity building and engagement) should complement rather than replace core U.S. federal support for these activities. This complementary support may be particularly useful for helping address priority areas identified by other nations and nongovernmental organizations in the Global South with independently developing research programs and interests as well as for rapidly advancing the near-term work needed to help inform research program design efforts (given that philanthropies can often make grants much more quickly than federal agencies).

Providing budget estimates for engagement and capacity building efforts is challenging, in part because such activities could be scaled to almost any size and ambition that one seeks—ranging from a few thousand dollars for modest individual events to tens of millions for ongoing globally comprehensive processes. Consistent with our earlier calls for assuring a primary focus on climate change mitigation, we suggest that philanthropic support for SG should remain a small fraction of the support provided for mitigation efforts. As a point of reference, the latter totaled $1.6–1.8 billion in 2019 (ClimateWorks Foundation, 2020).

CHAPTER FIVE

Solar Geoengineering Research Governance

5.1 INTRODUCTION

Effective research governance is a critical component of any robust research program. 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 work is being undertaken, procedural and control issues, who has input into decisions about whether research goes 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. There can be some inherent tensions among different governance goals. For instance, efforts to build trust and legitimacy through extensive public engagement could lead to some constraints on the goal of producing socially beneficial knowledge or could add to the costs of research. Importantly, however, governance and engagement efforts can also benefit and help enable research—especially for controversial, societally consequential issues such as SG—by building trust, legitimacy, accountability, and social responsiveness.

Building upon the analyses in the preceding chapters, which provided an overview of domestic and international mechanisms that could apply to the governance of SG research or deployment (Chapter 2) and considered the "decision space" and principles for SG research governance for SG research (Chapter 3), this chapter offers specific recommendations for governance aimed at SG research stakeholders, including researchers, funders of research, science agencies, national governments, international bodies, and other relevant organizations.

The limited efforts to date by states to engage in SG research governance suggest a potentially significant role for non-state actors in such governance. While Chapter 4 considered governance aimed at ensuring a socially robust research program, this chapter is more focused on the governance of individual research activities. Risks that play out programmatically may differ from risks that play out in the context of specific projects.

Many of the recommendations in this chapter—such as registries, codes of conduct, data sharing, and assessment—could be adopted at both national and international levels. However, with few exceptions, global agreements have evolved out of domestic laws and regulations—not necessarily as a matter of preference, but because initial momentum was built domestically (Morrow and Light, 2019). The exceptions, such as the creation of the United Nations (UN) Framework Convention on Climate Change, are important. Attempts at international governance, especially on new issues like SG, however, will confront the reality that the default multilateral consensus process often produces very weak initial agreements, especially among nearly 200 sovereign parties.

At a minimum, domestic and international governance should complement each other. Governance mechanisms and principles developed domestically can be informative to policy makers developing international governance mechanisms and may be developed and implemented more quickly than international efforts. In turn, successful international governance can improve domestic governance by reinforcing domestic efforts and creating expectations of greater levels of domestic enforcement. Simultaneous domestic and international efforts may increase the efficiency, effectiveness, and chance of success of advancing some level of effective governance.

Because domestic and international governance efforts are often pursued in different parts of governments and in different kinds of intergovernmental or nongovernmental institutions, this chapter is organized with the goal of enabling readers and policy professionals to readily identify the recommendations most relevant to them. The first section of the chapter provides recommendations that may be adopted by countries or subnational entities within countries and, in some cases, by the research community. The second section presents recommendations that may be adopted internationally. Several of the recommended governance mechanisms are discussed in both sections, as they would be useful at multiple levels. Analysis in support of recommendations in one section often supports recommendations made in the other section. The committee envisions that its recommendations will be acted upon in their totality, but each is worth pursuing individually.

Table 5.1 provides an overview of the governance mechanisms discussed in this chapter, goals and/or principles that they foster, and actors for the chapter's governance recommendations.

As discussed in Chapter 2, some existing U.S. laws and regulations are potentially relevant to SG research, but these were not crafted with SG research in mind. At the domestic level, environmental laws may impose procedural obligations (e.g., the National Environmental Policy Act, NEPA) or substantive limits on conduct (e.g., the U.S. Clean Air Act). Indoor SG research (i.e., laboratory and modeling studies) generally would

TABLE 5.1 Governance Mechanisms Discussed in This Chapter

Governance Mechanism	Goals/Principles Served by This Mechanism	Relevant Recommendations	Actor(s) Discussed in this Chapter
code of conduct	responsible science, effective practices	5.1a, 5.1b, 5.1c	researchers, funders of research, national institutions
registry	transparency, information sharing	5.1d, 5.1e, 5.1p	nations, researchers, funders of research, scientific publishers, appropriate international body
data sharing	transparency, information sharing	5.1j, 5.1k	researchers, funders of research, publishers
assessments and reviews	risk assessment, impact assessment, strengthen science, transparency, public engagement	5.1f, 5.1g, 5.1h, 5.1o	nations, funders of research, appropriate UN body or bodies
permitting	transparency, oversight	5.1i	nations
intellectual property	information sharing	5.1l	researchers
participation and stakeholder engagement	inclusivity, public engagement, transparency	5.1m, 5.1n, 5.1t, 5.1u	individuals, institutions, nations, researchers, funders of research, appropriate international and regional governance bodies
international cooperation and co-development on research teams	coordination of research, joint research projects/programs	5.1q	funders of research, researchers
international cooperation among national scientific agencies	coordination of research, information sharing, joint research projects/programs	5.1r	science agencies
international information sharing and cooperation on SG research and research governance	coordination of research, information sharing, transparency, participation, and public engagement	5.1s	coalition of state and non-state actors
international anticipatory governance expert committee	risk assessment, effective practices, conflict resolution	5.1v	UN body or other international institution

not trigger the application of existing environmental laws, and only some outdoor experiments would do so. Experiments with insignificant environmental impacts, and experiments lacking significant federal government involvement, would not be subject to NEPA's requirements to prepare an environmental impact statement that would undergo public notice and comment. Outdoor research intended to produce artificial changes in the atmosphere would trigger the Weather Modification Reporting Act's (WMRA) modest reporting requirements. The application of other environmental statutes to field research would depend on the nature of the research and the materials used and released. In any case, these statutes focus on physical impacts and not on the social or ethical concerns that frequently surround SG research. Tort law serves as another potential mechanism for governance of SG research, but it would generally require evidence that SG research caused harm to a plaintiff.

Current international law provides a general framework, but it does not explicitly promote, prohibit, or significantly limit SG research; nor does it provide a system of required or recommended research transparency or reporting mechanisms.[1] Current institutions of international law could potentially address transboundary physical effects of research but not the broader political or ethical concerns that have been raised in the literature and by civil society organizations.

At the current stage of SG research—consisting primarily of modeling, observational studies of natural phenomena, and proposed small-scale field research with minimal or zero environmental or transboundary impacts—there would be very limited applicability of international institutions. If such institutions were to begin a deliberative process to directly address SG research, it would likely be a lengthy process, subject to rules and norms of consensus that more often than not govern these institutions and sometimes result in less ambitious or stringent outcomes. Nevertheless, it is conceivable that certain international institutions other than treaty bodies (e.g., international scientific organizations) could initiate voluntarily collaborative research and research governance activities in the short term.

While there are broader principles of international law that could be appealed to—for example, precautionary principle, intergenerational equity, etc.—the mechanisms for applying such principles are not well established. Such principles could be self-applied by nations but would lack any application or enforcement across borders. In the

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[1] See Chapter 2 for a survey of existing international conventions that either have explicitly attempted to address solar geoengineering (e.g., the UN Convention on Biological Diversity; the London Convention/London Protocol), or could in principle form part of a global system of international SG governance given their current scope and activities (e.g., the UN Framework Convention on Climate Change; the UN Convention on the Law of the Sea).

particular case of an emergency situation involving unanticipated or unilateral deployment of SG, the UN Security Council could be convened in emergency session to respond. Options for recourse would, however, be unprecedented and subject to the veto powers of the five permanent members of the Council.

In addition to the various existing treaty bodies and agreements surveyed in Chapter 2 that could potentially continue discussion of SG research and its governance (e.g., CBD, London Convention and Protocol, UNFCCC and Paris Agreement, Vienna Convention and Montreal Protocol, CLRTAP, ENMOD, and UNCLOS), the topic could also be taken up by the UN Environment Assembly (UNEA), which has universal membership of all UN Parties. In spring 2019, the UNEA discussed, but did not agree to, a resolution from Switzerland that requested that the UN Environment Programme (UNEP) Executive Director conduct an assessment of geoengineering technologies (inclusive of SG but also going beyond it) and offer options for possible governance frameworks. As a consequence, the resolution was withdrawn. However, the UNEA could still direct UNEP to do something similar in the future, either alone or working with other UN bodies. It could also request action by one or more UN convention or treaty bodies to take up SG, as it has on other issues in the past. UNEA, or another relevant UN convention or treaty body, could also request a study of SG—or ongoing assessment or monitoring of the state of the science and technology—from an allied international scientific body such as the World Meteorological Organization (WMO)[2] or the Intergovernmental Panel on Climate Change (IPCC).[3]

Levels of international cooperation short of UN treaty bodies or organizations are more viable options. On climate change, the past decade has seen a steady increase in ministerial-level groups of countries working in parallel to UN processes to achieve complementary goals:

- In 2012, six countries (Bangladesh, Canada, Ghana, Mexico, Sweden, and the United States) along with UNEP created the Climate and Clean Air Coalition

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[2] WMO, the International Science Council (ISC), and the UN Educational, Scientific and Cultural Organization (UNESCO) Intergovernmental Oceanographic Commission co-sponsor the World Climate Research Programme (WCRP), which coordinates climate research initiatives at an international level. WCRP fosters innovation and collaboration through the organization of global meetings, workshops, and conferences (see https://www.wcrp-climate.org/wcrp-events). Scientific guidance is provided by the WCRP Joint Scientific Committee. Reynolds et al. (2017) have suggested that the WCRP's Working Group on Coupled Modelling could become the data repository and coordinator of standards for a research data commons on SG.

[3] The IPCC is another potential locus for aspects of SG research governance. WMO and UNEP created the IPCC in 1988. Its objective is to provide policy makers with regular assessments of the scientific basis for climate change, its impacts and future risks, and options for adaptation and mitigation. The IPCC has 195 member states and draws upon the expertise of international climate experts around the globe. The IPCC does not conduct its own research.

to Reduce Short-Lived Climate Pollutants (CCAC) to support research, deployment, and governance initiatives to reduce non-CO_2 greenhouse gases (GHGs), such as methane, black carbon, and hydrofluorocarbons. This voluntary coalition has since grown to include more than 120 state and non-state partners, who jointly fund an array of initiatives and projects and share domestic governance frameworks. CCAC is widely recognized as complementary to the objectives and goals of the UNFCCC and the Paris Agreement, neither of which has specific provisions or programs related to this class of GHGs.

- Similarly, Mission Innovation, a voluntary endeavor of 24 countries and the European Commission (representing most of the world's largest economies) founded on the eve of the negotiation of the Paris Agreement, commits its members to doubling their clean energy R&D investments in "selected priority areas" by 2020–2021. It has also evolved into a global "hub" and discussion forum for new cooperative initiatives, with members launching 59 collaborative research and technology programs since its founding. Mission Innovation is also tracking both public expenditures and private-sector investments in clean energy, providing an important window into this important world of climate-related technology development.

There are also a number of existing international scientific bodies that could serve as platforms for international cooperation and address some aspects of SG governance; for instance:

- The International Science Council (ISC) is a nongovernmental organization that brings together 40 international scientific unions and associations and more than 140 national and regional scientific organizations, including academies and research councils. ISC's goals include coordinating international action on issues of scientific and public importance. ISC draws upon scientific expertise across both physical and social science disciplines. ISC could also draw upon its partnership with WMO's Climate Change Research Programme.
- The InterAcademy Partnership (IAP) brings together three established networks of academies of science, medicine, and engineering: the InterAcademy Panel (the global network of science academies), the InterAcademy Medical Panel, and the InterAcademy Council (IAC). IAC has previously provided scientific advice on climate change. In 2010, for example, it conducted an independent review of IPCC processes and procedures. IAP also has contributed funding to the Solar Radiation Management Governance Initiative (SRMGI), which was launched in 2010 by the Environmental Defense Fund, the Royal Society, and The World Academy of Sciences to build capacity and

understanding, particularly in the developing world. Although the SRMGI does not have the capacity itself to develop a governance framework for SG research, IAP could draw upon the SRMGI's network and capacity building expertise.

- The Scientific Committee on Antarctic Research (SCAR), an interdisciplinary committee of ISC, provides a potentially useful model for international scientific cooperation. Established in 1958, SCAR initiates, develops, and coordinates international scientific research in the Antarctic region and provides independent scientific advice to the Antarctic Treaty System and the IPCC. The scientific community drives SCAR activities. In 2014, for instance, SCAR convened scientists, national program directors/managers, and policy makers from 22 countries to identify priorities for Antarctic research for the next several decades (the *Antarctic and Southern Ocean Science Horizon Scan,* Kennicutt et al. [2014]). An institution modeled upon SCAR could provide a mechanism for international scientific coordination of a science program, the prioritization of research questions, data sharing, and the provision of scientific advice on environmental issues to international policy makers.

While there are thus numerous potential models for collaboration, to date the vast majority of nations have not expressed formal views on the benefits and risks of SG research or on the merits and international architecture of research governance. It is quite possible that many national governments and civil society institutions may decide to oppose an expanded SG research enterprise, based on ethical, geopolitical, or scientific risk assessment grounds, and try to constrain efforts to create international governance practices and institutions.

Unless and until international SG research governance emerges through one or another path, it is incumbent on any country where SG research is being conducted to create mechanisms and institutions to govern this work. While ideally, international governance practices and institutions should be created as soon as possible, in reality, such mechanisms may emerge only after responsibility has been embraced at the national level (as mentioned earlier)—and there is commitment by more countries to engage with research, deter unsafe research activities, or to regulate activities with potentially significant transboundary impacts.

Recommendation 5.1: A U.S. national SG research program should operate under robust research governance and support the eventual development or designation of an international governance mechanism. Important elements of research governance include a research code of

conduct, a public registry for research, regular program assessment and review processes, permitting systems for outdoor experiments, guidance on intellectual property, inclusive public and stakeholder engagement processes, mechanisms for advancing international information sharing and collaboration (within research teams and among national scientific agencies), and establishment of an expert committee to advance discussions about international governance needs and strategies.

5.2 NATIONAL/DOMESTIC RESEARCH GOVERNANCE

In light of the limited applicability of existing U.S. law to much SG research, particularly with regard to research that has little to no anticipated physical impacts, it is important to consider other mechanisms for the domestic governance of SG research, as discussed below.

The recommendations below address concepts that are relevant to the governance of SG research in all countries, but they are largely framed in terms of applicability to U.S. institutions and the U.S. regulatory environment, as this report is the product of the U.S. National Academies' process and committee members are most familiar with U.S. institutions and processes. U.S. actors have been identified in certain instances, but robust governance is very important in all jurisdictions, and recommendations often have applicability to other countries conducting SG research. Nevertheless, as an expansion of SG research to other countries may occur in regulatory environments that are very different from those found in the United States, the full range of challenges and opportunities in those environments is difficult to anticipate.

Codes of Conduct

Codes of conduct offer a mechanism for responding to environmental, social, and ethical concerns. Researchers may voluntarily adhere to codes of conduct, funders of research may require adherence to such codes as a condition of funding, and funders themselves may adhere to code provisions (Hubert and Reichwein, 2015). Codes of conduct also may serve as a foundation for more formal governance efforts, whether domestic or international.

Codes of conduct typically emphasize that research should be performed for the public good. Codes of conduct often call for the maintenance and protection of the scientific quality of proposed research; the recognition and application of due diligence to environmental, social, and ethical implications of research; promotion of public notice and participation; post-project monitoring; and access to information.

Specific codes of conduct for SG research, such as the *Code of Conduct for Responsible Geoengineering Research*, developed by Anna-Maria Hubert and David Reichwein at the University of Calgary (hereafter, "Calgary Code"), have been developed, vetted with various stakeholders, and proposed (see Chapters 2 and 3). Some code provisions apply specifically to outdoor experiments (e.g., atmospheric experiments with the potential for transboundary impacts without some form of acceptable prior consent should be avoided), while others apply to SG research generally (e.g., research funding should be limited to entities that prioritize mitigation and adaptation).

A sanctioning body can revise a code and offer interpretative guidance as needed. However, no SG research code of conduct has achieved wide adoption by researchers, professional societies, businesses, philanthropies, or governmental institutions, and no code of conduct specific to SG has been formally sanctioned by any government, professional society, or other relevant institution.

Ideally, a code of conduct would be adopted at an international level. An international scientific society could assist in the development of a code of conduct. For example, the International Society for Stem Cell Research (ISSCR) developed guidelines for the responsible and ethical conduct of human embryonic stem cell research; ISSCR members make a personal commitment to uphold the society's guidelines. At this time, however, no equivalent professional society exists for the SG research community. Institutions that could, in principle, develop or accept a code of conduct for SG researchers include WMO, ISC, IAC, and the UN Educational, Scientific and Cultural Organization (UNESCO). These organizations have broad international membership, enabling them to reach scientists around the world.

Recommendation 5.1a: SG researchers should adhere to relevant provisions of an accepted code or, if none has yet been accepted, an adequate code. At a minimum, researchers should commit to

- **protect the scientific quality of proposed research;**
- **assess, monitor, and minimize potential adverse effects from research;**
- **avoid atmospheric experiments with detectable climate or other environmental effects (experimentation thresholds are discussed further in Recommendation 6.2);**

- **accept research funding only from funding entities that recognize the importance of an overall balance of resources that prioritize mitigation and adaptation;**
- **make public SG research activities, funding sources, and results;**
- **identify and limit and, when necessary, avoid conflicts of interest;**
- **provide for suitable levels of public and stakeholder participation and engagement independent of whether a proposed experiment has any known environmental risks (see Table 5.1 for a discussion of levels of public and stakeholder engagement); and**
- **actively support and advance the goals of racial, gender, geographic, and economic equity in the conduct of SG research.**

Recommendation 5.1b: Funders of SG research—including government agencies, universities, and philanthropic organizations—should mandate as a condition of funding that SG research adhere to an accepted code of conduct or, if no code has yet been accepted, a code that includes the elements enumerated in Recommendation 5.1a.

Recommendation 5.1c: In countries where SG research is under way, or where it is reasonably foreseeable, relevant national institutions should review existing codes of conduct for SG research, develop new codes should existing codes be found insufficient, and ultimately accept a robust code of conduct for SG research.

A pathway for the development of an international code of conduct is described below.

Public Registries

Transparency can serve multiple ends. With respect to SG research, it can promote public understanding of SG and its risks, foster accountable and legitimate decision making, and engender trust in institutions of SG governance (Callies, 2018; Craik and Moore, 2014; Rayner et al., 2013). Transparent reporting of research can also help researchers keep track of ongoing research and share information (Nicholson et al., 2018). Moreover, transparency can facilitate transnational research coordination and collaboration and build trust between states whose research agendas may be motivated by self-interest (Craik and Moore, 2014). Outdoor experiments or field tests warrant particular attention to transparency because of their potential physical impacts, but transparency rationales apply to other types of SG research as well (Craik and Moore, 2014; Rayner et al., 2013).

A public registry of SG research could be a powerful tool in an effort to promote transparency. For a registry to be credible, the institution maintaining the registry should be perceived as impartial (Craik and Moore, 2014). Such a registry could be established and administered by a research center, university, international research organization, government agency, or other entity.

Fundamental questions in registry design include whether participation would be voluntary or mandatory, whether funders or researchers would participate, whether the registry would include only field experiments or extend to all SG research, how SG research would be defined, what information would be reported and disclosed, and how to incentivize disclosure (Craik and Moore, 2014).

Useful examples of the registry approach may be found in several fields. In the medical field, for example, the International Committee of Medical Journal Editors (ICMJE) established in 2005 a policy requiring researchers, as a condition of consideration for publication, to post information about clinical trials in an approved public registry at the time of or before patient enrollment (Laine et al., 2007). Within the United States, Congress has mandated that sponsors and researchers post information about clinical trials on ClinicalTrials.gov, a public database available to clinicians, researchers, and patients (Laine et al., 2007).[4] Clinical trials registries have also been set up in other countries, driven by the leading journals' requirements that they will only publish papers on clinical trials if those trials have been put into a public registry.

To advance research, the National Institutes of Health established the Genetic Testing Registry "to advance the public health and research into the genetic basis of health and disease." It "provides a central location for voluntary submission of genetic test information by providers." Its "scope includes the test's purpose, methodology, validity, evidence of the test's usefulness, and laboratory contacts and credentials."[5]

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[4] "ClinicalTrials.gov was created as a result of the Food and Drug Administration Modernization Act of 1997 (FDAMA). FDAMA required the U.S. Department of Health and Human Services (HHS), through the National Institutes of Health, to establish a registry of clinical trials information for both federally and privately funded trials conducted under investigational new drug applications to test the effectiveness of experimental drugs for serious or life-threatening diseases or conditions." "ClinicalTrials.gov registration requirements were expanded after Congress passed the FDA Amendments Act of 2007 (FDAAA). Section 801 of FDAAA (FDAAA 801) requires more types of trials to be registered and additional trial registration information to be submitted." See https://clinicaltrials.gov/ct2/about-site/background.

[5] See https://www.ncbi.nlm.nih.gov/gtr/.

In the climate arena, the Greenhouse Gas Reporting Program collects GHG information "from large emitting facilities, suppliers of fossil fuels and industrial gases that result in GHG emissions when used, and facilities that inject carbon dioxide underground."[6] This system was implemented under 40 CFR Part 98, following the publication on October 30, 2009, of a rule by the U.S. Environmental Protection Agency (EPA). GHG emitters must submit annual reports that provide data collected during the previous calendar year (EPA, 2014).

With regard to SG research, reports required under the WMRA could serve as a starting point for a federal research registry, but such reports are only required for some field experiments and not at all for computer modeling or indoor experiments. Registries established in one or more nations could serve as a foundation for a multinational or international registry (see Recommendation 5.1p below). A model of this type is the World Health Organization's (WHO) Human Genome Editing Registry. Established in 2019, this registry "is a central database that collects information on clinical trials using human genome editing technologies . . . that uses data collected by the WHO International Clinical Trials Registry Platform (ICTRP). The ICTRP gathers the trial registration data sets provided by Primary Registries,"[7] national registries "that meet specific criteria for content, quality and validity, accessibility, unique identification, technical capacity and administration."[8]

In scientific publishing, there are instances in which editors require participation in a registry as a prerequisite to publication. As mentioned previously, the ICMJE "requires, and recommends that all medical journal editors require, registration of clinical trials in a public trials registry at or before the time of first patient enrollment as a condition of consideration for publication....The ICMJE recommends that journals publish the trial registration number at the end of the abstract."[9]

Recommendation 5.1d: A national public SG research registry should be created to collect information on all public- and private-sector SG research.

Recommendation 5.1e: Once a national SG research registry is established, SG researchers should participate in the registry, and

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[6] See https://www.epa.gov/ghgreporting/ghg-reporting-program-data-sets.

[7] See https://www.who.int/health-topics/ethics/human-genome-editing-registry#:~:text=The%20Human%20Genome%20Editing%20(HGE,Trials%20Registry%20Platform%20(ICTRP).

[8] See https://www.who.int/ictrp/network/primary/en/.

[9] See http://www.icmje.org/recommendations/browse/publishing-and-editorial-issues/clinical-trial-registration.html.

scientific publications should require participation as a prerequisite to consideration for publication.

Assessments and Reviews

Assessments of uncertainty and the impacts of SG research can identify risks, foster transparency and public participation, and enable consideration of risks in decision making processes (Rayner et al., 2013). Assessments may consider not only physical impacts, as in environmental impact assessments, but also social, economic, and other non-physical impacts, as is often done in assessments of emerging technologies (Lin, 2016; Rayner et al., 2013). Programmatic-level assessments, as opposed to assessments of individual projects, allow for the evaluation of the impacts of policies or multiple projects (Lin, 2016) and could analyze cumulative impacts from multiple experiments (Burger and Gundlach, 2018). A programmatic assessment may consider the cumulative developmental trajectory of all SG research activities, regardless of institutional affiliation or funding source, and need not be limited in scope to a formal program.

When combined with public comment mechanisms, assessment processes can help make risks transparent and promote public engagement (Craik and Moore, 2014). Specifically, it is important to allow the public to have meaningful representative input regarding whether and how SG research proceeds (recognizing that public engagement can also improve the processes and results of SG research). Public comment opportunities alone, however, do not ensure effective public engagement; it is likewise important to develop mechanisms that help ensure policy decisions about research directions and priorities are responsive to public engagement (Jinnah, 2018).

Assessment may be performed by the scientists undertaking the research, funders of research, an independent review body, or a government agency. Proposals are commonly subject to peer review as part of the process of determining whether to fund a research project. Assessment by an entity independent of the research scientists promotes impartiality and confidence in the assessment process (Rayner et al., 2013). Including social scientists, members of civil society, and natural scientists on a review body could promote the consideration of a broader range of concerns and perspectives. A transparent, open advisory body could review SG research on an ongoing basis, promote international cooperation, and recommend policies and practices on SG research and research governance (Winickoff and Brown, 2013).

Recommendation 5.1f: Any country engaged in SG research should establish a standing advisory body composed of experts from a broad range of relevant disciplines and representatives of potentially affected communities to recommend policies and practices on SG research and research governance.

Recommendation 5.1g: Any country engaged in SG research should prepare programmatic assessments that collectively assess the health, environmental, and social impacts of all SG activities that it sponsors or approves and any SG research program that it adopts. Such assessments, which should be revised on a regular basis, should incorporate broad and meaningful public engagement and protocols for public engagement.

Recommendation 5.1h: As a condition of funding for any proposed outdoor SG experiments, research funders should require independent peer review of the research and an assessment of the plausible impacts of the research. Consistent with the overarching need for broad participation in SG research, the peer review should include an assessment of public and stakeholder engagement in the design and review of research.

Permitting

A permit is a "statutorily authorized . . . granting of permission to do that which would otherwise be statutorily prohibited" (Biber and Ruhl, 2016). Permits may be issued in the form of *general* permits, for which an approved category of activities is allowed unless approval is withdrawn, or *specific* permits, for which an applicant must request permission to engage in an activity that is otherwise prohibited (Biber and Ruhl, 2016). If well designed, permit requirements (or other funding conditions or approval processes) can be an effective way to address some concerns associated with research. Poorly designed requirements may create undue barriers to research (Parker, 2014).

Approval processes may be designed in different ways—for example, to require affirmative approval of a permit application, to presume approval in the absence of objections, or to simply require notice (Bodle et al., 2014; Parker, 2014). A general permit system requires more work upfront to establish the parameters and conditions of the permit. General permits can cover the activities of a large number of actors at a relatively low cost. They can also reduce or eliminate the need for a permit application or for individualized approval of a contemplated activity (Biber and Ruhl, 2016). In contrast, a specific permit system shifts workload to the processing of permit applications (Biber and Ruhl, 2016). Specific permits, which can be tailored to particular situations, are better suited for activities in which the risks of harm are significant or highly variable (Biber and Ruhl, 2016). Different types of SG experiments (e.g., laboratory, process studies, and scaling tests) might be subject to different types of permitting systems, or even exempted, based on anticipated risks.[10]

Under existing U.S. law, indoor SG experiments, outdoor observational research, and some outdoor experiments could take place without giving notice to the public or to the government, or seeking government approval, though, as noted earlier, the WMRA requires any person engaging in weather modification activity—defined to include "any activity performed with the intention of producing artificial changes in the composition, behavior, or dynamics of the atmosphere"—to submit a report of such activity. Some SG field experiments would be subject to this reporting requirement, but the WMRA does not require a permit for weather modification activity, and such experiments may not trigger state permitting requirements for weather modification.

In the case of SG research, a permit requirement can promote information gathering on SG research activities and increase their transparency, ensure that harmful impacts are minimized, and provide public assurance that research is being undertaken in a responsible manner. The need to obtain social license for SG research in light of its mission-driven nature, and as suggested, for example, by public and stakeholder reactions to the Stratospheric Particle Injection for Climate Engineering (SPICE) experiment, points in favor of a permit requirement or similar form of governance.

Recommendation 5.1i: All outdoor SG atmospheric experiments should be subject to a national permitting system. Permitting systems should be designed to encompass transboundary research and research performed by international research teams.

The specific elements of a permitting system (e.g., the criteria/standards that the permitting entity would apply in determining whether or not to issue a permit) would need to be developed by the entity that assumes responsibility for the permitting system. The United States does not currently have a permitting requirement that clearly covers

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[10] While some SG will not engender physical risks, physical risks are not the only risks of concern to the public. To understand the range of issues that may raise public concern, transparency in the conduct of research is critical (Dilling and Hauser, 2013).

experiments of the type envisioned. Such a requirement would need to be introduced through the regulatory or legislative process. Until a uniform permitting system is developed, researchers would be expected to follow precautions captured within the previous recommendations in this section. Furthermore, the existence of a permitting system would not exempt researchers from continuing to follow recommendations that retain their relevance even in the presence of a permitting system, for example, adherence to a code of conduct.

Data Sharing

The National Academies study *Open Science by Design: Realizing a Vision for the 21st Century* noted that openness and sharing of scientific information are fundamental to the progress of science and the effective functioning of the research enterprise (NASEM, 2018b). The report describes a global research community trend toward an open science ecosystem to enable free availability to scholarly publications and research data.

Sharing of SG research data on both a national and international level offers many benefits. Data sharing enables other scientists to reproduce or replicate reported work, strengthening scientific rigor. It also allows researchers to bring data from multiple fields to bear on their work, opening up new areas of inquiry and expanding the opportunities for interdisciplinary collaboration. Data collected for one purpose may be reused to build upon the initial field of research or to study other fields of research. This reuse of data also facilities more effective use of resources, enabling faster and more inclusive dissemination of knowledge.

The United States has a long history of promoting public access to research data arising from federally funded research. The Director of the Office of Science and Technology Policy issued a February 2013 Memorandum "Expanding Public Access to the Results of Federally Funded Science," which directed federal agencies with more than $100 million in annual research and development (R&D) expenditures to develop plans for increasing public access to the results of research they support, including scholarly publications and digital data. The memorandum recognized that "making research results accessible to the largest possible audience—other researchers, business innovators, entrepreneurs, teachers, students, and the general public—can boost the returns from federal investments in R&D. Increased access expands opportunities for new scientific knowledge to be applied to areas as diverse as health, energy, environmental protection, agriculture, and national security and to catalyze innovative breakthroughs that drive economic growth and prosperity." As a result, 17 federal science agencies have issued public access plans covering digital data. Data sharing requirements are typically implemented by agency policies or grant conditions.[11]

On an international level, data sharing has been an integral component of international scientific research collaboration. For example, the Organisation for Economic Co-operation and Development (OECD) issued a recommendation on principles and guidelines for access to research data from public funding in 2006 to foster international cooperation (OECD, 2017); the Group on Earth Observations (GEOSS), an intergovernmental group dedicated to sharing environmental data and information collected from Earth observing systems, established data sharing principles which promote the full and open exchange of data with minimal possible costs, delay and restriction as a foundation for GEOSS (GEOSS, 2015); and the Multinational Coordinated Arabidopsis thaliana Genome Research Project[12] included a plan for data sharing, and the National Science Foundation (NSF) implemented data sharing requirements through the grant process.

Recommendation 5.1j: SG researchers should share their data and research results openly and freely. Researchers are encouraged to provide open access to publications and to register their projects through any available domestic and international research registries.

Recommendation 5.1k: Funders and publishers of SG research should assist and encourage researchers to share their data and research results openly and freely.

Intellectual Property

As discussed in Chapter 2, intellectual property law may influence the pace and direction of SG research by incentivizing innovation or by restricting others' access to inno-

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[11] For publications, the majority of agencies require investigators to make peer-reviewed journal articles resulting from funded research publicly accessible in designated repositories not more than 1 year after their official date of publication.

[12] The Multinational Coordinated Arabidopsis thaliana Genome Research Project unified the efforts of international teams who had been decoding this genome sequence since the early 1990s. In the United States, an interagency program began in 1996 with funding from the National Science Foundation (NSF), the U.S. Department of Energy, and the U.S. Department of Agriculture. Arabidopsis researchers from the United States, Europe, Australia, and Japan formed an ad hoc committee and drafted a plan for the Multinational Coordinated Arabidopsis thaliana Genome Research Project. See IOM, 1996 and NSF, 2002.

vation. To date, patents or other intellectual property protections have not obstructed SG research, and the dominant practice among SG researchers has been to share and make data publicly available (Reynolds et al., 2017). The expansion of SG research and involvement of commercial actors in such research may, however, reduce the openness that has characterized the sharing of SG research and of data.

National law governs many requirements for patents, and patent protections are limited to the jurisdiction where the patent was issued. Researchers may, however, seek access to an invention patented by inventors in other countries or inventions that are patented in multiple countries. International treaties administered by the World Intellectual Property Organization (WIPO)[13] (e.g., the Paris Convention,[14] the Patent Law Treaty,[15] and the Patent Cooperation Treaty[16]) have been developed to coordinate and harmonize patenting practices and provide mechanisms for the resolution of intellectual property disputes (Reynolds et al., 2017).[17]

Unobstructed national and international access to SG research and data can facilitate further research (Contreras, 2015), promote transparency, and foster public engagement. Pledges not to assert patents have been made with respect to open source software, information and communication technologies, environmental technologies, and life science technologies (Contreras, 2015). National and international efforts that enable researchers to access relevant patented technologies at little or no cost, or that encourage pledges from patent holders to refrain from asserting their patents against researchers, can stimulate research. The assertion of broad patent rights could influ-

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[13] "WIPO is the global forum for intellectual property (IP) services, policy, information and cooperation." "A self-funding agency of the United Nations, with 193 member states," WIPO's "mission is to lead the development of a balanced and effective international IP system that enables innovation and creativity for the benefit of all." Its "mandate, governing bodies and procedures are set out in the WIPO Convention, which established WIPO in 1967." See https://www.wipo.int/about-wipo/en/.

[14] The Paris Convention for the Protection of Industrial Property, as amended on September 28, 1979, provides for national treatment, the right of priority, and other common rules in the field of patent law. See https://wipolex.wipo.int/en/treaties/textdetails/12633.

[15] The Patent Law Treaty of 2000 provides common requirements for procedures before national/regional patent offices. See https://wipolex.wipo.int/en/treaties/textdetails/12642.

[16] The Patent Cooperation Treaty establishes an international patent filing system. See https://www.wipo.int/treaties/en/registration/pct/summary_pct.html.

[17] In addition, the World Trade Organization's Agreement on Trade-Related Aspects of Intellectual Property Rights (TRIPS) contains IP rules related to patents. Provision 30 of the TRIPS Agreement provides that members may be provided limited exceptions to the exclusive rights conferred by a patent provided that such exceptions do not unreasonably conflict with the normal exploitation of the patent and do not unreasonably prejudice the legitimate interest of the patent owner, taking account of the legitimate interest of third parties. A 2006 OECD Directorate for Science, Technology and Industry Working Paper 2006/2, "Research Use of Patented Knowledge," authored by Chris Dent, Paul Jensen, Sophie Waller, and Beth Webster, discusses TRIPS Provision 30 in the context of research use exemptions in national patent laws.

ence technological development in favor of private interests and undermine public trust in SG technologies (Reynolds et al., 2017). Indeed, as noted above, the field trial component of the SPICE project was suspended in the wake of concerns regarding patent rights to the technology being tested.

Pledges not to assert patents[18] or providing for royalty-free licenses are implementable via documented, uniform, and internationally coordinated commitments or via informal single commitments.

Recommendation 5.1l: SG researchers should pledge not to assert patents relating to SG against other researchers who are conducting related research.

Participation and Stakeholder Engagement

If SG research evolves from its current fragmented state to a full-scale research enterprise, then ambitious, inclusive, and effective public and stakeholder engagement will be important for the development of an SG research enterprise that could be widely viewed as legitimate, useful, and deserving of public support. Public engagement can "improve the quality [and] legitimacy" of environmental decisions and strengthen the capacity of all participants—including scientists and other experts—to develop policies informed by scientific knowledge and social values (NRC, 2008).

Designing effective public engagement requires determining when, why, in what contexts, by whom, and who to engage. While it may not be feasible or desirable for every SG research project to have its own dedicated public engagement effort, it will be important for researchers to consider how public engagement strategies should be implemented and how the results of such efforts can feed back into research projects (at the individual investigator and, where applicable, programmatic levels). One size does not fit all. For example, while computer modeling studies do not physically release particles into the environment, they can create a durable set of future imaginaries for the public that embody value choices (McLaren, 2018). While not every project needs to (or should) conduct its own public engagement effort, mechanisms could be developed at a program level to share public engagement findings with all researchers, who could consider the implications for their own research directions and

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[18] "A patent pledge is a publicly announced intervention by patent-owning entities ('pledgers') to out-license active patents to the restricted or unrestricted public free from or bound to certain conditions for a reasonable or no monetary compensation." See Ehrnsperger and Tietze (2019).

priorities. And, although field experiments might have negligible physical impacts, the implications of conducting field experiments in the open environment (over particular jurisdictions where people live) may trigger needs for dedicated public engagement efforts to build trust and understand what is permissible to the public and what is not.

Public engagement in SG research is supported by normative, instrumental, and substantive rationales (Flegal et al., 2019; see also Fiorino, 1990). Given the tremendous array of stakeholders that could ultimately be affected by SG implementation, it is important to develop mechanisms for meaningful representative input regarding whether and how research proceeds. While no formal guidelines for the design and governance of such engagement have been developed specifically for SG research, guidelines and tools designed and applied to support and encourage meaningful public and stakeholder engagement in U.S. and international environmental decision making are broadly applicable. The public participation guide developed by EPA (2012), for example, was "designed with government agencies in mind, to help those who must manage the process where public participation is important for decision making, while incorporating fair treatment, meaningful involvement and social inclusion of all people regardless of race, color, national origin, sexual orientation or income."

The EPA guidelines describe meaningful public participation as requiring "more than simply holding public meetings or hearings or collecting public comment." Rather, it entails "seeking public input at the specific points in the decision process and on the specific issues where such input has a real potential to help shape the decision or action." It consists "of a series of activities and actions over the full lifespan of a project to afford stakeholders the opportunity to influence decisions that affect their lives."

Both EPA and the International Association for Public Participation (IAP2) detail five possible forms, or levels, that public participation in decision making might take. These range from simply informing the public about a decision to be made to empowering the public with full decision-making authority. Table 5.2 describes these levels with examples and specific reference to SG research.

The level and specific approach to public and stakeholder engagement will likely vary across research domains: what is most well suited for the co-development of SG modeling scenarios, if applicable, may differ from effective practices for public and stakeholder engagement on decisions about stratospheric aerosol injection experiments.[19] Given the controversial nature of this issue and the global-scale impact of

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[19] Note that the committee has not attempted to specify acceptable levels of engagement for various SG research domains—these should be developed in consultation with engagement experts and stakeholder groups and incorporated into SG codes of conduct as described above.

TABLE 5.2 Levels of Public and Stakeholder Engagement in Solar Geoengineering Research and Research Governance

Level of Engagement	Explanation	Example Methods
Inform	Provide public and stakeholders with information on risks and potential of SG research in the context of climate change.	Fact sheets, educational webinars
Consult	Understand public and stakeholder preferences on scope and focus of SG research.	Public comment periods on federal rulemakings, focus groups
Involve	Engage with stakeholders early and throughout a process with multiple opportunities to provide input and nonbinding recommendations on various decisions over SG research design. Provide feedback to show how input influenced a decision or a response as to why it was not used.	Deliberative workshops with sets of stakeholders
Collaborate	In addition to the engagement described in "involve," include stakeholders directly with decision making with an intention toward building consensus/coming to an agreement. Ultimate decision making remains with the governance body.	Deliberative workshops building toward consensus agreement with decision makers
Empower	In addition to the engagement process in "collaborate," provide decision-making authority to the engaged public.	Informed consent in human subjects research

SOURCE: Adapted from the EPA Public Participation Guide (EPA, 2012), IAP2 Public Participation Spectrum (IAP2, 2014), and Talati and Frumhoff (2020).

potential deployment, a reliance only on low-level engagement mechanisms ("inform" and "consult") is likely not sufficient, especially if and when outdoor experimental components are included in SG research. Rather, the legitimacy and effectiveness of research programs to inform decision making may require more inclusive public and stakeholder engagement efforts (e.g., at levels of "involve" and "collaborate").

The committee has not attempted to specify acceptable levels of engagement for various SG research domains. Rather, these should be developed in consultation with engagement experiments and stakeholder groups, draw upon lessons from efforts to develop and test approaches to public engagement in SG research (see Box 5.1), and be incorporated into mechanisms for public and stakeholder engagement in the design of a research program (see Chapter 4) and in codes of conduct as described above.

BOX 5.1
Testing an Approach to Public Engagement in Decision Making Over Outdoor SG Experiments

Even small-scale proposed outdoor SG experiments draw public attention and scrutiny regarding concerns over possible direct risks as well as broader questions about the risks and efficacy of potential larger-scale outdoor SG experiments and potential deployment (see related discussion in Section 2.5b and Section 6.3). Hence, such efforts also provide important opportunities to develop, test, and learn from protocols designed to engage public input in decision making over whether and how such experiments should proceed.

Protocols for public engagement over outdoor SG research have recently been developed by the independent advisory committee established by Harvard University to advise on Harvard's proposed Stratospheric Controlled Perturbation Experiment (SCoPEx). In SCoPEx, Harvard researchers propose to release small quantities of calcium carbonate into the stratosphere from a balloon to assess their behavior and potential feasibility for larger-scale deployment.

The SCoPEx advisory committee has developed a societal engagement protocol to be carried out in advance on any experimental release of particles. Finalized in January 2021 after public and expert review of a draft proposal, the SCoPEx protocol includes a series of deliberative dialogues with representative publics in the local area of the proposed experiment, as well as broader input solicited from the global "research, advocacy, social equity, and other communities" with interests in the research.[a] Such inputs would be informed by briefing materials that describe potential local-scale impacts of the SCoPEx experiment, and the broader impacts and ethical issues associated with deploying (or not deploying) SG as a climate response. Researchers would draw upon this input as well as other considerations (e.g., a scientific review of the proposed experiment) to develop recommendations to Harvard on whether the experiment should proceed. Their recommendation, and the inputs upon which it was based, would be made public in advance of any particle release experiments.

This approach is broadly consistent with the nonbinding "involve" level of public engagement described in Table 5.2, and it could provide valuable opportunities to gain insights and inform the design of other future engagement efforts related to outdoor SG experiments. Such efforts do of course point to many questions that will need to be explored—for instance, regarding the effectiveness of the engagement processes utilized, the criteria used to assess effectiveness, and the appropriate scope of engagement and scope of concerns to consider in this engagement. (See "Public Perception and Engagement" in Chapter 6 for a list of other relevant questions that could be studied as part of a comprehensive SG research and engagement program.)

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[a] See https://scopexac.com/societal-review/.

Participation in SG research, governance discussions, and public engagement exercises has been extremely limited. To date, most public engagement initiatives have been centered in wealthy nations such as the United States. If this focus on wealthy nations continues, it could create inequities in the development of SG knowledge and governance and limit the range of knowledge that is produced. The current public understanding of SG, while low, will likely grow as SG receives more attention. Broader and more inclusive engagement could contribute to greater justice and legitimacy for research and research governance, and help avoid the perception that SG may be developed solely by one party or a small number of parties without international input or cooperation, further exacerbating climate-related inequities. Research suggests that, to be effective, inclusivity needs to be institutionalized as part of SG research and research governance through the establishment of systematic and sustained opportunities for public and stakeholder engagement.

Efforts to foster greater diversity and inclusion within the community of professional SG researchers, as well as those involved in developing research governance, can also play an important role. See Box 2.1 for discussion of the current challenges of limited diversity within the SG research field. Greater researcher diversity—along with inclusion, which requires that diverse contributors are *respected*, *involved*, and *empowered*—can contribute to a broader and more robust research process and more effective innovation (Hofstra et al., 2020; Nielsen et al., 2017; Page, 2017). For example, climate and social scientists from throughout the world could bring valuable region-specific knowledge and perspectives relevant to identifying priority research questions, developing and refining models, and assessing possible impacts. Winickoff et al. (2015) argue that greater geographical diversity, including broader engagement by researchers and experts from the Global South, will be important in "defining the most relevant climate engineering problems; designing models and experiments that best study them; collecting climate data where there are current gaps; and facilitating the exchange between experts and the broader society."

Recommendation 5.1m: Public and stakeholder engagement in significant SG research and research governance decisions can enhance the legitimacy and effectiveness of SG research programs. SG research and research governance should prioritize inclusive and equitable participation by individuals, institutions, and nations throughout the world, with particular attention to climate-vulnerable peoples, indigenous peoples, and the Global South. Any U.S. SG research program should include broad public and stakeholder engagement as a key component.

Recommendation 5.1n: SG researchers and funders should establish mechanisms to promote a diverse and inclusive community of SG researchers and research governance experts and set specific, measurable goals. These goals may be advanced through a variety of mechanisms, including offering incentives for international collaboration (e.g., requiring proposals to include stakeholder or international researcher participation, when appropriate), addressing gender and other biases in peer-review processes, supporting research and research governance training opportunities, and building capacity in underrepresented regions and nations. Researchers and funders should track progress in meeting these goals.

5.3 INTERNATIONAL RESEARCH GOVERNANCE

In addition to the recommendations for domestic governance of SG research discussed above, complementary action should be taken at the international level.

International Assessment

As discussed earlier, a resolution was introduced in 2019 by UNEA requesting that UNEP lead an assessment of geoengineering technologies. A lead negotiator involved indicated that relatively few negotiators participating in these deliberations were prepared for a discussion of geoengineering.[20] News reports from this UNEA session also noted that some parties opposed introducing this new initiative through UNEA, arguing that it should instead be taken up by the UNFCCC (Chemnick, 2019). This disagreement regarding where a discussion on SG governance should take place can in turn cut the conversation short in different forums before it starts.

Nonetheless, an authoritative international survey that gauges the scale and scope of SG research activities would be valuable. For those concerned that research on geoengineering could displace GHG mitigation research, an assessment of geoengineering research—particularly if updated annually—could provide an important benchmark

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[20] Franz Xaver Perrez, Head, International Affairs Division, Switzerland's Federal Office and Lecturer of International Environmental Law, University of Bern School of Law, Remarks Before the Committee, July 22, 2019. This may reflect the fact that active geoengineering research is under way in only a small number of countries to date.

to compare the relative levels of funding going to these different activities. An annual report could also form the basis for a global registry for SG research.

Recommendation 5.1o: An appropriate UN body or bodies (e.g., UN Environment Programme, UNFCCC Subsidiary Body for Scientific and Technological Advice, World Meteorological Organization) should conduct a biannual international survey of SG research activities, including but not limited to assessment of the funding levels, the duration, and intended goals or objectives of existing and projected activities.

International Registry of SG Research

An international assessment (such as that described above) might be limited by the availability of data and cooperation among countries, philanthropies, and the private sector, but a registry could eventually become more comprehensive and informative with increasing levels of participation by national governments that have effective means of acquiring information within their borders. Broad, meaningful, and verifiable participation in an international registry also could compel parties both to create their own authoritative domestic registries and to participate fully in the international registry. Funders, publishers, and others could require participation in the registry.

WHO recently created a registry for human genome clinical trials. The initial phase will use the ICTRP, a WHO entity. The lessons learned in the establishment of the WHO registry could inform the development of an SG registry. There is also precedent for such mechanisms at WMO, which established a registry of weather modification projects in the 1960s in response to international concerns at the time.

Recommendation 5.1p: An international registry or other reporting mechanism on SG research should be created and administered through an appropriate international body. Data should be gathered through a number of means, including at the country level, with each participating nation responsible for gathering information on all research, based on inputs from individual researchers and from civil society organizations tracking SG activity.

Promotion of International Cooperation and Co-development on Research Teams

A central goal of SG research is to understand the relative risks and benefits of different SG strategies and the distribution of these risks and benefits. An SG program that only benefits a small minority is likely not worth pursuing, especially if it magnifies risks for a majority and exacerbates already-existing global inequalities and vulnerabilities to climate change. As Chhetri et al. (2018) argue, international cooperation in SG research can provide a hedge against such outcomes.

International cooperation can begin with research teams and partnerships, in which researchers can bring to a common endeavor their understanding of differing national circumstances. International research programs provide opportunities to build trust among parties and open channels for cooperation that may eventually translate into channels for international cooperation on governance. Such partnerships provide opportunities for diffusion of best practices (e.g., through codes of conduct) and protocols for environmental and health safety. As noted in Chhetri et al. (2018), "State and private funders that choose to fund SG research should give priority to international teams and partnerships, keeping in mind that the scale and type of research will influence what level of partnership is possible for any particular undertaking" (ibid).

One good example of an effort to incentivize international research engagement is the Large-Scale Biosphere-Atmosphere Experiment in Amazonia (LBA), carried out in the early 2000s. The LBA's ecology mission, sponsored by NASA in collaboration with the government of Brazil, was "designed to better understand cycles of water, energy, carbon and nutrients, resulting from the changes in Amazonian vegetation cover, and associated climatic and environmental consequences at local, regional, and global scales."[21] LBA-Ecology science teams trained more than 500 students and were "involved in transferring of appropriate technological skills and capacity building in collaboration with graduate programs in Brazilian and South American institutions through a variety of initiatives." The LBA "provided infra-structure and financial support for a large number of scientific related activities for capability enhancement and dissemination of science."[22]

Recommendation 5.1q: Funders of SG research should promote international cooperation—including with participants from the Global South—within research teams by giving priority to research efforts

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[21] See https://geo.arc.nasa.gov/sg/lba.html.

[22] See https://lbaeco-archive.ornl.gov/lbaeco/out/out_activities.htm.

that include substantial international membership or institutional cooperation or, possibly in some cases, by requiring such cooperation and co-development as a condition for support, especially for large-scale or long-term projects.

Promotion of International Cooperation Among National Scientific Agencies

National research funding agencies, individually or as members of a national program, can promote international cooperation in SG research through coordination with other national-level research programs. Ideally, participants would include both nations that are funding SG research and members of the broader research community from countries that do not have national-level research programs. Some potential models for international coordination among national funding agencies include the Belmont Forum[23] and the Multinational Coordinated Arabidopsis thaliana Genome Research Project.[24] Cooperative activities may enhance international coordination among scientists and create a conduit for promoting best practices, even in the absence of "hard" governance institutions (Reynolds et al., 2017).

Recommendation 5.1r: Science agencies in countries that are funding SG research should advance international cooperation by coordinating with other national and regional level SG research programs. This cooperation should include

- **sharing information on national programs and effective practices, including codes of conduct;**
- **coordinating joint calls for research proposals;**
- **promoting inclusive engagement opportunities;**
- **promoting access to data from funded research projects;**
- **supporting partners from underrepresented countries; and**
- **exploring whether there is mutual interest in creating and funding an international facility for SG research.**

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[23] The Belmont Forum is a partnership of funding organizations, international science councils, and regional consortia committed to international transdisciplinary research for understanding, mitigating, and adapting to global environmental change. Members include the United States, Argentina, Australia, Brazil, Canada, China, the European Union, France, Germany, India, the Ivory Coast, Mexico, and South Africa. The Forum adopted an open data policy and principles. See http://www.belmontforum.org/.

[24] See footnote 12 above.

If not already undertaken by another international body, science-funding agencies could also establish a registry for research projects.

Voluntary Coordination and Cooperation by Countries and Non-State Actors

Negotiation of a new UN-based international body or agreement specific to SG is extremely unlikely at this time or in the near term. There are no comparable UN-level treaties or agreements on other climate-relevant technologies, and, as noted above, some observers believe that the level of familiarity with SG research among environmental ministries and departments is relatively low. Reaching an agreement for an existing international convention or treaty body to take responsibility for SG research governance, while more likely, is improbable in the near term, especially if the goal of such an agreement is to establish a binding governance mechanism. Nevertheless, there are pathways to achieving substantial international cooperation on climate-related governance among countries.[25] The CCAC, Mission Innovation, and other similar multilateral climate-focused institutions have demonstrated, with varying degrees of success, the potential for a group of self-selected countries to identify and collectively address a neglected and important area of needed environmental cooperation; pool resources; develop a common understanding of risk; coordinate research (by promoting efficiency, avoiding redundancy, saving money, identifying research gaps, etc.); and create global norms of transparency, accountability, and responsibility.

Recommendation 5.1s: A coalition of state and non-state actors should self-organize to promote international information sharing and cooperation on SG research and research governance through activities including (but not limited to) the following:

- **Piloting a transparency mechanism to share information on the current state, scale, and goals of national research programs.**
- **Providing grants for pilot projects or partnerships with countries that are underrepresented in the global research environment (e.g., capacity building institutions like the DECIMALS [Developing Country Impacts Modelling Analysis for Solar Radiation Management] program).**

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[25] However, the models discussed have not been applied specifically to SG.

- **Providing grants for SG-related public education and engagement initiatives, particularly those that increase understanding of differing consequences around the world.**
- **Creating working groups to**
    - **develop common frameworks for understanding the risks and benefits of SG as research evolves over time;**
    - **assess, evaluate, and, if necessary, author a code of conduct for responsible research in SG;**
    - **share and develop best practices for regulating risk, promote a responsible research environment, and investigate other elements of potential global architecture on governance; and**
    - **investigate issues of liability, compensation, risk sharing, and other options to address possible harms that could result from SG.**

At present, we cannot predict which state or non-state actors would take the lead in creating a coalition like the one envisioned. As in other international forums like the one envisioned here, different countries would appoint different lead agencies or ministries. It is expected that the responsible parties in each country would be identified by their national governments, and, as has been the case with similar efforts in the past, full participation from each country would be worked out at an intergovernmental level.

Public and Stakeholder Engagement

Mechanisms to foster public engagement in SG research may be more feasible to implement at the national level, given the limitations of international conventions and agreements. Nonetheless, every effort should be made to ensure that sound public engagement practices are applied when SG research governance is taken up by international institutions and that engagement activities are expanded when possible and appropriate. Most international institutions target particular stakeholder groups (e.g., Business and Industry, Children and Youth, or Farmers). Not all international institutions recognize all publics as relevant stakeholders. Some focus on certain communities rather than others, such as the special status afforded fishing constituencies in the relevant UN agreements on oceans. While this is appropriate in certain contexts (including this example), it is important that any international institution that engages in SG research governance examine the scope of its rules and policies on stakeholder engagement.

Recommendation 5.1t: If SG research governance is taken up by an international governance body, then inclusive engagement opportunities for stakeholder groups recognized by that body should be implemented at the first opportunity. The adequacy of the breadth of recognized stakeholders in that institution and the depth of stakeholder engagement should be examined, using the *UN Environment Programme's Handbook on Stakeholder Engagement* and other similar protocols as guidance.

Mechanisms have evolved to help explain new and emerging technologies to broader audiences and gauge civic reactions to these technologies. In the field of synthetic biology, for example, NSF funded the Multi-Site Public Engagement with Science–Synthetic Biology project (MSPES), a 3-year effort dedicated to public outreach. "The core goal of MSPES was to promote meaningful conversations and interactions between scientists and public audiences through outreach events hosted by informal learning institutions nationwide, using synthetic biology as the science topic of interest" (Rockman et al, 2018). Similar engagement strategies have been used to evaluate the public's response to and awareness of SG (Kaplan et al., 2019). Most of these exercises have focused on nationally homogeneous participant groups, but there is added value when participants interact with people from different countries (see Box 5.2).

Recommendation 5.1u: Transnational exercises designed to gauge the civic response to SG research and research governance issues (e.g., the "World Wide Views" multisite citizen consultation) should be promoted and adequately supported. Such exercises could be sponsored by appropriate global or regional bodies, such as the voluntary international association described in Recommendation 5.1s above.[26] Such work can also be supported by federal agencies or philanthropies.

Addressing Anticipatory International Governance

While this report focuses on recommendations for research governance, some field tests of proposed technology platforms could effectively be viewed as deployment or could incur transboundary effects that would likely be objectionable by some parties. It is also possible that certain SG technologies could be deployed unilaterally by states

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[26] Or, for example, under the auspices of the Escazú Agreement for Latin America and the Caribbean or the Aarhus Convention for Europe.

BOX 5.2
World Wide Views Citizen Consultations

World Wide Views is a multisite citizen consultation. It was developed and has been used three times for global citizen consultations, but it can also be used at the regional and national levels. In these exercises, citizens at multiple sites debate the same policy-related questions on a given issue on the same day and individually vote for prepared answers to the questions posed. Votes are collected and reported to the World Wide Views website, where results can be compared as they arrive. Comparisons can be made among countries, continents, and different groupings, such as developing and developed countries. The results are subsequently analyzed and presented to policy makers.[a]

World Wide Views is coordinated by the Danish Board of Technology in collaboration with the World Wide Views Alliance, a global network of partners including public councils, think tanks, parliamentary technology assessment institutions, nongovernmental civil society organizations, and universities.[b] A list of the countries and partners that have participated in the three global consultations (World Wide Views on Global Warming [2009], World Wide Views on Biodiversity [2012], and World Wide Views on Climate and Energy [2015]) is available online.[c]

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[a] See http://wwviews.org/the-world-wide-views-method/.

[b] See http://wwviews.org/the-world-wide-views-alliance/.

[c] See http://wwviews.org/wp-content/uploads/2015/11/wwviews_country_list_2009-2012-2015.pdf.

or non-state actors well before there is sufficient scientific understanding of the viability and risks of these technologies. Responsible governance is necessarily anticipatory (Guston, 2014), and, in the case of SG, it is appropriate to evaluate different future conditions under which field experiments with transboundary impacts or deployment might be actively contemplated by one or more parties.

Establishment of a high-level international committee charged by the UN Secretary General to assess hypothetical technologies is unlikely and perhaps imprudent. A group akin to the High-Level Panel of Imminent Persons that was enlisted by the Secretary General to write a report on options for the Sustainable Development Goals (prior to their negotiation in 2015), for example, seems inadvisable, as this could lead to overconfidence that some form of SG could resolve the climate crisis or raise fears of imminent deployment of a technology that some fear would exacerbate global inequality. At this stage, an advisory ad hoc committee on anticipatory governance seems more advisable, either composed of individual experts or sub-contracted to a collection of governmental and nongovernmental research institutions, and reporting to an appropriate international body.

Recommendation 5.1v: An ad hoc working group under the auspices of the UN General Assembly or another international body should be created to address future governance needs for SG research. It could provide a range of deliverables including, but not limited to, assessments of

- **the applicable principles of international law embedded in existing conventions, treaties, or agreements that could be brought to bear in the case of the emergence of an international debate (in the UN Security Council or elsewhere) in anticipation of or response to SG field tests with transboundary effects or actual SG deployment;**
- **which existing international conventions, treaties, or agreements and associated governance regimes could have jurisdiction in the case of SG field tests with transboundary effects or actual deployment;**
- **the strengths and weaknesses of possible institutional settings for making international decisions on SG research and research governance;**
- **the potential for SG research and possible SG deployment to exacerbate or ameliorate global inequalities;**
- **both the possibility and ethical permissibility of various approaches to address harm and compensation issues, including harms that may arise with SG field tests with transboundary effects or as a result of SG deployment in the absence of the existence of an applicable international liability mechanism (see discussion in Chapter 2);**
- **the adequacy of existing resources for capacity building related to SG research in developing countries, and advisability of opening some existing pools of climate finance to SG research or establishing new sources of funding; and**
- **the intergenerational implications of SG research, development, and potential deployment—examining, for example, how to take into account principles of intergenerational equity, considering the intergenerational benefits and burdens associated with SG, as well as the institutional challenges that would be involved in a multigenerational SG deployment (including initiation, monitoring and ongoing management, and eventual termination).**

CHAPTER SIX

An Integrated Agenda for Solar Geoengineering Research

This chapter presents the committee's recommendations for the research agenda to be pursued under the program discussed in Chapter 4. This builds directly upon the analyses presented in the preceding chapters, including the assessment of critical knowledge gaps discussed in Chapter 2 and takes into account the principles for a research program discussed in Chapter 3.

6.1 HIGH-LEVEL FRAMING FOR THE RESEARCH AGENDA

Unlike many typical research agendas that are organized largely around disciplinary fields of study, we propose here an integrated approach that emphasizes linkages across many traditional disciplinary divides. For clarity of presentation and organization, the key issues are categorized here as "clusters" of interdisciplinary research questions that target regions of the SG research landscape that could help reduce the most decision-relevant uncertainties; but these clusters should not be viewed as isolated silos of research. The agenda is also intended to address topics that are not already priorities for the broader climate change research enterprise; although at the same time, we acknowledge (and indeed hope) that some research can advance knowledge both for questions specific to SG and for climate change understanding more generally.

The diverse array of clusters encompassed by the proposed research agenda can be framed within a set of three broad categories, listed below. Note that the first of these categories may be seen as a departure from how a research agenda is traditionally conceptualized in that it focuses on building a stronger foundation for improving the research enterprise itself, and it thus underlies how all the other research areas will be approached.

- **Context and Goals for SG Research.** This category encompasses studies that help us better characterize the current and future contexts for SG research, development, and possible deployment—with the aim of better understanding the evolving "decision space" for these activities. It includes efforts to clarify the range of possible goals for an SG program and understand how these goals shape research priorities, guide development of modeling scenarios, and identify key considerations for decision making. This area of research will help inform decisions about *which* futures (among the wide range that are possible) may be most fruitful to investigate. It will advance exploration of whether and how SG can be developed to generate broadly beneficial outcomes, how to address the risks and uncertainties, and how to build the capacity needed for countries to engage meaningfully in research and research governance.

- **Impacts and Technical Dimensions.** This category encompasses research to better understand basic mechanisms determining the technical feasibility of different SG strategies, their effectiveness in terms of regional-to-global-scale cooling, and their potential impacts on other climatic variables (e.g., precipitation). This includes chemistry and microphysics research to understand the properties of injected reflective particles and interactions with clouds and other atmospheric processes, engineering studies of the technical requirements associated with different SG technologies, and advancing strategies to monitor and attribute the climate impacts of SG activities. Research related to human health, social systems, and ecology aims to develop systematic approaches to studying impacts, to better characterize the range of possible impacts, and to consider the uncertainties and limits to understanding impacts.
- **Social Dimensions.** This category encompasses a wide array of research exploring how to better understand public perceptions of SG research and its possible future deployment; how to fairly govern and effectively engage various publics and stakeholders in SG research, development, and deployment decisions; how to approach domestic and international conflict and cooperation in the SG arena; and how to integrate ethics, justice, and equity considerations. These research dimensions are essential for better understanding questions about the social acceptability of SG.

A critical concept to emphasize is that these general research categories are closely interlinked. Rather than progressing in some simple linear fashion from one stage of research to the other, these categories of research will need to advance in an integrated, interactive manner. For example, the ways in which future contexts are conceptualized (Context and Goals) will affect the scenarios used to study the possible effects of SG interventions (Impacts and Technical Feasibility) and vice versa. If research found that one type of SG intervention would have more widespread beneficial impacts than another type (Impacts and Technical Feasibility), that would likely shape the public acceptability of each of these strategies (Social Dimensions); however, social values and priorities (Social Dimensions) can also help guide the kinds of interventions that are considered and researched (Impacts and Technical Feasibility). These are just a few illustrative examples of the many linkages to consider. Identifying and investigating these interactions is itself an important aim of the proposed research program. Thus, in the recommendations that follow, we highlight the importance of engagement across research areas and suggest steps to support interaction and integration.

To help define the more specific research that is needed, the committee has identified a set of 13 clusters (listed below) as key locus points for an initial phase of an SG research program. These are framed as "clusters" because each represents a coherent but loosely grouped collection of related research questions and needs, recognizing that there are considerable linkages and overlaps among the different clusters. Figure 6.1 illustrates how the research clusters can be loosely grouped within the broader categories discussed above.

Recommendation 6.1: The agenda for the SG research program should encompass three broad, interconnected areas that address (i) the context and goals for SG research, (ii) the impacts and technical dimensions, and (iii) the social dimensions. Under these broad categories, the following are recommended as key research clusters to pursue:

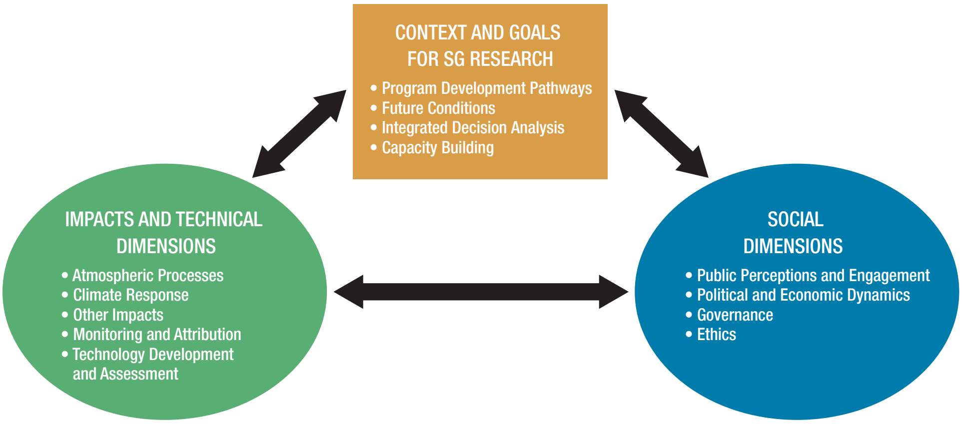

Figure 6.1 Three broad categories and 13 research clusters included in the Committee's proposed research agenda.

Context and Goals for SG Research

- **Program Development Pathways.** Designing an SG research program to maximize the prospects for broadly beneficial outcomes.
- **Future Conditions.** Exploring the range of future conditions under which SG-related decisions will be made.
- **Integrated Decision Analysis.** Understanding implications of, and strategies to address, persistent uncertainties that affect decision making related to SG.
- **Capacity Building.** Developing the capacities needed for all countries to engage meaningfully with SG research and research governance activities.

Impacts and Technical Dimensions

- **Atmospheric Processes.** Understanding chemical and physical mechanisms that determine how addition of materials to the atmosphere alters the reflection and transmission of atmospheric radiation.
- **Climate Response.** Assessing how different SG approaches would affect key climate outcomes.
- **Other Impacts.** Assessing the potential environmental and societal impacts of SG intervention strategies.
- **Monitoring and Attribution.** Designing an observational system (and understanding its limitations) for detection, monitoring, and attribution of SG deployment and impacts.
- **Technology Development and Assessment.** Addressing the science and engineering issues related to hardware, materials, and infrastructure underlying SG research.

Social Dimensions

- **Public Perceptions and Engagement.** Understanding public perceptions of SG and strategies for inclusive, meaningful societal engagement, and how to incorporate these insights into a broader research program.
- **Political and Economic Dynamics.** Exploring the implications of SG for national and international relations and related incentive structures.
- **Governance.** Developing effective, adaptive processes and institutions to govern SG activities.
- **Ethics.** Incorporating ethics and justice considerations for current and future generations into SG research and research governance.

6.2 THE RESEARCH AGENDA TOPICS

This section walks through the proposed 13 research clusters, each with a short overview followed by a collection of key steps forward related to each topic. The nature of these suggestions varies considerably among the different clusters (e.g., some presented as research questions, some as specific research activities). These variations arise because some of these fields are more developed than others in terms of the existing base of research and the theoretical foundations for defining new research activities. For the more nascent fields of research, the suggested steps forward are broader and more exploratory in nature. In addition, these 13 clusters represent widely varying types of research—for instance, ranging from laboratory and field studies, to computer modeling, to quantitative and qualitative social science investigations (e.g., empirical studies, data analysis, surveys, and case studies)—and thus the nature of the steps forward differ accordingly.

Context and Goals for SG Research

[1] Program Development Pathways: *Designing an SG research program to maximize the prospects for broadly beneficial outcomes.*

The exploration and possible implementation of SG—like any other technology—is inherently a sociotechnical enterprise. The generation of scientific knowledge and its application takes place in a particular societal context and therefore has to be cognizant of and responsive to that context; in turn, new knowledge and its application shapes societal discourses and institutions. The context for SG research includes the fact that these technologies would have global and intergenerational consequences. Yet, the institutional capacities to manage SG on behalf of a global, intergenerational public are currently very limited.

SG involves a particularly acute form of the technology control dilemma (also known as the Collingridge dilemma), which holds that social guidance of a developing technology is easiest in its early stages (Collingridge, 1982). However, the precise shape and implications of the emerging technology are often not well understood in these stages, making it difficult to know how to guide it. By the time the technology is developed and its implications are clearer, many features of the technology may be already locked in, making it difficult to shape it in response to societal input.

Even initial technical feasibility assessments for SG require assumptions and design choices that may further shape the trajectory of research and development. For example, models of stratospheric aerosol injection (SAI) require choices regarding where to inject aerosols (altitude, latitudes) and how much (based on the amount of warming to offset), and these choices can significantly affect the simulated impacts. Such choices can shape SG's effects and impacts and, concomitantly, its social acceptability. Similarly, in order to assess technical and social feasibility, researchers must make choices and assumptions about SG design. Ideally, such choices would enable the exploration of multiple possible approaches, while taking account of evolving social, political, economic, and climate contexts, as well as public and stakeholder perspectives. But in practice, knowledge of how to achieve these goals is very limited.

The design of an "SG system" (i.e., the constellation of activities and actors involved in the generation and application of scientific knowledge and the shaping and governing of that process) needs further research in multiple dimensions. System design issues reach across planning, research, development, and deployment phases, and these different elements are closely interlinked. For instance, the design of the research program will shape the nature of the scientific explorations undertaken, the knowledge from the scientific explorations will inform decisions about whether and how to proceed with further development and any possible SG deployment, and possible scenarios of SG deployment will inform relevant scientific explorations. The pathways taken in each of these dimensions will depend on the stakeholders involved in the discussions, their questions of interest, and the disciplinary perspectives brought to bear.

The notion of "design" itself implies that there is a goal the system is trying to achieve. For instance, an initial question might be about how much global cooling is desired. But how will that intent evolve over time? Would the goal be to maintain constant temperature, or limit the rate of change of temperature, or simply ramp up to a constant amount of SG (e.g., trying to maintain a specific concentration of stratospheric aerosols)? Even if a hypothetical future SG system could achieve a particular amount of global cooling, who would "decide" the temperature goal, and how would that decision be reached among all the parties that could be affected by the intervention? Are there ways other than temperature goals to conceptualize the SG design? Which stakeholders are part of this decision process? These are questions about the nature of "SG system" design that need further transdisciplinary research.

The way that SG implementation decisions are made can lead to real differences in outcomes. For example, decisions could be made in a well-intentioned, strategic way based on model projections, or they could be made in a completely opportunistic way (e.g., country X has access to airfield at latitude Y and so that is what it uses). For SAI, the type of aerosol itself and location and timing of injection will also affect outcomes and even the extent of uncertainties. But even in the absence of any real "plan," choices such as the latitude at which to inject aerosols (or equivalent choices regarding where to deploy marine cloud brightening [MCB]) will affect outcomes, and if SG were to be used, these choices could not be avoided. Thus, an important goal for SG design research is to ensure that those who would potentially be making deployment decisions have information regarding the differential projected impacts from different choices available to them and an understanding of the uncertainties associated with these projections.

Other important factors to understand include how an ongoing SG program might be designed to evolve over time and what information is needed to allow decision makers to evaluate adjustments or decision points as implementation proceeds. Ideally, one could monitor changes to the climate and adjust strategies (including potentially phasing the deployment back out) as new information is gained. Yet without further research, it is not clear which aspects of SG could be effectively monitored and on what timescales—thus, the degree to which it is possible to adaptively manage future SG deployment itself requires additional investigation. This becomes a key issue, given that the desirable and acceptable features of SG might change over time as societal preferences evolve.

Whether and how to proceed with SG research, design, and deployment are societal choices, although hopefully well informed by the science. Research in this area can help us develop an integrated understanding of how different choices would lead to different impacts and of the diverse range of perspectives on objectives and trade-offs. Approaching this issue from a broad "sociotechnical" perspective requires research that addresses a wide array of questions about SG system design, including (but not limited to) those listed below.

Some critical questions to address in this research cluster include the following:

- How and by whom are the scientific questions that need to be answered in an SG research program identified?
- How and by whom are the primary objectives of SG determined (i.e., what risks are to be mitigated and by how much)?
- How and by whom would decisions be made that there is enough understanding of SG benefits and risks either to abandon any further pursuit or to proceed with further development and deployment?
- What level of climate risk and mitigation effort would be sufficient to consider deployment? Who would make such decisions, and how would they be made?
- How do we deal with the distribution of risks and benefits of SG deployment? How should we deal with trade-offs? How do different stakeholders view different trades-offs? (See Section 7 below.)

- How and by whom would choices about SG deployment (e.g., type of aerosol, type of delivery technology, altitude, latitude, quantity of aerosol, frequency, and time of year) be made?
- How would we know that an SG deployment was achieving its objectives? How would we detect and attribute SG efforts? How and by whom would decisions be made about how much SG deployment is enough? How and by whom would decisions be made about the conditions under which SG deployment might be phased out and the process of doing so?
- How do we identify the "appropriate" stakeholders (e.g., natural and social science experts, ethicists, policy makers at different levels, and broader publics) and ensure that they have the capacity and opportunity to effectively participate in the SG design process?
- What dimensions of climate impacts matter most to people? How do these views evolve over time?

Questions pertaining to the underpinnings of design for SG research and deployment include the following:

- What are the limits to what can be achieved by SG interventions? What decision variables matter (e.g., latitudes, seasons, etc.)? What fundamental trade-offs must be considered (e.g., it would be important to know if you cannot maintain precipitation over both region X and region Y)? Is there an obvious "best" way to deploy (presumably connected to whose interests and concerns are represented)?
- How do we assess the sensitivity of the answers to these questions across different climate models or to uncertain physical parameters in models?
- How can one best use observational information combined with climate model projections to make reasoned decisions about how one adjusts key decision variables?
- What are some of the unforeseen factors that could affect deployment design choices (e.g., the climate response if country X only has access to an airfield at latitude Y and deploys only from there)?

[2] Future Conditions: *Exploring the range of future conditions (socioeconomic, geopolitical, climatic, and other environmental) under which SG-related decisions will be made.*

Future decision making over whether and how SG technologies might be deployed and governed will be informed by an explicit assessment of the range of plausible future conditions under which such decisions may be made and the implications of those conditions for the outcomes of key deployment and governance decisions. A starting point for such research is the "scenario analysis" approach taken in climate change impact assessments, wherein a broad spectrum of social, economic, political, and cultural elements of future societal pathways are rolled up into a discrete number of storylines. These storylines are meant to represent the range of plausible future conditions under which decision making regarding climate mitigation and adaptation could occur (O'Neill et al., 2017, 2019). Scenario analysis in climate modeling and risk assessment is used to represent uncertainties associated with future socioeconomic and geopolitical conditions whose parametrizations are not easily constrained using empirical methods.

The climate modeling community has long used "Representative Concentration Pathways" (RCPs), which offer a range of plausible future trajectories for greenhouse gas (GHG) atmospheric concentrations and resulting radiative forcing over the coming decades. More recently, these RCPs are being considered together with "Shared Socioeconomic Pathways" (SSPs) that characterize a broad range of possible societal trajectories over the course of this century. Five SSPs have been developed as inputs into climate models in the lead up to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (Hausfather, 2018; O'Neill et al., 2017, 2019). Providing broad context for assessing barriers and opportunities for mitigation and adaptation, the SSPs describe futures of sustainability-focused growth and equality (SSP1); a "middle of the road" world where trends follow historical patterns (SSP2); a fragmented world of "resurgent nationalism" (SSP3); a world of increasing inequality (SSP4); and a world of rapid and unconstrained growth in economic output and energy use (SSP5).

To inform SG decision making, scenarios would also need to consider the interactions between future climate forcing and societal trajectories with plausible trajectories for SG deployment and its climatic and socioeconomic consequences. To date, however, modeling work to assess possible future SG deployment and its impacts has been conducted with a more limited set of scenarios that are designed primarily to enhance understanding of physical effects and mechanisms under highly idealized conditions. Scenarios developed under the Geoengineering Model Intercomparison Project include those in which SAI is applied in conjunction with a quadrupling of atmospheric CO_2, with a 1 percent per year increase in atmospheric CO_2, and with a moderate warming scenario (RCP4.5). Recent single model studies have produced simulations that kept temperatures to 1.5 or 2.0°C levels (Jones et al., 2018; Tilmes et al., 2016, 2020).

On an ad hoc basis, individual research initiatives have also explored outcomes of a somewhat broader range of forcing and implementation scenarios. Papers have proposed scenarios that, for example, maintain a fixed temperature (Ricke et al., 2010) or a fixed rate of change of temperature (MacMartin et al., 2014a) or cut the rate of change of net radiative forcing in half (Irvine et al., 2019) in climate and economic models. But scenarios have not yet been established and adopted by the SG research community to explore and provide policy-relevant assessments of impacts under a more broadly representative range of plausible pathways of SG deployment. There are, for example, several scenarios under which SG might be deployed that have been characterized in the research literature and in broader societal discourse, including the following:

- "Peak shaving" under idealized conditions of modest climate overshoot and capacity for sustained effective governance (MacMartin et al., 2018b; Tilmes et al., 2020).
- Deployment in "climate emergency" conditions of continued rising GHG concentration, increasingly severe risks, and uncertain capacity for sustained effective governance.
- Unilateral deployment by an actor seeking to use SG as a means to control climate or with other unknown intentions, without informing others or abiding by any international governance norms that may be established (Victor, 2019).
- Deployment under conditions of competing objectives among nations regarding temperature and impact goals (Frumhof and Stephens, 2018).

These scenarios place the context of decisions to deploy as driven mainly by concerns over climate risk. There is also a need to systematically explore the possible socioeconomic and geopolitical conditions that national governments and other actors may experience in the future under all phases of a possible future use of SG. These included decisions to deploy, adjustments to implementation over time, detection and attribution of impacts, and decisions to terminate.

Socioeconomic and geopolitical conditions are important variables affecting SG outcomes and work is needed to more fully explore a sufficiently broad range of cases, including those that consider the distribution of impacts. Projects seeking to integrate input from diverse disciplines to develop a broader set of policy-relevant SG scenarios are now under way. The National Socio-Environmental Synthesis Center, for example, is convening experts to "develop a set of scenarios and models that integrate social and environmental aspects of climate engineering technologies and their interactions with mitigation efforts."[1] Building on this and other nascent initiatives, an SG research

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[1] See http://ceassessment.org/new-scenarios-and-models-for-climate-engineering/.

program could seek and incorporate input from decision makers and representative stakeholders to ensure that SG scenarios take account of diverse policy-relevant perspectives (engagement strategies discussed in earlier chapters). Research scenarios that are co-developed with stakeholders are likely to be more credible, salient, and legitimate and therefore more useful to support decision making (Cash et al., 2003; Dilling and Lemos, 2011).

An important limitation of scenarios in SG modeling is that they are inherently static; that is, they are not well suited to incorporate dynamic feedbacks from societal responses to SG deployment and other changing geopolitical conditions. Yet, uncertainties over societal feedbacks, such as the effect of SG research and development on emissions reductions, may dominate considerations over whether, for example, global SG might be effectively governed for a sustained (half-century or longer) time period. Thus, it will be important to characterize the limits to scenarios in SG decision making and explore ways to explicitly characterize the implications of socioeconomic and geopolitical uncertainties to decision makers. In addition, it will be important to consider novel approaches to representing societal feedbacks in climate impact assessments that reflect the much shorter timescales between deployment and climate response expected with SG relative to mitigation.

Some critical steps forward to advance this research cluster include the following:

- ***Develop an improved set of SG scenarios for use in impacts modeling and policy assessments.*** These scenarios should characterize a representative range of socioeconomic, geopolitical, and climatic and other environmental conditions under which SG deployment decisions might be made. They should be developed through collaboration among experts across relevant natural and social science disciplines as well as include substantial participation of experts from developing nations. They should foster alignment with the SSP scenarios (O'Neill et al., 2019) and other scenario processes as appropriate, such as those developed for the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (Rosa et al., 2017). The process of scenario development should include the solicitation of meaningful input and review from a representative range of policy makers and stakeholders, including from non-western and developing country perspectives. The scenarios to be developed are likely to be more credible, salient, and legitimate for informing decision makers if they are co-developed in consultation with a broad range of societal actors as described above (Cash et al., 2003).
- ***Develop new analytical approaches to socioeconomic uncertainty assessment.*** Such approaches are needed to accommodate the problem of the short timescale between implementation of shortwave SG forcings and

physical Earth system responses. This includes the development of novel socio-environmental systems modeling frameworks in which feedbacks between climate outcomes and climate decision making are represented as dynamic processes with uncertain, but empirically calibrated, parameterizations. For example, some models have previously explored the relationship among perception of climate change, support for emissions reductions policies, and policy-driven climate outcomes (e.g., Beckage et al., 2018; Ricke and Caldeira, 2014). Such models could be a valuable tool for understanding the dynamical relationship among SG, mitigation, and adaptation in a way that fixed emissions and forcing scenarios cannot. (See related discussion in Research Cluster 3, "Integrated Decision Analysis.")

[3] Integrated Decision Analysis: *Understanding implications of, and strategies to address, persistent uncertainties that affect decision making related to SG.*

If the aim of an SG research program is to reduce decision-relevant uncertainties, more comprehensive, innovative approaches to uncertainty analysis will be required in order to effectively integrate across many of the research questions discussed throughout this chapter.

Scenario analysis research. Some scholars suggest that dynamic social system feedbacks are the most fundamental uncertainty associated with long-term outcomes of SG implementation. But it is unclear whether socioeconomic uncertainty in analyses including SG can be adequately characterized through use of scenarios, which are inherently static. Instead, it may be more important to identify ways to incorporate a new category of socioeconomic model uncertainty into "partitioned outcome" uncertainty assessments that include SG. In addition, it will be necessary to develop decision analytic frameworks that accommodate simultaneous consideration of SG with other climate risk mitigation tools, for example, portfolio approaches (Cao et al., 2017; Ricke and Moreno-Cruz, 2020) or "cocktail geoengineering" (Cao et al., 2017). (See related discussion under Research Cluster 1, "Future Conditions.")

Integrated assessment research. Another tool broadly applied for examining the implications of uncertainty for climate decision making is integrated assessment modeling, wherein idealized models of the climate system and the economy are run simultaneously. Integrated assessment models (IAMs) have been used to explore the implications of key uncertainties to setting optimal climate policy or reaching specified climate policy goals, such as emissions or temperature targets. Applying IAMs for decision-analytic purposes requires having a robust integrated model of the socio-environmental system. In the near term, this presents a problem for application of

IAMs to uncertainty assessment of SG outcomes because the science of SG impacts is fairly immature. Without robust reduced-form, empirically parameterized models of the relationship between climate variables and socioeconomic outcomes the output of IAM-based SG decision analysis will not be reliable or meaningful.

Model intercomparison. IAMs can be powerful tools for bridging natural science, social science, and economics and for investigating critical questions about SG. At present, however, the different IAMs being used for climate-related research use widely differing assumptions, which makes results difficult to reproduce. Moving forward, it will be important to organize standardized intercomparison studies that utilize comparable scenarios and simulations.

Decision making under deep uncertainty. A number of separate but related methodologies have been developed for conducting decision analysis under conditions of "deep uncertainty," which is defined as "conditions … where analysts do not know, or the parties to a decision cannot agree on, (i) the appropriate conceptual models that describe the relationships among the key driving forces that will shape the long-term future, (ii) the probability distributions used to represent uncertainty about key variables and parameters in the mathematical representations of these conceptual models, and/or (iii) how to value the desirability of alternative outcomes" (Lempert et al., 2003). At present, questions about outcomes under potential future implementation of SG appear to meet such "deep uncertainty" conditions. Methods used for decision analysis under such conditions have been labeled as Robust Decision Making, Real Option Analysis, and Adaptive Policy Making.

Characteristics of these tools include consideration of a broad range of scenarios and decision strategies; application of satisfactory (as opposed to optimal) decision criteria; and use of adaptive learning, wherein decision strategies and criteria are iteratively adjusted with additional information. Prioritizing research that applies to SG critical methods for decision making under deep uncertainty could help identify strategies for executing research that quantifies uncertainty in a holistic way. This will aid future decision making about setting further research priorities and weighing pros and cons of SG implementation.

Some critical steps forward to advance this research cluster include the following:

- Develop methodologies to incorporate socioeconomic model uncertainty into SG outcome uncertainty assessments, including both empirical uncertainty from climate effect and impact studies, as well as parametric and model-form uncertainties.
- Develop more robust, empirically parameterized models of the relationship between climate variables and socioeconomic outcomes to support IAM-

based decision analyses, in particular relationships that do not primarily represent outcome-climate relationships as a function of temperature.
- Advance the application of methods for decision making under deep uncertainty to SG, including through the examination of outcomes under a diversity of sociopolitical scenarios, non-optimizing (satisficing) decision criteria, and adaptive learning strategies.
- Develop decision analytic frameworks that accommodate the examination of outcomes in the presence of heterogeneity in decision makers and a diversity of international institutional constraints (including lack of cooperation and coordination between parties engaging in SG activities).

[4] Capacity Building: *Developing the capacities needed for all countries to engage meaningfully with SG research and research governance activities.*

The need for helping countries around the world build capacity to participate in research and decision-making processes is a topic that often arises in discussions about SG intervention strategies. Yet there is almost no systematic exploration in the SG literature about what kind of capacities are most needed for allowing effective engagement with research and research governance efforts, and how these capacities might be developed and sustained across a wide array of geographical and cultural contexts. The importance of pursuing such questions stems from our recognition that involvement of a diverse range of stakeholders is critical for robust SG research, design, and governance—and that individual and community perspectives on almost all aspects of this issue are shaped by local context. While such realities greatly enhance the complexity of capacity building efforts, recognizing and addressing these diverse needs will help ensure a more robust SG enterprise.

Some critical questions to address in this research cluster include the following:

- What kinds of capacities are needed in order to engage meaningfully with critical dimensions of SG research and research governance?
- What are the current differences and commonalities in capacities between the Global North and South? What capacity exists today, and what are the key gaps?
- What kinds of capacities are needed to enable a transdisciplinary, robust, and adaptive SG research enterprise? What types of capacities are desired by countries not currently involved in SG research?
- What kinds of physical science (e.g., experimental, modeling, or engineering) and social science, humanities, policy, and legal expertise might be needed?
- What kinds of "boundary" actors might be important to serve as bridges across disciplines, issues, and stakeholders?

- What types of organizational entities (e.g., academia, civil society, private firms, governments, or international organizations) should be focal points for capacity building?
- What kinds of capacity might be needed in broader general "publics," in order to fully and effectively engage with the SG research enterprise?
- What kind of institutional forms and capacities might be required in order to suitably organize and coordinate among the many actors involved in an SG research program?
- What kinds of expertise and institutional capacities are needed in order to design an SG research enterprise that is truly transdisciplinary, sociotechnically robust, and adaptive?
- What kinds of expertise and institutional capacities would be needed to suitably design and govern SG deployment activities?
- How might such capacities be developed, strengthened, maintained, and assessed?
- What might be the role of various actors (e.g., national and sub-national governments, academia, philanthropies, and international organizations) in supporting the development of needed capacity in the Global North and South? What kinds of efforts and resources are being devoted currently to building such capacity?
- What might be the role of and best mechanisms for international (N-S, S-S) cooperation in developing different kinds of capacity pertaining to scientific knowledge generation, research governance, and SG governance?
- What are the greatest areas of opportunity for capacity building, and what are the most significant barriers? How can opportunities be best utilized and barriers be reduced?
- What levels and kinds of financial, institutional, and political support would be needed to build the capacity for robust engagement by climate-vulnerable regions, indigenous peoples, and nations of the Global South in SG research and research governance, and how might such support be secured?

Impacts and Technical Dimensions

[5] Atmospheric Processes: *Understanding chemical and physical mechanisms that determine how addition of materials to the atmosphere alters the reflection and transmission of atmospheric radiation.*

There is a wide array of research questions to explore in order to better understand the technical feasibility of SG interventions, and the exact nature of these questions varies depending on whether one is focused on SAI, MCB, or cirrus cloud thinning (CCT). The discussion in this part of the research agenda is thus longer than the other topics discussed in this chapter; it is broken out into three separate sub-sections, each focused on the different SG strategies.

Stratospheric Aerosol Injection

It is clear from the Chapter 2 discussion that adding aerosols to the stratosphere would result in global cooling at the surface. Predicting the magnitude of this cooling, the climate response more generally, and the resulting impacts requires use of a climate model (discussed in Research Cluster 6). Those predictions depend on the concentration, size distribution, and spatial distribution of the aerosols injected, their radiative properties, and chemical effects; thus, predictions depend on the ability to adequately characterize and simulate important aerosol processes that occur at small spatial scales (relative to the grid scale of a climate model). The uncertainties in processes translate into uncertainty in predicting policy-relevant impacts. Reducing uncertainty in the relevant stratospheric processes is thus a high priority.

This cluster will involve higher resolution simulations along with observational, laboratory, and (potentially) outdoor experiments. Because of the long lifetime of aerosols in the stratosphere (relative to transport timescales), and because some of the relevant observations that might constrain processes are at a larger scale, research to resolve process-level uncertainties cannot be conducted completely independently from climate modeling research (described further below and in the next section).

As described in Chapter 2, the overall magnitude and spatial distribution of the forcing produced by SAI depends strongly on the aerosol size distribution (or, equivalently, ratio of surface area to volume or mass), as well as feedbacks that depend on the aerosol-induced stratospheric heating (e.g., changes in stratospheric water vapor concentrations, in stratospheric circulation, and in upper tropospheric cirrus cover). Here we discuss the need to accurately represent these processes in climate models (capturing both longwave and shortwave effects from aerosols), and other related dimensions of this issue are discussed under Research Cluster 6. In addition, given that one of the key SAI impacts of concern is the effect on stratospheric ozone, chemistry also needs to be accurately predicted, both for sulfate aerosols and for any other proposed material.

Processes will need to be understood as a function of how much material is added for different choices of injection latitude, altitude, and season, and for different choices for the aerosol material itself (e.g., sulfate, calcite, or other solid aerosols). The method of delivering the material also matters—for example, for sulfate, whether delivered as a precursor gas (SO_2 or H_2S) or as small H_2SO_4-containing aerosols. If lofting is via aircraft (as is likely), then ions present in aircraft exhaust may play an important role in the ultimate size distribution.

One of the research priorities for SAI is thus to address critical gaps in knowledge about the evolution of the aerosol particle size distribution—specifically, to explore plume dynamics (i.e., what happens after release from an aircraft in a coherent plume versus release uniformly mixed over a gridbox of a climate model and how long that plume stays coherent), particle nucleation (which is influenced by plume dynamics) and subsequent growth (which will depend on the existing background aerosol concentrations), and how implementation choices impact outcomes. This includes a need for improved understanding of stratospheric dynamics (mixing) and oxidation timescale (for gas addition) for an SAI. Finally, it is important to understand chemical interactions and how SAI impacts may be affected by future changes in atmospheric composition and chemistry (e.g., changes in halogen chemistry related to decreases in chlorofluorocarbons and bromine; increases in ambient NO_x due to increasing N_2O), and feedbacks on ozone due to stratospheric temperature changes.

Understanding how aerosol surface area and volume evolve in response to the localized addition of aerosol or aerosol gaseous precursors requires detailed simulations of nucleation processes (Lee et al., 2019) to identify the relevant rates of competition between nucleation and growth. The initial stages of particle formation and growth occur at sizes smaller than 10 nm diameter, which have thus far only been reliably quantified by simulation and laboratory experiments (Lee et al., 2019). Observations of the resulting size distributions could provide constraints that improve representation by climate models, but these observations would not be able to distinguish among the driving processes (e.g., vapor oxidation, heteromolecular and ion-induced nucleation, plume dynamics, or near-field coagulation of particles smaller than 10 nm diameter); nor could such observations distinguish interactions among chemistry, microphysics, and large-scale circulation. Establishing a quantitative and causal link between inputs and the aerosol size distribution must rely on laboratory experiments to verify model parameterizations, which must then be constrained by field observations. Designing optimal methods to inject vapors or particles requires understanding these causal links.

Understanding the impact of SAI forcing on stratospheric and upper tropospheric composition requires quantifying the impact of the particles emitted (and any exhaust from the delivery system) on ozone chemistry and stratospheric dynamics. Aerosols will affect stratospheric dynamics through heating (from absorption of infrared [IR] radiation). Predicting the changes to stratospheric circulation requires a climate model, and those predictions depend on an accurate parameterization of the heating rates. The impact of aerosols on upper tropospheric cirrus also needs to be understood; cirrus may be influenced by changes to vertical temperature gradients and hence aerosol heating, as well as potentially by aerosols themselves. As changes to cirrus would affect the overall radiative forcing, these processes will also need to be understood and properly represented in climate models.

Some open research questions associated with the aerosol microphysics of SAI include the following:

- For gaseous additions, what is the rate of formation and growth of particles from their precursors, and how does this depend on the time and location (latitude and altitude) of injection? How does this depend on the aerosol concentrations already in the stratosphere? What aspects of these processes are not well represented by available models? How well can these processes be constrained by existing observations (e.g., after volcanic eruptions)?
- For direct addition of aerosol, what are the effective concentrations of particles that determine the coagulation rates in the near field following injection, and how are these affected by aircraft and local dynamics? To what extent do these processes affect the resulting particle size distribution?
- How is plume dispersal influenced by the wake of the aircraft, and how does that depend on the location and height of injection? Do ions generated in the engine enhance the rates of nucleation significantly (i.e., by a factor of 10 or more)?
- Given the results of the items above, are existing models of nucleation, aerosol dynamics, and plume dispersion sufficient to adequately predict the timing and properties of the particle size distribution for a given input of aerosol or precursor over a range of altitudes and latitudes?

Addressing these questions requires a mix of (i) laboratory measurements of the rates of oxidation of aerosol precursors, (ii) accurate simulation of microphysical processes, and (iii) a sufficiently realistic representation of both the small-scale turbulence and the larger-scale circulation. Modeling of turbulence in the lower stratosphere is improving, but it needs to be constrained by comparison to observations (including capabilities to measure both background conditions and aircraft-perturbed turbulence). Near-field dynamics will necessarily be parameterized in large-scale models used to evaluate SAI; thus, accurate parameterizations need to be constructed to adequately describe the subgrid-scale processes and their dependence on injection parameters.

To better understand the impact of SAI forcing on stratospheric and upper tropospheric composition, open research questions include the following:

- What are the rates of heterogeneous chemistry occurring on the surfaces of SAI particles? This requires knowledge of what the surfaces are and their interaction with, for example, existing sulfate, N_2O_5, HCl, and $ClONO_2$ (factors that could be examined in laboratory experiments).
- How would SAI interventions (addition of gases, liquids, or solids) alter ice and nitric acid trihydrate nucleation rates in the stratosphere, and how would this influence polar denitrification/dehydration?
- What are the heating rates associated with the SAI? This requires knowledge of the optical properties of the injected particles and their volume and mass, which need to be predicted from the injection material and conditions.
- How does stratospheric circulation adjust to the changes in shortwave and longwave forcing? How does stratospheric water vapor change as a result of the circulation changes and tropopause heating?
- How does stratospheric ozone change due to changes in heterogeneous chemistry and stratospheric circulation? Models based on laboratory measurements provide a starting point for these questions, but verification with in situ measurements may be needed.
- How much of an increase in aerosol concentration in the upper troposphere (UT) will occur? What is the impact of the additional or larger aerosol particles on cirrus (or at higher latitudes, on polar stratospheric clouds)? How does this compare to changes in vertical velocity from stratospheric heating?

Addressing all of these questions will require a combination of modeling, laboratory studies, new observations, and, potentially (if these other approaches prove inadequate), controlled-release experiments. Addressing the microphysical questions in particular likely requires a combination of plume-scale microphysical modeling and laboratory measurements of chemical reaction rates and yields, followed by comparison of the model results with relevant observations.

Collecting observations after volcanic eruptions, such as those suggested in the NASA Major Volcanic Eruption Response Plan (NASA, 2018), may be able to help reduce some of the uncertainties (specific to sulfate), by putting some constraints on aerosol coagulation, chemistry, and heating rates (as well as water vapor, or circulation changes), along with potentially reducing uncertainty in stratospheric circulation and transport.

Laboratory studies may be appropriate to reduce uncertainties in processes that occur on short timescales and small spatial scales (e.g., within an aircraft plume), but it is difficult to maintain stratospheric conditions in a laboratory setting over substantial timescales. Thus, there is a potential role for deliberate controlled-release experiments to better constrain processes occurring within an aircraft plume in particular, especially for direct injection of sulfate aerosol (as accumulation-mode H_2SO_4) or alternate aerosols for which there is no natural analogue.

Some critical steps forward to advance this research cluster (for SAI) include the following:

- Advance rigorous analysis of existing uncertainties—including how well they are or are not constrained by existing data (e.g., how much parameters can be varied while still matching observations) and how much that range of uncertainty influences projected climate outcomes from SAI (i.e., how to prioritize which sources of uncertainty to reduce)—and assessment of which uncertainties can be reduced and by how much (using existing and new observational data, laboratory measurements, and/or in situ deliberate releases of material).
- Identify quantitative linkages with uncertainty estimations (using realistic rather than idealized scenarios) among the different steps from release of injected materials to the resulting changes in aerosol surface area and volume, and changes in stratospheric composition. Critical sources of uncertainty should be identified, bounded if possible, and their impact on predictions assessed.
- Develop a program to characterize the gas and aerosol dynamics and chemistry following volcanic eruptions that inject substantial H_2S and SO_2 in the stratosphere (observed over several months) to provide key observations for reducing uncertainty associated with SAI. One such plan has been developed, but not yet deployed, by NASA (see above).
- Advance laboratory measurements and high-resolution microphysics plume model simulations to quantify some of the uncertainties in near-field aerosol particle size distributions. If such uncertainties cannot be reduced by laboratory measurements, then direct releases of materials into the stratosphere to study the aerosol dynamics and chemistry could be performed; however, heterogeneous chemistry of proposed alternatives to sulfate should be investigated in laboratory experiments before considering atmospheric release.
- Study the impact of enhanced aerosol input to the UT by improving understanding of the ice nucleation properties of the different proposed particles and of the size distribution and lifetime of such aerosols in the UT. Laboratory experiments and detailed simulations provide a starting point for these questions.
- Climate models are the critical tool to assess large-scale climate responses associated with SAI. Currently, these rely on adequate parameterizations of subgrid cell processes; thus, the output of all of the above steps needs to be incorporated in improved parameterizations.

- **Observational Needs.** Expand monitoring of baseline conditions of the stratosphere, for model evaluation, for improving the representation of the aerosols in the stratosphere without SAI, for understanding how stratospheric aerosols influence dynamics and chemistry, and thereby for understanding the impacts of SAI on stratospheric ozone and the resulting tropospheric ultraviolet (UV) dose. The following observational recommendations from the World Meteorological Organization Ozone Managers Meeting (2017)[2] are suggested as a necessary precondition for SG research involving stratospheric aerosol manipulation:
    - Understanding the important connections among changes in ozone, climate, and atmospheric transport—and in particular expected changes in the global meridional Brewer-Dobson Circulation and unexpected events like the recent break of the Quasi-Biennial Oscillation—require appropriate monitoring of temperature, winds, and trace-gas profiles (especially of dynamical tracers like N_2O and SF_6) as well as ozone and water vapor.
    - Continuation of ground-based stations—especially those with long-term records of ozone, trace gases, UV, temperature, and aerosols—is necessary to provide a reliable baseline for trend estimation and for assessments of polar ozone loss. The steady decrease in the number of stations, especially for profile measurement capabilities, is endangering the unambiguous determination of trends and the capturing of unexpected events, as well as our ability to validate satellite data records.
    - Continuation of limb emission and IR solar occultation observations from space is necessary for global vertical profiles of many ozone and climate-related trace gases and parameters. Without such observations, the accuracy of the predictions of data assimilation systems and related services to policy makers will degrade.

Marine Cloud Brightening

For understanding MCB, the highest priority research questions are how aerosols interact with clouds locally (and immediately) and regionally (and over days). These same questions are also issues of great importance for advancing fundamental understanding of climate change, and thus any advances in this understanding would be beneficial on multiple fronts.

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[2] See http://conf.montreal-protocol.org/meeting/mop/cop11mop29/presentations/English/10ORM_COP_MOP_Jucks_V2.pdf.

Resolving these questions requires observations, including controlled release experiments, to improve model representation of stratocumulus radiative response to aerosols. Specific links between aerosol size and composition and forcing changes should be mapped out, along with the types and properties of clouds that can be brightened. These results will be needed to inform the design of a distribution system, because the production and delivery system required depends on the size and tolerance of the cloud interaction processes as well as the ocean region and season. For example, we need to understand the conditions in which excess droplet numbers could cause cloud dissipation, since such "overshoots" in number concentrations could sufficiently reduce cloud fraction, thickness, and optical depth so that the increase in reflectance is more than offset. Particle size could impact such feedback processes but we do not yet have the observations and models needed to determine the design criteria for a particle production and delivery system.

Uncertain cloud processes. As discussed in Chapter 2, given the complex interaction between microphysics and turbulence in the marine boundary layer, at scales too small to be captured in global-scale models, idealized climate model simulations of MCB interventions do not provide reliable projections of climate impacts. There are two types of processes that need to be considered, and they differ in scale and impact. First is the intended effect—brightening of clouds by increasing the number of droplets. This effect occurs locally and within minutes of when particles reach the cloud layer (an effect that underlies the canonical observations of ship tracks [Twomey, 1974]). The second type of effect is a consequence of changes in the drop distribution (and possibly the buoyancy and turbulence), which alters the precipitation and the extent of the cloud. This effect relies on larger-scale interactions with heat and water transport and determines the evolution of the cloud over hours to days. While the first type of process affects how much a cloud will brighten, the second type can alter the so-called lifetime of the cloud, and so it affects how long the brightening will persist in the atmosphere.

For the first type of process, observations and high-resolution modeling studies need to address the following questions (for the relevant conditions, i.e., regions, seasons, and frequency):

- How does the distribution of updraft velocities in a cloud result in which particles are activated to droplets?
- How does turbulence in the boundary layer drive entrainment of free tropospheric or unsaturated air into a cloud and affect droplet growth and evaporation?
- For what size and density range of particles is boundary layer turbulence sufficient to distribute particles emitted at the surface into the cloud layer?

- Since drop formation is a strongly threshold-dependent process in most warm clouds, are there nonlinearities associated with spatially localized particle sources that may enhance or dampen MCB in ways not predicted by current observations of such isolated perturbations as ship tracks?
- Do multilayered clouds reduce the effectiveness of MCB because of vertical structure and scattering processes not represented by models?
- Is particle absorptivity sufficient to dampen buoyancy in clouds and reduce liquid water path? (This question relates to whether combustion emissions that form ship tracks are qualitatively different from the salt, which would likely be used as CCN for MCB.)
- How is the vertical distribution of droplet sizes within a cloud affected by turbulence variability and strength?

The second type of process is dependent on the first, since the drop distribution and air motion (turbulence) changes are the starting points for drizzle formation. However, the longer time needed for these processes to interact and evolve means that their impacts are more widely distributed to downwind regions, and this requires additional observations and constrained modeling to address the following questions:

- How much do giant CCN and turbulence contribute to droplet spectral broadening (Feingold et al., 2002; Witte et al., 2019)? Do these large particles need to be avoided when attempting MCB?
- Will additional droplet numbers result in enhanced cloud evaporation, causing cloud thinning rather than brightening?
- How does aerosol mediate the diurnal cycle of precipitation? Does this vary depending on either aerosol amount or CCN spectrum (activation curve as a function of supersaturation) associated with different airmass regimes?
- What is the role of aerosol in controlling drizzle fluxes from the cloud layer, and how does the drizzle redistribute moisture and heat in the sub-cloud layer?
- Do models initialized with the measured aerosol properties reproduce the observed ACI evolution along Lagrangian tracks from the coast into the stratocumulus regions offshore (Christensen et al., 2020)?

Because these processes are complex and interacting, existing observational data sets are not sufficient to establish causal relationships. Observations and models need to address these questions jointly in order to assess whether model microphysics and turbulence are realistic (with chemically and optically realistic particles). Large eddy simulation (LES) modeling is an important tool for providing realistic turbulence, but it needs to be constrained by comparison to relevant observation and often lacks particles with realistic size distributions and chemical composition. Therefore, field measurements are needed to provide the range of conditions and constraints that parameterizations must represent for the regions in which the model is applied.

Controlled emission experiments. Because the variability of turbulence in the Marine Boundary Layer (MBL) has few observations to constrain a very complex problem, observations need to target a series of measurements in three specific target regions (northeastern Pacific, southeastern Pacific, and southeastern Atlantic) to obtain the statistics needed to constrain LES and identify statistically robust answers to the research questions posed above. For example, satellite evidence indicates that the northeastern Pacific stratocumulus cloud decks in the subtropical region are most susceptible to changes in their outgoing shortwave radiation due to changes in cloud microphysics (Painemal, 2018). This means that existing efforts have been insufficient to make progress on this problem due to both limited resources and limited ranges of CCN in otherwise similar (or effectively "controlled") conditions. Current shipping routes do not provide the frequency or spatial coverage needed to assess MCB in clean regions with the necessary amount of sampling because when ships are transiting, they tend to follow shipping lanes that provide the highest fuel efficiency, rather than provide coverage of clean regions needed to sufficiently assess MCB.

Measurements of the effects of land-based urban and industrial pollution sources do not provide the independent information needed to assess causal relationships because it is not possible to disentangle the co-variability of meteorology and aerosol perturbation. For example, in many regions, such as the northeastern Pacific coast, polluted air masses also tend to be dry and warm, whereas clean air masses tend to be wetter and colder (Atwood et al., 2019). This means that the driving forces of the clouds (temperature and water) cannot be investigated independently from the size and concentration of pollution particles.

For these reasons, an effective MCB research plan would include controlled emission experiments in the atmosphere. The rationale for this is the overwhelming need for in situ process studies in MCB-relevant conditions. To a large extent, observational research on the Earth system has relied on existing phenomena and the way that their changes over time and space yield correlations. This means that causal and quantitative relationships rely on laboratory analogues and numerical simulations. However, neither laboratories nor models can represent the full complexity of the actual atmosphere, ocean, and land system. By introducing a controlled perturbation into the Earth system, in which the particles and meteorology are not related, it is possible to gain new and more accurate characterizations of that system. The resulting information is qualitatively different from that from existing modes of research and can serve to accelerate our understanding of both potential interventions and future climate change. Moreover, the type and scope of the controlled emission experiments that would be required are very small compared to the nature and emissions of many current human activities for recreation, entertainment, conservation, and commerce purposes, and they are far less than those of ongoing military exercises. Examples of past experiments that used controlled sources include the U.S. Department of Energy (DOE) Free-Air CO_2 Enrichment (FACE), Eastern Pacific Emitted Aerosol Cloud Experiment for paraffin particles (Russell et al., 2013), and Fire Influence on Regional to Global Environments and Air Quality (FIREX-AQ) for biomass burning emissions.[3]

One example of an open question that requires a process study with controlled emissions is aerosol-related cloud feedbacks. Specifically, the second type of lifetime processes can include self-limiting feedbacks of aerosol effects on cloud precipitation (self-limiting because precipitation removes water and then the process stops) that could be uniquely targeted with controlled experiments (Ackerman et al., 2004; Gryspeerdt et al., 2016, 2019b). For example, there is recent evidence that drizzling of stratocumulus clouds can lead to cloud dissipation in some areas, which are evident in observations as pockets of open clouds (POCs; Feingold et al., 2015; Sorooshian et al., 2009; Wang and Feingold, 2009; Xue et al., 2008; Yamaguchi and Feingold, 2015). While POCs are important because they are widespread and they appear to be associated with aerosol removal by precipitation scavenging, disentangling effects from aerosol sources and sinks is nearly impossible without the ability to do repeated controlled experiments in the relevant region and season.

Testing for both brightening and lifetime effects is central to MCB because it means that aerosol effects would not scale with the amount (and spatial coverage) of aerosol, since it could mean that a large number of clouds either are insensitive to particle addition or have counteracting feedbacks such as increased dissipation. This behavior is also at the center of inter-model disagreements about aerosol indirect effects on the radiative balance. The complex interplay of a variety of chemical and physical processes—scavenging rates, precipitation frequency and distribution, entrainment of high or low humidity air and particles, cloud dissipation, cloud air motion spectra and buoyancy changes, and cloud heating from water condensation and particle absorption—means that observed correlations will not imply causation and that model results may suffer from counteracting errors that need to be isolated (Mulmenstadt and Feingold, 2018). In short, it is not known whether radiative forcing is more buffered to the effects of added aerosols than is included in current climate models.

Climate model development. The best tools for integrating our knowledge of atmospheric processes, and for evaluating whether our understanding of those processes

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[3] See DOE/FACE, https://facedata.ornl.gov/; FIREX-AQ, https://blogs.nasa.gov/earthexpeditions/tag/firex-aq/.

is consistent with observations, are global climate models. Climate models are also needed to study the effectiveness of MCB and the possible unintended consequences of MCB for precipitation and other impacts. Thus, a priority is to develop climate models with the skill to simulate MCB implementation and to represent accurately three basic components: (i) cloud occurrence and properties, (ii) aerosol emissions and processes, and (iii) interactions between aerosols and clouds.

(i) **Clouds.** Marine stratocumulus clouds are a persistent feature of the northeastern Pacific, southeastern Pacific, and southeastern Atlantic, with a variety of classic studies characterizing some of the key features of the cloud climatologies in those regions (Lenschow et al., 1988; Painemal and Zuidema, 2011; Painemal et al., 2014, 2015; Stevens et al., 2003; Wood et al., 2011). However, most global models do not represent accurately the horizontal and vertical extents and frequency of these cloud regions (Klein et al., 2013; Su et al., 2013; Xiao et al., 2014), although some decadal trends do appear to be correctly represented (Norris et al., 2016). Likely the shortcomings of climate models in representing clouds reflect the limitations on gridbox size and available variables, which are limited by computing power (Schneider et al., 2017b). Innovations are needed for improved parameterizations that specifically target persistent low stratocumulus in upwelling regions. Several approaches have shown promise, including 2-D simplifications (Jones et al., 2019), statistical representations (Chinita et al., 2018; Kawai and Teixeira, 2012; Wu et al., 2020), and adjustable gridding with embedded LES (Schneider et al., 2017a). Other approaches using observational test beds and combined measurement studies are needed. Testing whether the process-based knowledge that we have obtained from these earlier studies is sufficient when incorporated in global models requires a sufficiently long and accurate measurement record to provide statistical overlap. The detailed characterization of the full annual cycle of clouds and their properties is the first and most basic objective that will fulfill this need for global climate models, some of which can be verified with existing satellite records, but providing accurate measurements of cloud vertical extent and more detailed radiative properties, in addition to characterizing the range and frequency of regional precipitation that occurs, would require in situ measurements. Clouds simulated by models should be evaluated in relevant regions and seasons to assess the following relationships:

- What model development is needed for the simulated variability in cloud fraction, rain and drizzle frequency, and intensity in the marine stratocumulus clouds to represent what satellite and in situ observations show?

- What are the key simulated large-scale meteorological and radiative factors that cause marine stratocumulus clouds to form and persist, and how may the availability of these clouds for MCB change in a world with higher concentrations of GHGs?
- How does the parameterized contribution of turbulence change stratocumulus structure and susceptibility to brightening and precipitation?

(ii) **Aerosols.** In order to predict the response of adding aerosol particles to clouds, models must first correctly represent the size, concentration, and properties of particles that are already present in the atmosphere. Ongoing efforts for air quality and climate change provide initial validation of many of the major features of aerosol concentrations over continents and particularly in urban areas, which have ongoing monitoring in most developed regions. However, there is a lack of in situ monitoring in ocean and remote regions, as these areas are not of concern for human exposure to particulate pollutants. Consequently, it is not surprising that there are substantial uncertainties and sensitivities to natural marine CCN sources (Burrows et al., 2018; McCoy et al., 2015; Wang et al., 2018), meaning that to reduce uncertainties in indirect effects in ocean regions, we must be able to better quantify the marine CCN budget at background and urban-influenced conditions (Lohmann and Feichter, 2005; Twomey, 1977). While models are needed to identify which processes contribute to aerosol uncertainties, quantifying the relevant processes requires substantial observations in order to characterize the variety of aerosol sources (Reddington et al., 2017). Recent work has provided improved seasonal quantification of CCN budgets in the North Atlantic (Croft et al., 2020; Sanchez et al., 2016, 2017b, 2018; Zheng et al., 2018), but this region does not have as much continuous stratocumulus coverage and evidence of persistent ship tracks for MCB since the stratocumulus are more short-lived and synoptically driven. Similar evaluations of measured and modeled aerosol budgets and concentrations that target the northeastern Pacific, southeastern Pacific, and southeastern Atlantic are needed to address the following types of questions:

- What processes and emissions need to be improved to represent the observed seasonal frequency and relative contribution of background and manmade aerosol particles in these regions?
- Are the simplified model representations of photochemical oxidation, cloud processing, and other physical-chemical interactions sufficiently well represented to predict CCN?
- How well do climate models predict aerosol properties relevant to CCN activation (aerosol amount, size distribution, composition, and hygroscopicity) and their associations with different air masses in these regions?

(iii) **Interactions.** If the cloud and aerosol simulations of models are realistic when considered separately, then it makes sense to assess the processes by which they interact. Here the evaluation includes the interaction of two complicated aspects that cannot be explicitly calculated in climate models: the microphysics and the turbulence. We expect that to some extent both of these aspects are included in simulated clouds to begin with and hence can be verified to a large extent by comparison with observations. However, these aspects influence both the radiative changes in clouds that affect temperatures and the feedback processes of the clouds that affect lifetime, and this causes a number of additional issues for introducing MCB-like new perturbations that may include conditions not represented by past observations:

- Which aspects of model errors matter most to the cloud properties that are most important for MCB?
- What is the role of in-cloud microphysics and entrainment and detrainment in changing the drop distribution? Do these processes affect the cloud lifetime?
- Can we separate the roles of aerosol, meteorology, and radiation in determining changes in cloud properties (including cloud droplet number, liquid water path, precipitation rate, boundary layer depth, decoupling, and diurnal cycle) (Gryspeerdt et al., 2016, 2017, 2019b)?
- To what extent does adding aerosol change the formation and cycling of precipitation, and is that effect accurately represented in models? Does the aerosol affect drizzle fluxes from the cloud layer, and are these processes included accurately in models? Can models represent the redistribution of drizzle and the resulting impacts on heat fluxes in the sub-cloud layer?
- Do models initialized with the measured aerosol properties reproduce the observed aerosol cloud interactions along Lagrangian tracks (Christensen et al., 2020)?
- How much do giant CCN and turbulence contribute to droplet spectral broadening, and is this effect suppressed by MCB (Feingold et al., 2002; Witte et al., 2019)?

All three of these areas of model development require both satellite and in situ measurements to ensure first the accuracy and completeness of particle and drop distributions and air motion spectra provided by in situ observations and then the extension of those properties by tying to improve satellite capabilities. Multiseason and multiyear surface observations in ocean regions are required to provide the range of background conditions in regions where MCB may be implemented.

Then controlled-release experiments can be used to test model behavior and assess verisimilitude.

Characterizing impacts. If climate models can be developed that represent MCB accurately, then they provide important tools to assess the impacts of MCB on regional climate and ecosystems. Climate models could then also be used to design experiments to test whether those impacts are well represented. Addressing questions related to MCB impacts requires a series of studies that can be organized under the following research questions:

- How does the (resuspension and) deposition of salt particles impact downwind ecosystems and communities? Will deposition affect soils, rainwater, and vegetation?
- Will the geographic localization of radiative cooling have unexpected, unintended consequences for rainfall, temperature, or other climate variables that could harm vulnerable communities?
- Will downwind communities have costs associated with additional salt deposition and removal?
- Will local or regional cooling, or teleconnections, affect crops or other livelihoods?

The open questions that require better ongoing and targeted observational studies are those of cloud distributions and types, associated precipitation and other deposition, and the susceptibility of specific ecosystems. For this, networks of observations could provide the long time series of observations required to constrain models and evaluate their performance.

Some critical steps forward to advance this research cluster (for MCB) include the following:

- Prioritize coordinated observations and modeling that quantify and constrain the effectiveness of brightening. These efforts will likely be most efficient and productive if they include intentional atmospheric perturbation studies (controlled emission experiments). But these can be done on small scales that do not detectably alter climate variables (e.g., temperature, precipitation, and global mean forcing) (see Section 6.3 on considerations for outdoor experimentation).
- Target geographic regions that are most likely to be effective for MCB (e.g., persistent stratocumulus cloud decks covering large fractions of the northeastern Pacific, southeastern Pacific, and southeastern Atlantic rather than regions that lack persistent stratocumulus coverage, such as the tropical western

Pacific and North Atlantic). Research should include efforts to track and predict expected changes in cloud coverage, extent, and susceptibility.

- Pursue, for the near term, modeling studies at the scale of LES, parcel and column models, and nested regional models—all of which can help inform the improvement of climate model parameterizations. Pursuit of global-scale MCB modeling will be more useful after climate models are further developed on several key fronts: to better represent Earth's current cloud cover, to better quantify the uncertainties and feedbacks associated with perturbing cloud processes, and to provide a more accurate estimate of how changes in aerosol will alter climate. Tie modeling at all scales to observations, with the evaluation of new parameterizations for climate models based on satellite and in situ measurements.
- **Observational Needs.** These research needs require improved capabilities and availability and support of observational facilities including aircraft, satellite, ship, and ground-based. Such improvements would be of value for both SG and broader climate change research, as progress in both suffers from a need to better understand marine boundary layer cloud processes and feedbacks. Existing ground-based observational networks (which focus largely on monitoring gas-phase atmospheric composition) with substantial enhancements in instrumentation and geographic coverage could serve to verify the climate-relevant aerosol and cloud properties produced by models. Lidar technologies (based on ground, satellite, and aircraft platforms) could likely be used to allow tracking of aerosol plumes and cloud structure, but the absence of quantitative calibrations will mean that they are only useful when validated by in situ observations. To be more useful for SG research, existing observational resources should be expanded to better monitor in situ and remote properties of cloud and aerosol number distributions, their spatial and temporal evolution, and multiscale properties, including the following steps:
    - Research aircraft should be equipped with instrumentation for comprehensive boundary layer measurements of aerosol and droplet size distributions and composition, turbulence, and radiative fluxes.
    - Satellites should be designed to measure cloud and turbulent properties at minimum 100 m resolution in the lowest 1 km of the atmosphere to allow in situ results to be extended to broader regions.
    - Research vessels should be modified to accommodate and supported to collect continuous in situ and remote aerosol and cloud properties so as to facilitate multi-month open-ocean studies of aerosol and cloud properties.
    - Ground networks should be enhanced and expanded to provide coastal measurements of stratocumulus properties and extent in the northeastern

> Pacific, southeastern Pacific, and southeastern Atlantic, incorporating lidar and balloon measurements of the vertical extent of cloud altitude, water, and frequency as well as aerosol, for comparison to climate models.

Cirrus Cloud Thinning

CCT is currently the most uncertain of the three methods considered here. Model predictions of how this form of intervention could affect climate outcomes vary widely, with some indicating minimal effects and some showing the ability to produce negative radiative forcing (see Chapter 2). Most studies agree that the uncertainties are driven by a lack of knowledge of the nucleating conditions that are present for the existing global distribution of cirrus clouds. The different and yet all very plausible assumptions made about these conditions produce the wide range of climate outcomes.

Until some of this fundamental uncertainty is resolved by improving our observations of cirrus clouds (addressing the types of questions listed below), we see relatively little value in research investments aimed at global simulations of how the climate system would respond to this form of intervention. It would similarly be premature to explore technical feasibility and costs of this approach (which are likely to be less of a challenge than for SAI owing to the lower altitudes and smaller payloads required). Nonetheless, because CCT would act on outgoing longwave radiation rather than incoming shortwave radiation, it could have significant advantages relative to either SAI or MCB in terms of avoiding potential adverse effects on the hydrological cycle, depending in part on the deployment scenario. Thus, despite its relatively higher uncertainty (perhaps attributable to the lack of much research to date), CCT should still be considered an important element of a complete research agenda.

Some critical steps forward to advance this research cluster (for CCT) include the following:

- Expand observations to better constrain how often cirrus forms and the current distribution of homogeneous versus heterogeneous cirrus formation. How much of the natural cirrus forms on ice nucleating particles? This will require a combination of in situ aircraft observations (e.g., ice crystal size and number concentration) and satellite observations (overall coverage).
- Compare and constrain climate model parameterizations to ensure that models can reproduce the current range of observations of homogeneous and heterogeneous nucleation.
- Provide additional constraints for model parameterizations of ice nucleation

schemes, perhaps through a combination of cloud-chamber experiments to test different ice nucleating particles and validation with in situ observations.

- After improvements have been made in the areas above, conduct research to assess the feasibility of realistic implementation strategies. (Is it possible to identify regions or seasons where cirrus is consistently formed through homogeneous freezing? Is it possible to develop seeding strategies that avoid introducing new cirrus in places where there is supersaturation but no existing cirrus?)

[6] Climate Response: *Assessing how different SG approaches would affect key climate outcomes.*

One of the central goals of SG research is to predict how the climate would respond to a hypothetical deployment. The current state of scientific understanding about possible climate responses to different SG approaches was assessed in Chapter 2. In general, studies to date indicate that SG interventions would decrease globally averaged temperature and precipitation, but regional effects are less clear, and such interventions may alter the ocean and atmospheric circulation in unique ways.

Climate models are the critical tool to assess large-scale climate responses associated with SG intervention strategies. Many early SG climate simulations simply "turned down the sun" as a proxy for SG (Kravitz et al., 2011), but the climate response to any specific approach (SAI, MCB, CCT) will differ from such idealized simulations and will depend on the method, spatial distribution, and magnitude of the intervention strategy employed. There will also always be uncertainty in the predicted climate response; thus, research needs to not only estimate the "best guess" response but also explicitly attempt to characterize the degree of uncertainty. Uncertainties in the climate response to SG result both from uncertainties in representing SG-specific atmospheric processes (described in the previous section) and from some of the same shortcomings that limit our understanding of the response to other climate forcings, such as the regional hydrological response to increasing concentrations of GHGs. There is also uncertainty in projecting the climate response due to climate change alone without SG, and for some processes the overall uncertainty in future climate projections might be smaller with SG than without it.

Work is required to further improve the ability of climate models to assess the climate response to SG, especially in terms of robustly representing key climate processes. As discussed in the previous section, it is well understood that adding aerosols to the lower stratosphere will produce surface cooling, but uncertainties in the climate response to SAI arises from how well different models capture the resulting changes in stratospheric water vapor concentrations, changes in the stratospheric circulation with subsequent links to the tropospheric circulation, or details of the radiative properties and chemical effects of the aerosols, among other factors. The ability of models to predict the climate response to MCB is even more limited fundamentally because how aerosols interact with clouds locally as well as regionally is a major uncertainty. Presently, for instance, it is unclear whether global climate models simulate low clouds that are too susceptible to aerosols and thus overestimate their potential cooling effect, or whether the models are correctly estimating the aerosol cooling efficacy of low clouds but for the wrong reasons. Thus, assessments to date of the effectiveness of MCB in climate models are unable to determine the efficacy or impacts of this type of SG.

Global climate models include parametric representations, called "parameterizations," that are designed to include the transports of energy, momentum, and other quantities by the unresolved or "subgrid scale" motions of the air and water, as well as by radiation and precipitation. Many of the uncertainties described in the previous section that are important to address in order to accurately predict the climate response to SG relate to subgrid-scale climate processes. Despite decades of research on this front, current parameterizations are still problematic.

Today, however, continuing increases in computer power are making it possible to replace some problematic parameterizations with explicit, smaller-scale processes. For instance, "cloud-permitting" or "storm-resolving" global models have much more realistic simulations of clouds and precipitation systems (Stevens et al., 2020), but their grid spacing is still not fine enough to allow detailed simulations of individual large clouds or of the thin boundary layer clouds targeted by MCB. In particular, the balance among radiative heating, turbulent mixing, and cloud microphysics represents a challenge even for the application of very fine-scale simulations, and there are still known deficiencies in their representation. Nonetheless, numerous studies have shown that global storm-resolving models are able to realistically simulate important atmospheric processes that lower-resolution models miss (e.g., Stevens and Bony, 2013). Such high-resolution global models, however, present an enormous computational challenge and have not yet been used to study SG.

For SAI, validation of climate responses with observations after volcanic eruptions provides some basis for confidence in using global climate models to assess the response to deliberate injection but with uncertainties, as described earlier. Evaluating effects of subgrid-scale mixing (e.g., at the scale of the "plume" released behind an aircraft) is an important next step for SAI research, and this could also be aided by the development and application of higher resolution models. Modeling of stratospheric chemistry and transport to date has been dominated by coarse-grid climate models. Yet observations of rocket emissions indicate that plumes can remain as coherent structures for weeks or longer in the stratosphere. Other studies have shown that chemistry in aircraft plumes is misrepresented at the grid scale, which can result in significant errors in the estimated impacts of aviation on atmospheric composition. Considering these findings together, work is needed to ensure that plume-scale effects are correctly represented in SAI studies as described elsewhere in this chapter.

Overall, climate models are an extremely useful tool to examine the climate response to SG; however, they are imperfect. Two relatively new approaches to target research questions specific to clouds and aerosols and their representation in models are: (i) constraining to specific sets of observations that provide a more explicit way to ensure factors such as aerosol distributions are realistically represented in models (e.g., Tunved et al., 2006, 2013); and (ii) separating the processes to which specific effects can be attributed and allowing model improvements to focus on those processes that are most deficient (Ghan, 2013).

Some critical steps forward to advance this research cluster include the following:

- Use climate models to establish better estimates of the uncertainties in regional climate responses to SG interventions and assess how much those uncertainties can be reduced through research.
    - Model-based research should incorporate observational constraints to provide a path toward more realistic simulations.
    - Model processes should be investigated individually and tracked so that specific deficiencies and inter-model differences can be identified and improved.
- Develop more realistic climate model scenarios that explore the range of possible SG strategies and explore how SG forcing differs from other anthropogenic climate forcings (as well as exploring their individual and combined climate responses). Modeling approaches should consider the following:
    - The utility of large ensembles in order to quantitatively document the irreducible uncertainty in climate response arising from unforced natural (or internal) variability.
    - Framing projected responses in the context of the full probability distribution of possible outcomes (as opposed to only the best-estimate response) and in the context of different SG implementation scenarios and strategies.
- Enable the representation of MCB in global climate models, in particular through the following:
    - Simulations with observationally constrained or process-tracked models at

global and smaller scales to provide process-specific information needed to interpret observations and predict future scenarios.
  - Improved parameterizations to better represent low cloud distributions globally, seasonally, latitudinally, and vertically, with cloud properties that reflect observations.
  - Incorporation of realistic causal links between cloud drop number concentrations and aerosol particle size distributions, which show the sensitivity and limitations of number enhancement.
- Improve representation of SAI in global climate models.
  - Explore whether global aerosol optical depth (AOD) distribution is significantly affected by plume-scale effects for a single given scenario; by subgrid-scale changes in the injection strategy (e.g., flight paths).
  - Examine how the accuracy of climate model simulations of SAI is limited by grid resolution. (e.g., Do we need to parameterize our plume models, rather than just inject uniformly in a gridbox? Are nested grids needed to represent plume processes? What spatial resolution is needed to faithfully represent the radiative forcing and impact outcomes?)
- Evaluate the trade-offs in computational resources and simulation accuracy between grid resolution and aerosol representation. Enable possible future representation of CCT in global climate models through model development efforts.
  - Models need to correctly capture the distribution of homogeneous versus heterogeneous freezing conditions.
  - Parameterizations of cirrus-aerosol interactions and of UT vertical velocity may need improvement.
- Address observational needs for improving and evaluating climate models.
  - Long-term observational networks generally provide the most significant constraints on climate model performance because long time series of data are often required to constrain models and evaluate their performance. While ground-based observational networks cannot address all of the needs referred to in the "Atmospheric Processes" section, they can provide validation of aerosol loadings and distribution of clouds through measurements that include (i) a long-term stratospheric aerosol and trace gas measurement program that maintains or enhances current space- and ground-based measurements of temperature, ozone, aerosol, and trace gas stratospheric profiles; and (ii) a long-term coastal aerosol-cloud measurement program to provide ground-based measurements of cloud, aerosol, precipitation, and radiation properties that target stratocumulus clouds in MCB-susceptible regions..

- ○ The timely transfer of information from process and observation studies into climate and Earth system models is critical. The "Climate Process Team" (CPT) concept[4] could help address the modeling needs specific to SG strategies, as key processes (e.g., stratospheric transport, cloud microphysics, aerosol indirect effects, subgrid scale mixing) could be targeted with this approach.

[7] Other Impacts: *Assessing the potential environmental and societal impacts of SG intervention strategies.*

SG interventions are designed to alter global or regional climate, which can affect numerous environmental factors such as atmospheric and sea water temperature, precipitation patterns and intensity, extreme events (e.g., heat waves, droughts, and hurricanes), sunlight intensity and quality, ocean acidification, and nutrient mixing. Changes in any of these factors can in turn affect the magnitude and distribution of risks posed to biodiversity, ecosystem services, and human well-being. For example, changing temperatures and precipitation patterns will affect the distribution and productivity of terrestrial vegetation, ocean primary production, and crop production, as well as the abundance and distribution of organisms and the health of critical biological habitats such as coral reefs and tropical forests; changing quality and quantity of solar radiation can affect the efficiency of plant growth and solar energy production; and exposure to increased UV radiation from loss of stratospheric ozone can increase human health and ecosystem risks. And as discussed in Section 2.2c, the underlying challenge is to understand whether SG interventions would alleviate, or would make worse, the impacts on all of these systems stemming from climate change alone.

The uncertainties in climatic responses to SG intervention (discussed in the previous research cluster) limit our understanding of the cascading impacts on associated ecosystems and their goods and services. Existing global climate and Earth system models can estimate the coarse-scale distribution and magnitude of some direct climate effects, and these estimates have been applied to examine the potential effects of SG interventions on terrestrial vegetation, but there are substantial gaps that limit

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[4] See https://usclivar.org/climate-process-teams. A CPT can be defined as a funded multi-institutional project that assembles observation-oriented experimentalists, process modelers, process diagnosticians, theoreticians, and climate model developers from two or more modeling centers into a single project that focuses on a specific process (or set of processes) to assess model sensitivities to process uncertainties; establish observation and model metrics; and develop, test, and implement parameterization improvements. CPTs provide effective mechanisms to facilitate close collaboration and enduring links between process experts and model developers, thereby accelerating scientific understanding of key physical processes and leading to improvements in their representation in climate models.

our ability to use such models to estimate impacts in many other areas—including, for instance, the cryosphere and ocean biogeochemistry. The coarse resolution of projected climatic responses to SG interventions renders it difficult to assess impacts on natural and human systems at the finer spatial scales that are most relevant to decision making.

Moreover, SG analyses to date have largely focused on a limited range of climatic variables—temperature and precipitation. While some impacts depend in a fairly straightforward manner on these variables (e.g., human mortality can be directly affected by extreme heat conditions), many impacts of concern depend on concurrent changes across numerous climate variables (e.g., agricultural productivity can be affected by temperature, precipitation, humidity, and solar radiation levels, as well as atmospheric CO_2 concentration, which in turn will depend upon how the emissions scenario is being applied in a given study). Adding to these challenges is the fact that many SG impacts will depend upon the particular type of intervention, on the manner of its deployment, and on how much cooling is exerted, and the fact that impacts can be affected by individual and societal responses to the changing environmental conditions and by the widely varying scenarios in which SG development and deployment could unfold (see Research Cluster 1).

Due to these current limitations, there has thus far been very limited research on the impacts of SG interventions on environmental and human health. Much of the existing work is based on extrapolation from known responses of ecosystems or health risks to climate-related drivers, using simplified scenarios of SG deployment. The research proposed under this cluster aims in large part to simply advance approaches for *how* to effectively investigate these sorts of impacts. The needed research approaches range from detailed mechanistic studies of impacts on specific ecosystems or sectors to broader integrated studies of how different types of impacts and risks may be distributed across populations and geographic regions.

Some critical steps forward for this research cluster include the following:

- Explore the effects of SG interventions on a broader range of climatic and biogeochemical variables that are relevant to social-ecological systems, including studies carried out at high enough resolution to inform understanding at regional and local scales and including a fuller range of SG deployment scenarios. Advance integrated system modeling and assessment approaches that improve our understanding of the possible distribution of benefits and risks from SG impacts.
- Include a broader range of social-ecological systems in SG-related studies, for instance, encompassing coastal, ocean, and cryosphere ecosystems and

human-managed ecosystems such as agricultural and fisheries. Include better linking among radiation, land and ocean components of models, and tracking changes in direct and diffuse radiation in order to assess effects on photosynthesis in crops, vegetation, and phytoplankton. Such research may include studies of historical analogues and mesocosm experiments[5] along with modeling studies.

- Explore the economic impacts of SG on production processes and key inputs to those processes (e.g., agricultural irrigation, labor participation, capital flows, and land quality), trade and commerce (e.g., international trade and global supply chains), and demand for goods and services, as well as impacts on aggregate economic indicators (e.g., gross domestic product and income distribution).
- Advance downscaling of climate and ocean projections under SG scenarios and model representation of cloud and precipitation processes (which drives regional representation of temperature and precipitation changes that affect wildlife and human habitats). Extend regional observations of climate change-related temperature and precipitation changes (including related factors such as extreme weather and changes in direct and diffuse radiation) to provide the long-term trend data needed for quantifying population responses to these changes (and other epidemiology-like research approaches).
- Advance networks of co-located observations of multiple relevant environmental variables (e.g., sites that collect observations of temperature, precipitation, humidity, and chemical- and radiative-atmospheric variables) to facilitate population-specific impact studies—given that populations may be affected by combinations of any of these variables.
- Study impacts of specific proposed SG aerosol chemical components on ecosystems and human health, including laboratory studies of population-specific dose-response effects and studies at the levels that might actually be required for deployment. Conduct small trials that examine how different types of candidate SG particle composition affects tissue samples and plant analogues (or other related epidemiological- and ecosystem-impact studies). Any outdoor deliberate release experiments should at a minimum include monitoring of potential exposure to provide evidence of in situ effects.

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[5] This refers to bounded, partially enclosed outdoor experiments that are used in environmental science to bridge the gap between laboratory studies and the real world.

[8] Monitoring and Attribution: *Designing an observational system (and understanding its limitations) for detecting, monitoring, and attribution of SG deployment and impacts.*

Research is needed to understand the requirements of a monitoring system for analysis of SG technologies deployed at climate-modifying scales. The goals for such a system would be (i) to diagnose unexpected deployment (in the absence of international consultation and cooperation); (ii) to provide observations needed to tailor, adjust, or cancel SG interventions following deployment; and (iii) to understand the broader global effects of deployment.

One key question to be considered in the design of an observational system is: If deployment were pursued unilaterally, how do we know this deployment is happening? Any deployment at scales intended to alter the climate would likely be detectable within a short timescale (weeks to months), given the size of the effort needed to affect such a change. For example, for SAI, the large increases in AOD would be obvious from numerous existing sensors. A robust monitoring system would also improve understanding of the aim and approaches of the actor(s) involved.

Some components of an SG monitoring system would share attributes of the observational approaches needed for SG research activities. This includes, for instance, the suite of in situ and remote sensing capabilities proposed herein for study of SAI (e.g., rapid response to volcanic emissions) and MCB (e.g., in situ sampling of cloud aerosol interactions and their radiative forcing impacts).

The 2017 Earth Science Decadal Survey (NASEM, 2018a) recommended a number of space-based observation capabilities in support of the report's proposed program. Of the proposed observing system priorities, the "Designated" Aerosols and Clouds, Convection, and Precipitation missions would be highly useful for MCB research, and of the "Earth System Explorer" class, the Ozone and Trace Gases mission would be most useful for SAI research. These missions would not advance in time to actually contribute to the initial years of the research program recommended herein, but when these new observations do become available (likely in the 2025–2035 period) they will eventually provide helpful data in support of SG research.

A broader SG monitoring system centered on space-based remote sensing observations and associated modeling needs to be developed prior to considering deployment. There are typically long timescales involved in the development of needed observational instrumentation; thus, research is needed now to define the requirements for such a system and to estimate the efficacy, cost, and development schedule.

To enable such developments, there is a need for research to evaluate the potential for (and limitations of) our ability to attribute changes in the environment to SG deployment. For instance, the ability to diagnose radiative forcing changes from an SAI or MCB intervention using existing spaceborne radiometer instrumentation could be relatively straightforward for large-scale interventions but much more challenging at smaller scales, where induced perturbations may be difficult to detect amidst natural variability. For any type of intervention, diagnosing and attributing climate impacts is likely to be very challenging, because many of these impacts will evolve over long timescales and will be difficult to separate from natural variability.

Some critical steps forward to advance this research cluster include the following:

- Determine what variables would provide the earliest and highest signal-to-noise signals that could assist in attribution.
- Explore approaches to improve the signal-to-noise in such observables to reduce the time needed for attribution (such attribution studies should explicitly consider the importance of natural climate and geophysical variability).
- Advance critical observational systems and infrastructure for long-term monitoring of stratospheric and lower atmospheric composition (as described in the previous sections "Atmospheric Processes" and "Climate Response") and incorporate the following:
    - Aircraft, balloon, and ship facilities for calibration/validation of satellites and to provide a broader suite of observations needed to diagnose impacts.
    - Capability to monitor the diffuse and direct solar radiation at Earth's surface to aid the study of biological impacts.

[9] Technology Development and Assessment: *Addressing the science and engineering issues regarding SG implementation related to hardware, materials, and infrastructure underlying SG research.*

As discussed in Chapter 4, the proposed research program does not include the goal of supporting technology development that is specifically oriented toward building the capacity for SG deployment. Yet the development of some specific technology capabilities is needed to advance fundamental understanding of particular scientific questions proposed in this research agenda (in particular the "Atmospheric Processes" cluster) or to better understand the technical feasibility challenges of particular approaches. This line between technology capability for research and technology capacity for deployment, for both SAI and MCB,[6] is discussed below.

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[6] CCT research remains sufficiently immature as a concept that the capabilities needed have not yet been documented, but they are unlikely to be as challenging as either MCB or SAI deployment.

For **SAI,** relevant questions include whether and how one could deliver a useful payload to a sufficient altitude, and what is a reasonable estimate of the economic and other costs for doing so. As described in Chapter 2, studies indicate that aircraft are likely the cheapest delivery option, and there is strong evidence that delivery at ~20 km can be achieved with purpose-designed aircraft (Bingaman et al., 2020). An altitude of 20 km would be sufficient to achieve cooling, but deployment at higher altitudes offers the benefit of significant reductions in the amount of material required and thus reductions in some associated impacts. While altitudes as high as 25 km have been assumed in some recent climate model simulations (Kravitz et al., 2019b; Tilmes et al., 2018a), there has been essentially no exploration of how material might be lofted this high. Understanding how engine and airfoil design choices alter chemistry and physics in the nearfield plume would also be important.

There can also be engineering effort required for aerosol delivery itself. It is not expected that there are any significant challenges to injecting a gas such as SO_2 directly into the stratosphere; however, direct injection of sulfate or alternative aerosol particles will likely require additional capabilities (e.g., to disperse solid aerosols). These injection techniques have not been well researched in part because understanding the detailed technology needs will depend on the outcome of microphysical research (discussed in the earlier "Atmospheric Processes" section).

There are no obvious additional engineering challenges associated with the remainder of the SAI delivery system. This approach would require basic infrastructure, such as runways, but no novel challenges that motivate near-term research; although once likely aerosol precursors emerge, additional study may be warranted on issues such as large-scale extraction and processing efficiencies for these materials. From a "life-cycle impacts" perspective, it is worth noting that construction of new aircraft fleets will require energy and other resources and that flying fossil fuel-based aircraft will emit CO_2 and NO_x.

For **MCB,** the primary question is the capability to produce salt particles of an appropriate size distribution that can be lofted into, and serve as nuclei for, boundary layer clouds. MCB deployment would also require the development of appropriate ships (or other delivery approaches) with capacity to produce and distribute aerosol. The aerosol composition most likely to be employed is salt (NaCl), available either from seawater or dissolved from a bulk supply. If the dispersal method used requires extracting salt from seawater, then the ship must have facilities for filtering and processing large volumes of water for this extraction process. Relevant technology is already in use at desalination facilities, but the scale-up and at-sea implementation will require some development. To date, there has been some engineering development of the nozzles that would be required to produce salt spray with appropriate size distribution—this has been tested in a laboratory setting and, recently, outdoors.[7]

At this stage, we do not recommend for two reasons any large-scale research on detailed designs or prototypes of the engineering hardware that would be required for deploying either SAI or MCB. First, developing detailed designs for deployment now would justifiably raise public concern that the research program was going beyond its stated purpose to solely inform future decisions about deployment. Second, detailed designs are premature, given that many technical requirements will depend on the outcomes of research.

Nonetheless, there are several reasons why a research program should include small investments in understanding the engineering of deployment capability:

- Such efforts could provide insights needed to assess whether or not particular intervention strategies are technologically and/or economically feasible. If it is found that deployment of particular strategies is infeasible, then there is no reason to conduct any further research. (In other words, sufficient effort is needed to know whether proposed capabilities are possible but not to go further toward developing deployment capacity.) Initial studies will also better identify the "lead time" for technology development (i.e., how long it would take to develop the necessary hardware).
- It is also essential to understand the engineering challenges sufficiently well to influence the range of options considered in more basic scientific research. For instance, for SAI, if the projected costs make delivery to the stratosphere at 25 km extremely unlikely, then climate research should prioritize understanding the implications of injection at lower altitude. Similarly, if dispersing solid aerosols were found to be far more challenging than expected, that might suggest deprioritizing further research on this front.
- Some development of specific capabilities may be necessary simply to enable scientific experiments. For instance, for MCB studies, there will be a need for spray nozzles that can produce a particular range of aerosol size distributions. For SAI, even small-scale tests of solid aerosols will require some dispersal capability. We do not foresee any near-term need for larger-scale SAI experiments that would require delivering a payload large enough to warrant developing new capacity (i.e., it is likely experiments could be conducted using existing platforms for lofting material to the stratosphere). To avoid concerns over research representing a "slippery slope" toward deployment, simulta-

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[7] See https://www.scu.edu.au/engage/news/latest-news/2020/scientists-trial-world-first-cloud-brightening-technique-to-protect-corals.php.

neously developing the capacity to deploy as part of conducting scientific experiments is not recommended.

- In principle, a cursory understanding of deployment technology might inform both scenario development and governance through better understanding of what actors would be capable of deploying and in what time frame. For example, in addition to adequate financial resources, is there a barrier to SAI deployment through access to specialized aerospace capability, or is the capacity sufficiently generic to be accessible to anyone with adequate resources? An example of research in this area is the question of what radiative forcing could be achieved through widely distributed individual balloon launches.

Some critical steps forward to advance this research cluster include the following:

- Conduct design and costs estimates for aircraft to deliver payload at altitudes up to 25 km (SAI).
- Research dispersal requirements for solid aerosols to better assess the viability of these options (SAI).
- Continue to advance nozzle design by improving understanding of the optimal properties of the particle size distribution needed for efficient nucleation. In the near term, focus on small-scale prototype design, testing, and control for the range of size and composition of particles that would be needed for laboratory- and outdoor-based research (MCB).
- Improve understanding of the boundary layer dynamics and the conditions under which particle emissions may require added heat to overcome limitations in lofting of particles and mixing to cloud level (MCB).

Efforts to advance these technical capabilities to conduct SAI experiments, and similarly the efforts to advance MCB dispersion nozzle design, would be focused on facilitating the "atmospheric processes" research discussed earlier in this chapter not providing pathways toward deployment. By focusing the technology-related work on these critical research questions, one is likely to reduce the potential for mission creep toward developing deployment capability.

Social Dimensions

[10] Public Perceptions and Engagement: *Understanding public perceptions of SG and advancing effective societal engagement strategies and incorporation of resulting insights into a broader SG research program.*

The importance of understanding public perceptions of and responses to SG activities, and developing effective means of public engagement to inform decision making over SG research and research governance, has been discussed earlier in this report and highlighted in numerous previous publications:

- The U.K. Royal Society Report (Shepherd, 2009) noted, "The acceptability of geoengineering will be determined as much by social, legal, and political issues as by scientific and technical factors" and recommended that "geoengineering research… should not proceed in the absence of a wider dialogue between scientists, policy makers, the public and civil society groups."
- Corner et al. (2012) note, "Questions about the morality of intentional manipulation of the climate, the sociopolitical implications of nation-states embarking on programs of geoengineering, and the requirement for responsible innovation and governance are not issues that scientists can easily address." Such decisions involve both scientific knowledge and social values and can benefit from "collaborative, broadly based, integrated, and iterative analytic-deliberative processes" (NRC, 2008).
- Flegal et al. (2019) note, "Public engagement is widely regarded as important for geoengineering governance, largely for normative and instrumental reasons. The substantive rationale—that public engagement can improve the content of geoengineering research itself—is underappreciated." (According to the normative rationale, broad publics should have opportunities for input on SG research, since these technologies have global reach and may affect people around the world; the instrumental rationale holds that public engagement with SG research may reduce conflict and controversy.)
- The NRC (2015) assessment called for "open conversations about the governance of such research" and recommended to "encourage civil society in the process of deciding the appropriateness of any research efforts undertaken."

Furthermore, research by Burns and Flegal (2015) finds that to avoid "hollow" participatory exercises lacking legitimacy or meaningful impact, there needs to be a direct connection between the outcomes of deliberative processes and relevant decision-making bodies (see also Bickerstaff et al., 2010). They also highlight the insufficiency of public consultations focusing only on nongovernmental organizations and parties with a political or vested interest in particular outcomes, as this approach is not representative of society as a whole and typically fails to represent interests of the Global South. Instead, they suggest the need for nonpartisan, large-scale public deliberative processes that are not run by parties with vested interests in particular outcomes and that are sustained and iterated over time.

There is a small but growing base of research on public perception of SG activities (much of it addressing the types of questions listed below), but much more needs to be learned. Some key observations from the earlier review of existing research on this subject (Chapter 2) include the fact that general awareness of SG in the lay public is low, and the framing of the subject can greatly affect public acceptance and perception. Studies find conditional support for SG research (depending on factors such as the participants' views on climate change as a problem and the ways that the research is conducted) but much lower support (or outright opposition) to the notion of deployment. This research is "incomplete" in that little work has been done to assess perception of SG among Global South publics, decision makers, or those most vulnerable globally.

Some critical questions to address in this research cluster include the following:

- What constitutes effective practices for "meaningful public engagement" in SG research and research governance?
- What does public engagement lead to in practice for SG research? Does evidence support outcomes in the normative, instrumental, and substantive arenas when public engagement is undertaken in an SG program?
- What levels of public engagement are best suited for different components of the SG research enterprise?
- Who are the relevant publics, and how should engagement take place?
- How do we close the gaps between the critiques and prescriptions raised by public perception researchers and use that knowledge to create improved public engagement processes that support better outcomes for research and society?
- How is perception and framing of SG issues affected by geopolitical and economic contexts and the perception of other climate policies?
- How do populations in the Global South, extremely vulnerable populations, and other less-studied groups perceive SG research and deployment?
- How do cultural worldviews and differing attitudes toward risk affect perceptions of SG issues?
- How do science policy makers, political leaders, and other decision makers view the trade-offs and decision contexts involved in SG research or deployment (recognizing that much of the public perception research thus far has been done with lay publics)?
- How might SG research and implementation interact with other aspects of climate research and policy (e.g., is it possible to monitor for moral hazard effects or to structure SG activities in a way that reduces such effects)?

- How can public engagement be effectively incorporated into the development and planning of SG activities to increase legitimacy, build trust, reduce conflict, and provide accountability?
- How can public engagement facilitate constructive deliberation about justice, ethics, and equity concerns related to SG research and governance, and how can the results of this deliberation be incorporated into ongoing SG research and research governance?
- How can SG research be responsive to various publics, stakeholders, and policy makers' values, interests, and concerns?

Research is also needed to better understand factors such as the perceptions of those who are most vulnerable to climate change, and the information needs and perceptions of decision makers involved in SG research and deployment (e.g., government funding agencies and other institutions might fund research; those who could play a role in eventual deployment decisions).

[11] Political and Economic Dynamics: *Exploring the implications of SG for national and international relations and related incentive structures.*

Research on the political and economic dynamics surrounding SG research, development, and implementation has evolved (in tandem with natural sciences SG research) through important contributions of political scientists, policy analysts, scholars of global governance, and economists. Yet there remain numerous gaps in our understanding of how SG affects and is affected by political and economic processes and outcomes. This research needs to advance on numerous fronts. For example, IAMs, an important tool for SG research discussed earlier in this chapter (see "Integrated Decision Analysis" cluster), will need substantial input from political science and economics—both at the macro level (e.g., regarding scenario design) and the micro level (e.g., regarding strategic dynamics to be represented in these models).

Research to date has focused largely on idealized strategies for SG governance, but it is also important to examine how dynamics are likely to play out in real-world settings and how to both design practically implementable rules and regulations and incentivize or "nudge" desired practices, standards, and behaviors. This may include studies of "mini-lateral" or "pluri-lateral" clubs of countries engaged in mutual work on SG (see Recommendation 5.1s) short of a full global multilateral agreement, in which countries can agree to common research and research governance exercises, which can then be socialized more broadly. It may include issue-linking, in which mitigation and SG are leveraged to generate an incentive-compatible governance structure.

To date, some research has focused on international relations and interactions, but very little research has considered how local politics and election cycles may affect the creation of SG research programs, deployment trajectories, and their sustainability over the long term. At the international level, there are political studies focused on high-level game theoretical frameworks, but more consideration needs to be given to the real politics and inter-party dynamics of climate change negotiation processes. Any international agreements or other international approaches to governance will require approval and support at the national level; thus, a domestic consensus on decisions concerning research, development, and potential deployment is also required, pointing to the need for research on the critical constraints of domestic policies and politics.

As discussed in Chapter 5, a common dynamic in the creation of international agreements is that first a cluster of leading countries develop national regulations, and then they initiate a process to form an international agreement that approximately mirrors and hopefully improves and extends these national regulations (Morrow and Light, 2019). More work is needed, however, to understand how these dynamics may apply to SG and to understand the incentives required for moving from the current environment of unregulated, largely privately funded research projects to the sort of coordinated national program that is described in the preceding chapter.

The creation of such a program will likely motivate further assessment of what existing domestic regulations and laws could be applied to governance of SG or what new governance mechanisms could be created specifically for this area of research. A critical mass of countries engaging in such exercises would, in turn, increase the likelihood of a concerted attempt at creating global research platforms and global systems of (soft or hard) governance mechanisms.

In addition, as discussed in other parts of this report, concerns have been raised that the interaction between SG and climate change mitigation measures could raise problems of "moral hazard" or "slippery slope" toward deployment. Together with the ethics research related to such concerns (described later in this chapter), economics and political science research can help with finding empirical evidence of the development of these dynamics, tracking the steps that lead to these phenomena, and assessing their actual success or failure at "mitigation deterrence" or technological or economic lock-in. Finally, there is a debate in the political science literature on the very governability of SG, or its very compatibility with democracy at all, that should continue to be discussed (see Horton et al., 2018 and Szerszynski and Galarraga, 2013).

Some critical questions to address this research cluster include the following:

- What dynamics have led to the creation of SG research communities in some countries as opposed to others?
- How has the emergence of these communities affected the development of national research programs or governance systems (including hurdles that have arisen to inhibit creation of research or governance programs and the success or failure of attempts to overcome such hurdles)?
- How do different national models of technology development interact with a country's broader environment related to perception of climate risks, responsibilities, and success or failure of policy responses?
- What factors have influenced the relative failure of global governance institutions to seriously take up SG to date? What would be required to elevate national-level SG programs and governance initiatives to mini-lateral, plurilateral, or international fora?
- What policy frameworks or conditions might accelerate or decelerate activity toward SG at the national or local level (e.g., carbon prices, border adjustments, or other instruments)?
- Are there predictable tipping points with respect to climate impacts that could accelerate or decelerate interest in SG at national or global scales?
- Are different systems of government relatively more or less compatible with broadly considered principles for SG governance (e.g., transparency, accountability, public engagement, etc.)?

[12] Governance: *Developing effective, adaptive processes and institutions to govern SG activities.*

The most pressing knowledge gaps on governance of SG activities are at the international level, where governance institutions are comparatively weak, and cooperation, coordination, and engagement can be difficult to establish.

As noted in Chapter 2, substantial research already addresses how existing law might apply to SG. However, such research has tended to focus on the potential application of existing law to SAI, as opposed to MCB, even though the latter raises distinct issues and might be governed by different treaty regimes (Brent et al., 2019). Moreover, additional research can provide more fine-grained analysis of international legal principles and governance options relevant to specific scenarios that international policy makers might face. Such analysis might inform, for example, a response of the United Nations (UN) General Assembly or UN Security Council to SG field tests with transboundary effects or to unilateral SAI deployment at a global scale.

As discussed in Chapter 2, a number of treaty regimes and institutional settings could serve as loci for formal international governance of SG research. Institutions vary widely in their decision-making mechanisms, adaptability, degree of state and non-state participation, scientific input, and other features, and further research is needed to analyze the relative strengths and weaknesses of these and other possible institutional settings in the specific context of making international decisions on SG research governance. At the same time, moving too quickly into a consensus-based international agreement may unintentionally create a weak or ineffective governance regime. Alternative governance structures, including options that would defer establishing a foothold in one of the existing international agreements, may be better suited for some types of SG and some phases of SG research and/or deployment, and overlapping governance structures may be appropriate in some instances.

Research on liability and compensation for transboundary harms that could result from SG field tests or deployment has recognized not only the challenges in attributing climate-related harms but also the difficulties in developing a political consensus behind any particular international approach to liability and compensation (Horton et al., 2015). A further exploration of liability and compensation mechanisms, with particular attention to their ethical, political, social, and economic implications, is needed, as is research on the possible application of game theory and other hypothetical scenarios to look at how claims of liability would impact research in the absence of an existing legal regime or agreement.

Past research has noted the importance of expanding developing country participation in SG research and governance (Sugiyama et al., 2017; Winickoff et al., 2015). Considerations of justice argue in favor of a central role for developing countries in SG research and decision making (Rahman et al., 2018). Moreover, joint knowledge production can foster trust, political cooperation, and public acceptance of the resulting scientific knowledge (Winickoff et al., 2015). Relatively little research has examined the adequacy of existing resources for building capacity for SG research in developing countries or mechanisms for expanding that capacity. In addition, research aimed at identifying and addressing governance needs once SG is deployed—assuming that it is deployed—is a subject that warrants additional attention.

A permit requirement specific to SG can help provide oversight of risks, generate information, and serve as a form of social license. Relatively little attention has been devoted to the design of domestic permitting systems specific to research or deployment. Not all SG activities would necessarily require a permit, and some activities may be subject to permitting requirements under laws designed for other purposes. Issues for further consideration in this area include the following: the types of SG activities that might be subject to permitting, the choice of general versus specific permits, the information to be required of permit applicants, public participation in the permitting process, and the conditions to be imposed on permittees.

Some critical steps forward to advance this research cluster include the following:

- Survey principles of international law that could be relevant to an international debate in the UN Security Council or elsewhere in the face of SG field tests or deployment with transboundary effects.
- Continue to explore existing international conventions, treaties, or agreements and associated governance regimes that could have jurisdiction in the case of SG field tests or deployment with transboundary effects, as well as opportunities for some level of international cooperative governance outside of these existing instruments.
- Study strengths and weaknesses of possible institutional settings for making international decisions on SG research and research governance.
- Study the possibility and ethical permissibility of various approaches to address harm and compensation issues, including harms that may arise with SG field tests with transboundary effects or as a result of deployment.
- Assess the adequacy of existing resources for capacity building for SG research in developing countries and advisability of opening some existing pools of climate finance to SG research or establishing new sources of funding.
- Study the intergenerational implications of SG research, development, and potential deployment, examining, for example, how research, development, governance, and any future use of SG can take into account principles of intergenerational equity, considering intergenerational benefits and burdens, as well as the institutional challenges that would be involved in a multigenerational SG deployment.
- Evaluate the desirability of a permitting requirement for SG activities and possible elements of permit system design.

[13] Ethics: *Incorporating ethics and justice considerations for current and future generations into SG research and research governance.*

As discussed in Chapter 2, there is a substantial and growing body of literature on ethics, justice, and equity in relation to SG, and there are important connections between this literature and broader discussions of climate ethics and climate justice. Existing research addresses a range of issues, including whether and under what conditions geoengineering (from research to deployment) would be morally permissible;

whether and how SG could be fair and equitable, considering multiple dimensions of justice (e.g., distributive, procedural, recognitional, and intergenerational); what principles might guide ethical governance of SG; and how to evaluate SG in relation to other climate response options and address interactions between SG and other climate responses.

Early literature tended to consider geoengineering at a general level, frequently addressing carbon dioxide removal and SG together. More recently, ethics research has attended more closely to the specific techniques under consideration and to distinct aspects and stages of research, development, and future decisions to proceed with or abandon SG. Although fundamental questions regarding the moral permissibility of geoengineering remain important, the increased attention to specific geoengineering approaches is welcome because "geoengineering" is not a single, fixed technology; rather, it is an evolving array of ideas that includes not only possible SG technologies themselves, but also various approaches to researching, developing, governing, and making decisions about these technologies and how they might fit (or not fit) into a broader climate response (Stilgoe, 2015).

Research on ethics, equity, and justice can provide a more nuanced understanding of the ethical issues associated with various stages of SG research, from modeling to laboratory and field experimentation, and can help to guide research governance. Ideally, ethics research would be integrated with natural and social science research, so that ethical analyses can both inform and be informed by research on the social and technical dimensions of SG (Tuana et al., 2012). As Tuana et al. (2012) explain, "Ethical analysis is not simply to be put into operation once the scientific and social scientific analysis is completed. On the contrary, ethically significant decisions are often embedded in the scientific analysis itself, as well as in how scientific models represent impacts and vulnerabilities."

Cross-disciplinary and integrated work that engages ethical issues is already a component of SG research (e.g., Carr and Preston, 2017; Lenferna et al., 2017; Morrow et al., 2009; Tuana et al., 2012), but further research of this kind is needed, because virtually all stages and aspects of SG research and research governance involve normative questions. As Tuana et al. (2012) put it, although much important research on the ethics of geoengineering has taken place already, "what has been lacking is a clear delineation of the ethical issues that must be addressed in the course of scientific decision making about research and testing and the types of scientific knowledge and levels of confidence about models that would be ethically required to warrant responsible SRM [solar radiation management] deployment." A related point applies to SG governance: research has played an important role in identifying ethical issues associated with governance and developing ethically grounded governance principles; however, more work is needed to identify and prioritize principles most important at various stages of SG research and development, to propose ways of institutionalizing these principles, and to identify opportunities and barriers for ethical and equitable governance.

The integration of research on ethics, justice, and equity into a broader SG research program could enhance both processes and outcomes, strengthening the legitimacy of research and its governance. Ethical issues and questions associated with different aspects and stages of research, governance, and possible deployment are identified below, along with priority areas associated with each. The critical research questions outlined here emerge from an assessment of existing research and current understanding of key ethical issues. Additional social science research to identify the values, perspectives, and concerns of diverse publics and stakeholders globally should inform ongoing priorities for ethics research.

Some critical questions to address in this research cluster include the following:

Justice and equity issues

- How can SG research take account of the full range of ethical perspectives on this issue? On what issues is there significant ethical convergence (e.g., regarding transparency in research), and where is there significant divergence (e.g., regarding governance of field experiments)? How might disagreements regarding research and research governance be fairly addressed?
- What would constitute fair and ethically justifiable forms of public and stakeholder engagement? What constitute best practices for inclusive engagement in research and research governance at various stages of development?
- What are the ethical implications of the current concentration of SG research, policy, and governance efforts in wealthy countries, and how can existing inequities in research and research governance be addressed? What mechanisms could help to develop capacity for those who are underrepresented (e.g., poorer nations, climate vulnerable communities, and indigenous peoples) to participate more fully in research and research governance? More generally, what steps are need to strengthen and institutionalize equity and inclusiveness in research, development, and governance?
- What are the ethical considerations associated with the potentially uneven distribution of benefits, risks, and harms associated with SG? In developing research models, exploring possible deployment scenarios, and developing SG-related policy and governance, how should distributional considerations be taken into account?

- How can intergenerational ethical considerations be better incorporated into SG research and research governance? How can the social and technical feasibility of SG be evaluated from an intergenerational point of view, and how should risks to both present and future generations be evaluated? What institutions are needed to ensure that research, development, and decisions take account of intergenerational equity?

Ethical issues embedded in SG research

What ethically significant assumptions are embedded in SG models and scenarios, and how might models and scenarios be developed with explicit consideration of ethical issues?

- What ethical values and principles should guide the development and governance of field experiments? How can ethical considerations inform the development and justification of permissibility thresholds for outdoor experimentation? How might ethics guidelines and permitting requirements for outdoor experiments take into account concerns that go beyond just physical effects? What role, if any, should the concept of informed consent play in governing SG field experiments?
- What ethical considerations should guide the development and comparative assessment of various SG approaches and techniques? For example, are there important ethical differences between regional and global approaches? Between MCB and SAI? Between different kinds of possible particles being considered for SAI? Different delivery systems?
- How should risk, uncertainty, and ignorance[8] be treated in relation to SG? What are the ethical implications of judging the importance of SG risks based on their estimated magnitude and probability? How might low-probability high-impact risks best be addressed? What role should risk trade-off assessment, the precautionary principle, or other approaches play in research and decision making?
- What core ethical principles should inform development of a code of conduct for SG research, and who should be involved in the development of such a code?

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[8] See https://heep.hks.harvard.edu/files/heep/files/zeckhauser_presentation_0.pdf.

Ethical issues associated with governance

- Are there central ethical principles that should guide SG governance? If so, what are they, and how can they be institutionalized for research, decision making, and any future deployment?
- From an ethical perspective, to what extent are existing legal and governance institutions adequate to guide and regulate SG research, development, and any possible future use? Where are the gaps, and how might they be filled?
- How can SG research and research governance be structured to build trust and cooperation among nations and to minimize damage to already-fragile relations surrounding international cooperation on global climate change?
- How should issues of potential loss, damage, and liability be addressed in relation to SG? What approaches are ethically justifiable (and why), what institutional mechanisms are feasible, and who should be involved in the development of these approaches?
- What are the central ethical concerns associated with possible moral hazard, technological lock-in, and slippery slope in relation to SG, and how might these concerns be addressed? For example, how could and should these concerns be monitored and assessed in relation to research and development? What institutional mechanisms could be developed to limit the possibility and extent of mitigation deterrence?

Ethics issues associated with SG deployment, management, monitoring, and termination[9]

- Under what conditions would an international body, individual nation, or other entity be ethically justified in making decisions to utilize SG? What institutions, laws, or processes are needed to enable ethically defensible decisions? What role should consensus, voting, or other processes play in these decisions? What agent(s) or institution(s) would have the legitimacy to make decisions about deployment?
- Could SG deployment be managed ethically and equitably over multiple decades or centuries (in the face of major disruptions such as wars or pandemics), and, if so, what would be required to achieve this? How and to what extent could an SG system be prepared to respond to conflicts, disagreements, and unintended consequences?
- What ethical considerations should inform research and research governance

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[9] Note that the recommended research on these questions reflects the need to better understand and anticipate ethical issues associated with deployment in order to inform SG decision making. This does not presuppose that SG should or will be deployed.

planning for the phase-out and termination of SG? What level of agreement and certainty in long-term planning (for monitoring, adaptive management, compensation for harm, and termination) would be required for responsible use of SG?

Research on these questions about ethics, justice, and equity strongly interfaces with other research areas recommended in this chapter—for instance, it can inform and be informed by investigations of SG technical feasibility, social feasibility, and impacts, as well as the development of governance. Much of this research would benefit from interdisciplinary approaches and multidisciplinary research teams.

6.3 OUTDOOR SOLAR GEOENGINEERING EXPERIMENTATION

Outdoor experimentation is currently the most controversial dimension of SG research, posing the largest potential for public attention, concerns, and objections. This stems in part from arguments that outdoor experimentation at a scale large enough to affect regional to global climate is tantamount to actual deployment, and outdoor experiments short of that are legitimizing a road to deployment. For some, these objections are absolute, based, for instance, on fundamental objections to the idea that a small group of people has the right to "tamper with nature" in the absence of broad public input and consent and concerns about unintended consequences, intentionality of researchers toward outdoor experiments of increasing scale and impact, and lack of controllability and reversibility of outcomes.[10]

At the same time, some scientists involved in SG research argue that some form of outdoor experimentation is essential for advancing understanding of certain core physical processes, and that gaining such understanding will be essential if we are to credibly inform societal decisions about operational pursuit of SG. The 2015 National Academies report noted that small-scale field experiments may be informative and provided a number of conditions that such experiments should meet (NRC, 2015).

Recognizing both the philosophical/ethical and the technical/scientific dimensions of this issue, it is the committee's judgment that, subject to appropriate governance and oversight, outdoor experimentation could feasibly be pursued in a balanced manner that is sufficient in scale to acquire critical observations not available by other means (see discussion in the "Atmospheric Processes" section of this chapter)

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[10] For example, see the Climate Action Network's "Position on Solar Radiation Modification (SRM)" at https://climatenetwork.org/resource/can-position-solar-radiation-modification-srm-september-2019/.

but that is small enough in scale to limit impacts. This judgment is based in part on the recognition that such experimentation can be done at small enough scales that the real-world impacts would be much smaller than impacts of many other deliberate human activities that are freely undertaken by society and the belief that good governance can limit concerns over a slippery slope to deployment. This judgment is also based on concerns that moving too quickly and ambitiously toward outdoor experimentation could induce public objections and subsequent delays or restrictions. Thus, the committee believes that a tempered approach to the initial phase of outdoor experimentation provides the best pathway to a successful research endeavor.

Given the contentious nature of outdoor experiments that involve the release of substances into the atmosphere, *all* proposed experiments should be subject to the governance described in Chapter 5 (see in particular the permitting system and impact assessment recommended in Recommendations 5.1i and 5.1h, respectively). These governance mechanisms can be important means to limit unacceptable and to enable useful outdoor experimentation. Furthermore, these mechanisms, if designed effectively, will provide a way to ensure that the aggregate of experiments undertaken by different entities do not result in any undesirable impacts.

In addition, the committee considered how to set thresholds for the scale of outdoor experimentation. Such thresholds have been debated in the broader community as a way to provide more clarity about what scale of experiments should or should not be carried out. We agree that such clarity would be helpful in defining material releases that are too large to qualify as research, given current understanding of SG and the societal demand for SG responses to climate change. Based on extensive discussions of the topic, the committee offers proposals for initial thresholds (see below), with the expectation that thresholds may need to be revisited on a regular basis as SG research and research governance advance.

General Considerations for Setting Thresholds for Outdoor SG Experimentation

The committee believes that thresholds for outdoor experimentation should address both the impacts of the potential perturbation on the climate and the impacts of the test materials on the environment. These dual concerns about outdoor experimentation motivate the dual threshold requirements—based on the expected global mean surface temperature change and the mass of materials injected into the atmosphere—that are described below.

The proposed limits are based on the approach of (i) erring on the conservative side and (ii) being sufficient for a variety of experiments that address priority research questions (based on past studies, including analogues). In the committee's judgment, experimentation at the proposed scale has the potential to provide valuable knowledge (i.e., helping to resolve many critical process-level uncertainties), presenting justification for the small amount of impact risk within and across national boundaries.

A practical challenge in setting and enforcing these sorts of thresholds for outdoor experimentation is that research activities are undertaken and sponsored by multiple countries and other nongovernmental entities. It is conceivable that individual countries could independently conduct experiments in which each experiment individually satisfies the threshold requirements, while leading to an aggregated perturbation that exceeds the thresholds. Governance mechanisms intended to ensure international coordination and transparency, several of which are discussed in Chapter 5, are essential to help avoid such situations.

The potential for multiple independent experiments to have a larger aggregate effect on global temperature also makes it challenging to set firm thresholds for outdoor experimentation by individual countries. Thus, the committee suggests a threshold for individual experiments as well as for the aggregated effects of all outdoor experiments conducted globally in a given year. The contribution from outdoor experiments conducted by individual countries, including the United States, should be well below these global aggregate thresholds.

Furthermore, the committee has taken a precautionary approach in choosing relatively conservative thresholds to allow for the possibility that, lacking the necessary governance and coordination, outdoor experiments could be undertaken without full disclosure to governments, the global scientific community, and the public. This consideration motivates the recommendation that the temperature thresholds for individual experiments be two orders of magnitude below detection limits, assuming that there are unlikely to be more than 10 experiments conducted each year by the international research community. This temperature threshold would therefore limit the global annual temperature change to be less than the detection limit by approximately one order of magnitude (i.e., if 10 experiments were conducted right at the threshold, the temperature change would be approximately 10 times less than what can be observed globally).

These thresholds will need to be revisited and revised periodically to account for evolving SG research and research governance. Scientists and stakeholders are likely to make compelling arguments for both lower and higher thresholds. Furthermore, the temperature threshold suggested here focuses just on concerns about physical climate effects (and, implicitly, the related environmental and human system impacts). Social or political impacts that could be associated with outdoor substance release experiments should be independently assessed prior to each experiment.

Experiments that fall below the thresholds would be eligible to be considered on a case-by-case basis, in light of relevance to open questions, expected benefits of the study outcomes, and timing relative to other steps; they would be subject to approval based on the governance guidelines adopted by the larger SG program as outlined in Chapter 5. This case-by-case consideration would also include evaluation of potential local effects specific to the experimental design and location (e.g., could an MCB experiment expose sensitive ecosystems to excess salinity?). Interventions larger than these limits should be allowed only after new thresholds have been established, in a review process to be held within 5 years of establishing the research program.

Recommendation 6.2: Deliberate outdoor experiments that involve releasing substances into the atmosphere should be considered only when they can provide critical observations not already available and not likely to become available through laboratory studies, modeling, and experiments of opportunity (e.g., observing volcanic eruptions, rocket plumes, or ship tracks). All outdoor experiments involving the release of substances into the atmosphere should be subject to the governance established pursuant to the Chapter 5 recommendations, including a permitting system (5.1i) and impact assessment (5.1h).

In addition, any outdoor substance releases should be limited to a quantity of material at least two orders of magnitude smaller than the quantity that could cause detectable changes in global mean temperature or adverse environmental effects (see Recommendations 6.2a and 6.2b below for details on what these limitations mean in practice). These limitations should apply for at least the next 5 years and then be revisited and revised if needed, based on program review guidance from a diverse inclusive panel of experts and stakeholders as discussed in Recommendation 4.1.

Considerations for Setting a Temperature Change Threshold for Outdoor SG Experimentation

In setting a temperature change threshold for field experiments, it is important to consider the timescales and spatial scales to which it will apply. The committee recommends a reference timescale of 100 years, which allows one to use the same scale for experiments involving aerosols with widely varying lifetimes (days for MCB, on the order of 1 year or more for SAI). A 100-year timescale also allows for a reasonable comparison to the warming associated with CO_2. In addition, it is important to compare equivalent spatial areas; thus, the committee recommends that temperature changes should be scaled to global-scale differences. In practice, this means that for small particle emission tracks, the area of cooling is divided by the surface area of Earth. Using a global-scale threshold allows for experiments in which the cooling would be detectable in a small area (typically over the ocean) but would not be measurable in global surface mean temperature.

The committee recommends limiting the perturbation allowed per experiment to less than two orders of magnitude smaller than currently detectable changes in global mean surface temperature. Given current observational capabilities, this limit would constrain the temperature perturbation to 100 nK (100×10^{-9} C) per experiment and to 1 μK (1×10^{-6} C) for the sum/aggregate of all experiments conducted globally (both limits for a 100-year time horizon). Experiments below this threshold can allow for useful scientific inquiry. For example, an MCB experiment designed to comply with this threshold (i.e., to generate a global surface temperature change of no more than 100 nK normalized to 100 years) is equivalent to a typical ship track that induces more than 15 percent albedo change over 2,500 km^2 for 6 hours. Microphysical changes produced by such emissions are more than large enough to allow useful measurements to be collected in process studies (Russell et al., 2012).

Recommendation 6.2a: To avoid detectable changes in global climate:

- **for any individual experiment, any induced change in global mean surface temperature should be less than 100 nK (100×10^{-9} C) for a 100-yr time horizon (or 10 μK normalized to a 1-yr time horizon); and**
- **for the sum/aggregate of all experiments conducted globally each year, any induced change in global mean surface temperature should be less than 1 μK (1×10^{-6} C) for a 100-yr time horizon (or 100 μK normalized to a 1-yr time horizon).**

Considerations for Setting a Mass Threshold for Outdoor SG Experimentation

The mass threshold is also designed to be conservative, both in limiting the overall amount of material emitted per experiment to 1,000 kg and globally to 10,000 kg annually and in ensuring that the material is considered sufficiently safe from an environmental and human health standpoint. This amount of emissions is significantly less than other commonly accepted anthropogenic emissions to the atmosphere. For example, fuel dumped by aircraft with mechanical difficulties is reported to be up to 53,000 kg per incident;[11] U.S. firework usage for 2017 was estimated at more than 100,000,000 kg.[12]

The proposed mass thresholds assume that the substance released is known to be relatively inert and of low toxicity. This assumption is consistent with materials currently being considered for outdoor SG experiments. For example, MCB studies have proposed using NaCl (salt from seawater), which is naturally present in marine environments; SAI studies have proposed either sulfate (which occurs naturally in the stratosphere in much higher quantities after volcanic eruptions) or calcite. That said, even materials that might be considered safe in a general sense may be harmful in specific conditions, such as at high concentrations or if sensitive organisms are exposed. Before proceeding, proposed outdoor experiments would need to do a complete accounting of the environmental effects of an outdoor experiment that would consider how long and at what levels sensitive ecosystems might be exposed to a substance and the toxicity of the specific substance to organisms that would be exposed. These issues will need to be addressed by the required environmental impact assessments described in Recommendation 5.1h and the permitting processes discussed in Recommendation 5.1i.

Recommendation 6.2b: To avoid toxicity and environmental effects, test materials should be relatively inert and nontoxic, and

- **for any individual experiment, distribution of test materials should not exceed 1,000 kg (mass of non-aqueous particle components) released to the atmosphere; and**
- **for the sum/aggregate of all experiments conducted globally each year, distribution of test materials should not exceed 10,000 kg (mass of non-aqueous particle components) released to the atmosphere.**

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[11] See https://en.wikipedia.org/wiki/Fuel_dumping#cite_note-3.

[12] See https://www.americanpyro.com/assets/docs/FactsandFigures/Fireworks%20Consump.%20Figures%202000-17.pdf.

6.4 FUNDING CONSIDERATIONS FOR SOLAR GEOENGINEERING RESEARCH

Implementing the recommended research and research governance will require dedicated resources. It is beyond the scope of the committee's task and resources to develop detailed budget estimates for the proposed research program;[13] indeed, many aspects of the SG research program are not yet mature enough to allow for the development of detailed budget estimates. Nonetheless, to help shape the planning for these detailed budgets, the committee offers a set of general guidelines and an indicative picture of a national investment in a research program.

In the committee's view, the following guidelines provide a reasonable foundation for shaping the budget of a national SG research program:

- **Funding for SG research should not shift the focus from other important global climate change research, and it should recognize the risk of exacerbating concerns about a slippery slope toward deployment.** This guideline implies that the near-term budget for SG research should be small relative to the overall investment in global change research.
- **The research program should support equitably all of the research clusters discussed in this chapter from the outset.** The committee considers all of the recommended elements of the program as essential and believes that the program's success will be diminished if any elements are omitted or delayed.
- **The budget should be able to accommodate major field campaigns, should proposals for such campaigns meet other requirements outlined in Recommendation 6.2.** Such campaigns might involve aircraft, ocean vessels, large deployments of autonomous sensors, or potentially a combination thereof, as well as modeling, analysis, and research, including on human dimensions and other impacts.
- **A substantial fraction of the research program should be dynamically allocated** in order to allow the research program to flexibly adapt as learning proceeds.
- **Research funding should be accompanied by support for implementing research governance and public engagement.** Achieving the integrated strategy of research, research governance, and engagement requires dedicated funding for advancing these other (non-research) activities.

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[13] It is likewise beyond the scope of this specific study to evaluate or make recommendations regarding the "opportunity costs" of supporting SG research compared with supporting other research priorities. Such choices often encompass more than just scientific considerations and will need to be weighed by decision makers.

Taken together, these guidelines can help align the program with the principles for SG research in Chapter 3 with the integrated research program design presented in Chapter 4 (see for example, Figure 4.1) and with the governance framework recommended in Chapter 5.

The committee suggests that a reasonable initial investment in SG research is in the range of $100–200 million over 5 years. A research program of this size would represent a small fraction of the national budget for climate change research. For comparison, in 2019, the U.S. Global Change Research Program (USGCRP) "cross-cut" budget for global change research overall was $2.546 billion, of which $1.047 billion was to support non-satellite research activities (Our Changing Planet, 2020). Likewise, leading foundations spent roughly $1.6–1.8 billion on advancing climate change mitigation, including for research, in 2019 (ClimateWorks Foundation, 2020). While small relative to the overall investment in global change research, a 5-year investment of $100–200 million would be a several-fold increase in funding for SG research over recent levels (see Table 4.2).

At the same time, a 5-year research investment of $100–200 million should be sufficient to advance, to varying degrees of completion, all the research topics identified in Recommendation 6.1. As a starting point for planning, the committee suggests that the budget be allocated along the lines shown in Figure 6.2. This budget would set aside approximately a quarter of the funding for dynamic allocation as learning proceeds. For the remainder, the committee proposes that, initially, roughly half of the funding be directed to research on impacts and technical dimensions (with an appropriate balance across MCB, SAI, and CCT), a quarter to research on social dimensions, and a quarter to research on context and goals. These rough budget allocations reflect differences in the cost of different kinds of research, without implying that some topics warrant more or less focus than others. Some kinds of research are more expensive than others; for example, efforts requiring advanced laboratory equipment or field campaigns involving aircraft- or ship-based observing are more expensive than computer-modeling work and most social science activities. As illustrated in Figure 4.1, these allocations should evolve as knowledge improves and the research needs adjust accordingly, thus the importance of ensuring flexibility for a large fraction of the funding.

Field campaigns to obtain in situ measurements are likely to be the most expensive element of the SG research agenda. Costs of past field campaigns have ranged from a few million up to a few tens of million for major multiyear aircraft campaigns (see Box 6.1). It is reasonable to expect that MCB and SAI field campaigns might have comparable budgetary requirements, though detailed estimated costs for specific proposed missions have not been published. Experiments involving controlled releases of substances would entail some additional costs to develop injection technologies; these costs could vary widely depending on the experimental design. While these controlled-release experiments would be useful in advancing our understanding (see "Atmospheric Processes" section earlier in this chapter), undertaking them will require significant progress in developing appropriate governance, environmental review, and public engagement, as described in Chapter 5. The large range in the proposed 5-year investment in SG research, along with dynamic allocation of a significant fraction of the overall investment, can accommodate two or more field campaigns, should these various requirements be met.

Spinning up any major new research program takes time, and structuring support as a funding ramp allows for a thoughtful process of building capacity, adapting plans based on new information, and developing a research community over time. The budget is proposed to start smaller in the first year, because the workforce capacity would not yet be in place to execute a large new program. Among the reasons why it is important for all of the research elements to launch early in the process is to enable capacity building across the elements and inform decisions about future research directions. Targeted efforts to build capacity and new funding mechanisms for the "Social Dimensions" and "Context and Goals" categories will likely be required because

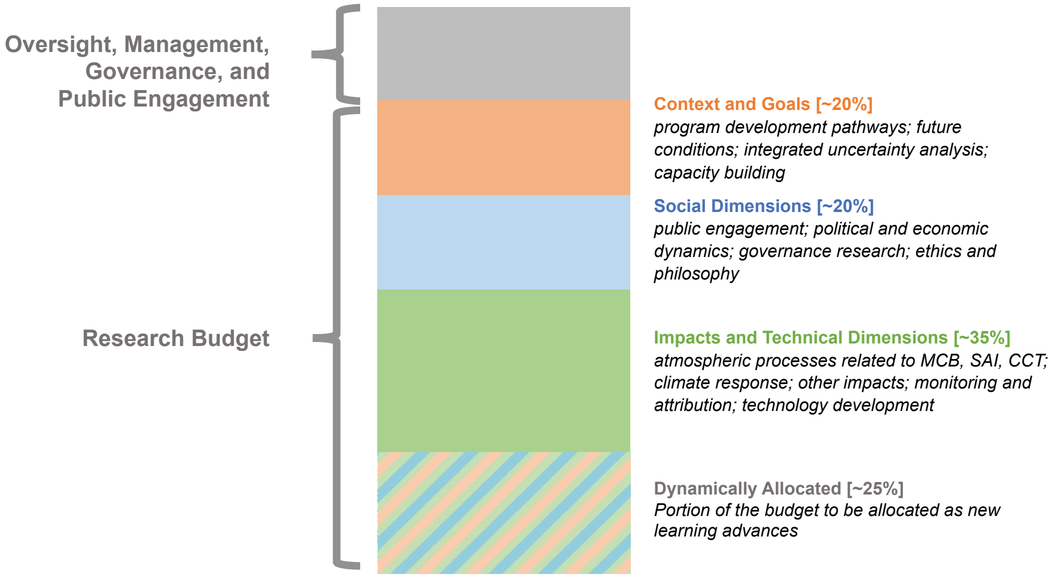

Figure 6.2 Overview of the proposed allocation for the SG research program budget.

these areas of research are typically not well represented within the USGCRP research portfolio (NASEM, 2021).

Ramping up the funding over time also provides opportunities to allocate funding in later years, based on the findings from the research up to that point. In other words, some fraction of the research funding would not initially be assigned to particular research topics but instead would be allocated based on opportunity and need (guided by the program steering group recommended above). Likewise, exit ramps need to be built into funding plans in order to accommodate the possibility that, based on findings from the research, some (or even all) lines of inquiry may at some point be defunded.

In addition to funding research itself, support is needed for implementing robust research governance at national and international scales, including public participation and engagement. As discussed in Chapter 5, the committee envisions robust research governance that incorporates public participation and engagement and builds on the learnings from studies of research governance. Achieving the integrated strategy of research, research governance, and engagement (illustrated in Figure 4.1) requires support for carrying out these other (non-research) activities. The committee suggests as a general rule that these governance and engagement efforts be supported at approximately 20 percent of the level of the total research program support—an investment that would scale with the overall size of the research program. The 20 percent target is based on the committee's assessment of the level of activities that are essential for this research program overall. These efforts could either be supported by the same agencies that support research or perhaps through different funding streams (e.g., U.S. Department of State, regulatory agencies, the White House Council on Environmental Quality, or public–private partnerships with philanthropy).

This budget is intended to indicate incremental funding that adds to any current or anticipated near-term funding of SG research and research governance. While the committee expects that the proposed research would be federally supported, it is also possible that support from philanthropic sources could help enable some of the proposed activities that are particularly challenging for government agencies to advance. Any philanthropic support for an SG research program would need to be pursued in a way that embodies the principles for the conduct and governance of research discussed in Chapter 5 and that ensures that the federally and privately funded activities are well coordinated.

BOX 6.1
Examples of Costs of Field Campaigns and In Situ Measurements

Federal science agencies—including NASA, NOAA, NSF, and DOE—have many decades of experience in conducting field campaigns, both on their own and in collaboration with other agencies or nations. Many factors contribute to the costs of these campaigns, including the number and kind of aircraft used, the duration and location of the campaign, the number of instruments required to make the desired measurements, and the size of the science team assembled to plan the campaign and analyze the results. In addition, some field campaigns incorporate human dimensions research, engaging local communities and incorporating research on the implications for local policy and decision making (e.g., in the Large-Scale Biosphere–Atmosphere Experiment in Amazonia; [Avissar and Nobre, 2002]).

Below are some examples of the rough costs of elements of atmospheric chemistry aircraft campaigns funded by NASA, NOAA, and NSF over the past 15 years.

Airborne platform costs (per mission year, excluding costs of research and analysis of data collected)[a] are as follows:

- $1.5–2.0 million for an aircraft that can access the lower to mid-troposphere (e.g., NOAA WP-3; SONGNEX 2015, SENEX 2013).
- $5–6 million for an aircraft that can access the entire troposphere (e.g., NASA DC-8; ATom 2016–2018, FIREX-AQ 2019).
- $5–9 million for an aircraft that can access the stratosphere (e.g., NASA WB-57; VIRGAS 2015; HS3 2014).
- $3–6 million for a high-altitude unmanned aircraft (e.g., NASA Global Hawk; HS3 2011–2014; ATTREX 2011–2015).

Other example campaigns include the following:

- NASA Earth Venture Suborbital Program funds up to $30 million over 5 years (Allen et al., 2010) to address one or several related scientific questions (e.g., ATom, ACTIVATE).
- The MILAGRO campaign in 2006 cost $26 million (adjusted for inflation) and included aircraft, ground sites, and building capacity that did not previously exist (Velasco et al., 2020).
- SOAS (2013), $8.1 million; DC3 (2012); $7.8 million (Avallone and Baeuerle, 2017).[b]

Annual agency program costs dedicated to field measurements[c] (NASEM, 2016) are as follows:

- NSF Atmospheric Chemistry Program averaged $10 million per year from 2006 to 2015 (excluding costs borne by the deployment pool).
- NOAA Ocean and Atmospheric Research atmospheric chemistry research averaged $14 million per year from 2005 to 2015.

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[a] Approximate information about campaign costs were provided through personal communication with representatives from NOAA. Platform costs may not include additional costs for data analysis, instrumentation, engineering, personnel, etc.

[b] Cost in 2009 dollars. Cost is for NSF only and does not include contributions from other federal agencies.

[c] Costs for field measurements may not include additional deployment costs.

6.5 CONCLUDING THOUGHTS

As the discussions throughout this report illustrate, the scientific community is at an early stage of understanding the complex array of issues surrounding SG. Research today offers indications that SG strategies do have potential value as one of the tools that could be used to help meet goals for limiting global warming. But research also points to many uncertainties and possibilities for unintended harmful consequences that have significant societal implications. Understanding the "social feasibility" of these technologies (e.g., societal perceptions and reactions, political and economic ramifications, and ethical concerns) is just as important as understanding the technical question of "will it work."

The SG research program proposed herein is, by design, quite different from most traditional environmental research and development programs—with an array of interlinked research "clusters"; stepwise, iterative planning; and a strong governance framework that helps ensure transparency, accountability, human and environmental safety, and robust public engagement. Rather than being a burden on the research community, we suggest this governance framework will enable this research to proceed effectively. What has been proposed herein is just the first phase of a research program. Based on the insights gained from this initial phase of work, many aspects of this program (e.g., research goals, governance measures, and funding support) will need to be recalibrated and revised. The research program may continue to expand—or it may in fact shrink if early research suggests strong reasons to discontinue research.

Many of the difficult questions that society may eventually face about actual deployment of these SG interventions are beyond the scope of this study. We have confidence, however, that if the research program is pursued as envisioned, it will yield a much stronger foundation for addressing those critical questions. Ultimately, the growing insights about SG must be considered within a much broader lens that includes the other (primary) strategies for addressing climate change—reducing GHG emissions, capturing and sequestering carbon, and preparing for and adapting to climate change impacts. Advancing understanding of individual strategies themselves is necessary but not sufficient as "real-world" decisions will require finding an appropriate balance and interplay among all of these strategies. While not the focus of this study, we strongly encourage pursuit of a broad integrative approach.

Given that climate change is one of the most complex challenges that humanity has ever faced—and that SG is one of the most controversial aspects of the response to climate change—the scientific community must rise to this challenge with humility and creativity and stretch itself in new ways, across disciplines and national boundaries and beyond business-as-usual approaches to research.

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APPENDIX A

Statement of Task

The National Academies of Sciences, Engineering, and Medicine proposes to undertake a study that would develop a research agenda and recommend research governance approaches for climate intervention strategies that reflect sunlight to cool Earth. The proposed study would aim to address research needs and relevant research governance in tandem, such that the understanding and thinking on each can inform the other.

The study will focus on sunlight reflection strategies that involve atmospheric interventions, including marine cloud brightening, stratospheric aerosol injection, and cirrus cloud modification. It will consider trans-disciplinary research related to understanding the baseline chemistry, radiative balance, and other characteristics of the atmosphere; estimating the potential impacts and risks, both positive and negative, of these interventions on the atmosphere, climate system, natural and managed ecosystems, and human systems; technological feasibility of these interventions; and approaches and metrics for detecting, monitoring and quantifying the multiple physical and societal impacts of solar climate interventions.

The study will explore and recommend appropriate research governance mechanisms at international, national, and sub-national scales. It will consider research governance that already exists, examples of research governance mechanisms currently being used or considered for other areas of scientific inquiry that could be adapted to the realm of climate intervention research, and any potentially new frameworks required.

The committee will include two subpanels (composed of members of the committee) that will organize two workshops to address the research agenda and research governance considerations listed below. Drawing upon these workshops, other information gathering activities, and deliberations among the full membership, the committee will author a single consensus report providing its findings and recommendations. The committee will:

1. Develop a detailed trans-disciplinary research agenda for sunlight reflection strategies. The committee will assess questions such as:

    - What research is needed to assess the feasibility, efficacy, and risks of the proposed approaches?

- What research is needed to assess likely impacts and risks of reduced solar radiation on key global systems (including the oceans, ice sheets, food and fiber production, human health, solar and wind energy, terrestrial ecosystem functioning and biodiversity, and global biogeochemical cycles) and on achieving the UN's Sustainable Development Goals? What are the risks (environmental, social, geopolitical) of conducting such research?
- What research is needed to assess how reducing solar radiation could help avoid or trigger critical transitions in environmental systems?
- What relevant research is happening currently in the United States and abroad? What have we learned from this work?
- What are the important knowledge gaps and key technical constraints (such as model resolution or cloud physics)?
- What research is needed to address the knowledge gaps and key technical constraints? What are reasonable research goals for the next decade?
- What investments in observations, modeling capabilities, and other supporting research infrastructure will be necessary to advance the research agenda?
- What are benefits of the proposed research in advancing other areas of science?

2. Explore and recommend appropriate research governance mechanisms. The committee will assess questions such as:

    - How best to foster meaningful public participation and consultation in research planning and oversight, and to ensure transparency and accountability regarding a project's goals and plans, potential risks, and eventual results?
    - How to ensure that research is designed to minimize the chances of unintended impacts and is aimed at promoting the collective benefit of humankind and the environment?
    - How to identify and apply professional standards of good scientific conduct?
    - How to balance adequate oversight, review, public consultation, and approval mechanisms with norms for freedom of scientific inquiry?
    - How to harness the benefits of potential private sector involvement (e.g., innovation, capital investment, cost minimization) without creating vested financial interests in operational deployment, inappropriate intellectual property claims, or threats to national and international public good?

- What statutory limits might affect what work can be funded by federal agencies and what research may need to adhere to particular existing federal policies or international agreements or processes?
- How to identify the governance mechanisms that should be in place in advance of field research at various scales?

The committee will be encouraged to look at examples of research governance mechanisms currently being used or considered for other areas of scientific inquiry that could be adapted to the realm of climate intervention research.

APPENDIX B

Speakers from the Committee Meetings & Webinars

MEETING 1: WASHINGTON, DC; APRIL 30–MAY 1, 2019

Lili Fuhr, Heinrich Böll Foundation
Steve Hamburg, Environmental Defense Fund
Anna-Maria Hubert, University of Calgary
David Keith, Harvard University
Ben Kravitz, Indiana University
David Morrow, Forum for Climate Engineering Assessment, American University
Daniel Sarewitz, Consortium for Science, Policy, and Outcomes, Arizona State University
Michael Stoever, Office of U.S. Rep. Jerry McNerney (CA-09)
Pablo Suarez, Red Cross Red Crescent Climate Centre
Janos Pasztor, Carnegie Climate Geoengineering Governance Initiative
Kelly Wanser, SilverLining
Kyle Whyte, Michigan State University

WEBINAR 1: JULY 22, 2019

Melanie Nakagawa, Princeville Capital
Pete Ogden, United Nations Foundation
Franz Xaver Perrez, Switzerland's Federal Office and University of Bern School of Law
Nigel Purvis, Climate Advisers

RESEARCH WORKSHOP AND MEETING 2: BOULDER, CO; AUGUST 7–9, 2019

Waleed Abdalati, University of Colorado, Boulder
Rob Bellamy, University of Manchester
Colin Carlson, Georgetown University
David Fahey, National Oceanic and Atmospheric Administration/Earth System Research Laboratories
Jane Flegal, Arizona State University

Sean Garner, Palo Alto Research Center
Cheryl Harrison, University of Texas, Rio Grande Valley
Frank Keutsch, Harvard University
Ulrike Lohmann, ETH Zurich
Allison McComiskey, Brookhaven National Laboratory
Karen Parkhill, University of York
Steve Platnick, National Aeronautics and Space Administration/Goddard Space Flight Center
Phil Rasch, Pacific Northwest National Laboratory
Alan Robock, Rutgers University
Isla Simpson, National Center for Atmospheric Research (NCAR)
Brian Soden, University of Miami
Jack Stilgoe, University College London
Simone Tilmes, NCAR
Gernot Wagner, New York University
Rob Wood, University of Washington

GOVERNANCE WORKSHOP AND MEETING 3: STANFORD, CA; SEPTEMBER 10–12, 2019

Louise Bedsworth, California Strategic Growth Council
Daniel Bodansky, Arizona State University
Holly Buck, University of California, Los Angeles
Wylie Carr, U.S. Fish and Wildlife Service
Alta Charo, University of Wisconsin, School of Law
Drew Endy, Stanford University
Stephen Gardiner, University of Washington
Gary Gardner, GreenFaith
Tracy Hester, University of Houston Law Center
Joshua Horton, Harvard University
Sheila Jasanoff, Harvard Kennedy School,
Sikina Jinnah, University of California, Santa Cruz
Deneb Karentz, University of San Francisco
Robert Lempert, RAND Corporation
Lisa Levin, Scripps Institution of Oceanography
Andy Parker, Solar Radiation Management Governance Initiative
Ted Parson, University of California, Los Angeles School of Law
Jonathan Pershing, William and Flora Hewlett Foundation
Nick Pidgeon, Cardiff University

Steve Rayner, University of Oxford
Stuart Russell, University of California, Berkeley
David Santillo, Greenpeace International
Alex Wellerstein, Stevens Institute of Technology

WEBINAR 2: SEPTEMBER 26, 2019

Daniel Harrison, Australia Marine Cloud Brightening for the Great Barrier Reef
Jan McDonald, Australian Forum for Climate Intervention Governance
Jeffrey McGee, Australian Forum for Climate Intervention Governance

WEBINAR 3: SEPTEMBER 27, 2019

John Moore, Beijing Normal University, College of Global Change and Earth System Science

WEBINAR 4: DECEMBER 16, 2019

Paula Caballero, Lands for Life Program, Rare
Arunabha Ghosh, Council on Energy, Environment and Water
Youba Sokona, Intergovernmental Panel on Climate Change

APPENDIX C

Scenarios Developed By the Committee for the "Decision Maker Needs" Webinars

Instructions to the invited speakers: For each scenario below, what questions need to be answered before you could make an informed decision about pursuing a research program for solar geoengineering (inclusive of outdoor experiments with possible trans-boundary impacts) or deploying solar geoengineering? In particular, what high level considerations (e.g., efficacy, attribution or traceability, known risks, risks of inaction because of climate impacts, potential for—and extent of—unintended consequences, costs, technological readiness, technical capacity, political risk, etc.) would most likely affect your decision making?

THE SCENARIOS

Scenario 1: Launching a Coordinated National Research Program on Climate Engineering

It is 2020 and you are a cabinet member for a large developed country in an administration that has committed itself to aggressive climate action consistent with the temperature targets of the Paris Climate Agreement. Nonetheless, your government's chief science advisor has produced a report duplicating similar analyses by other sources that it is highly unlikely that the world will achieve this target at the current rate of international action. These findings were received with intense criticism and concern, especially from countries considered to be the most vulnerable to climate change. The science advisor also warns that there is ample evidence that even with aggressive adaptation measures, your own country will suffer far higher economic and health impacts by the end of the century at the current rate of temperature increase than lower scenarios. In addition to scaling up other more conventional RD&D efforts, your government decides to initiate its first coordinated national research program on solar radiation management. You are given the lead responsibility for creating and executing it, with a multimillion USD budget for the first 5 years.

You create a team to set priorities for research on specific technological pathways with a focus on scaling up and enhancing modeling work, and design and execution of initial outdoor experiments. These experiments will be limited to testing physical properties for dispersion and control of substances that might be used in a deployable technology (or proxies for such substances) or testing prototypes of equipment that might be used in a deployable technology. You stipulate that these initial outdoor experiments must have minimal or no environmental impacts and can have no physical transboundary impacts or implications. They will not result in a temperature response. Nonetheless, once these plans become public, some governments and civil society organizations express grave reservations about the proposed research program. Some are skeptical that these outdoor experiments can be designed without creating environmental or human health risks. Others argue that experiments like these might set in motion political or economic forces that would bias future national and international decisions toward continuation and expansion of solar geoengineering research, or even a gradual slide into full-scale operational deployment, without adequate assessment, deliberation, or public consultation.

You have been asked by your head of government's science advisor to prepare and present a plan that responds to these concerns, which can include plans concerning the design, funding, oversight, or control of the research program to protect against such risks. We are your team of technical and policy advisors tasked with preparing this plan for you. What information would you like to have in hand about the risks and benefits of this research program in order to inform future directions including a response to public perceptions of the program? What options for responding to these concerns, if any, would you like us to prepare? Looking further down the road, what issues do you imagine would be most important for a research program to explore to inform a later discussion of large-scale outdoor experiments or possible deployment?

Scenario 2: Launching Field Tests with Possible Temperature Response and Transboundary Implications

It is 2027 and you are a senior official working directly for your head of government, whose responsibilities include running an interagency task force on solar radiation management in the country in Scenario 1. Your responsibilities include coordinating the ongoing development of research priorities for the program; ensuring that the program is producing usable, relevant science for policy makers; overseeing a domestic program which responds to public concerns about it; and coordinating the response of your government to the growing number of formal and informal international discussions on climate engineering. On the latter, while there is a system of voluntary reporting of climate engineering activities coordinated by the United Nations, there is as yet no other system of international governance for solar radiation management.

Several years after the initiation of your national research program, predictions are now nearly universal that stabilization of global average temperature at 1.5°C is out of reach, unless it follows an extended overshoot of 2°C or higher. The science agencies working in your research program have presented a plan to move to outdoor tests of possible deployable technologies. One team funded by this program proposes a limited test of a marine cloud brightening system to be conducted either within your country's maritime boundaries or over a small uninhabited Pacific island protectorate of your country, to measure the potential temperature response and durability of the system. Because your country has been compliant with the voluntary international transparency system, many close observers have anticipated a decision like this, and your country has received several formal diplomatic inquiries about whether you plan to execute such a test, expressing skepticism that impacts can be contained within your boundaries.

Your next step is to convene a cabinet level interagency meeting to make recommendations to the head of government on whether to move forward with this limited outdoor test. What items and questions do you want to put on the agenda for this meeting that the heads of the various science, domestic, and foreign policy agencies involved should be prepared to answer? What background information do you require to create this agenda?

Scenario 3: Regional Marine Cloud Modification

You are the Minister of Science for an island nation, which depends on its world-renowned reef system, rainforests, and wildlife to generate 50 percent of gross domestic product through tourism, with the remainder coming predominately from agriculture. Global efforts for climate mitigation continue, but your country is already experiencing a 3°C increase in average annual temperature. The combination of that temperature increase, corresponding local seawater warming and acidification, and poorly understood changes to ocean and atmospheric circulation seem to be negatively impacting your weather and natural resources. The reef system off your coast has decimated. Average annual rainfall has decreased 5 percent per year over the past 5 years, causing the rainforest to recede and decreasing crop yields. As a result, revenue from tourism and agriculture are falling off rapidly, causing an economic shock, lowering the standard of living of your citizens, and leading to increasing civil discord.

A proposal has been submitted to your government to institute a marine cloud modification program to manipulate cloud cover to reflect more sunlight back to space. The proponents claim that for a moderate but affordable investment, they can locally augment marine cloud formation, sustainment, and brightness. They claim that these cloud modifications can lower local average air temperatures, lower local seawater temperatures, at least partially restore rainfall, and enhance natural rainforest growth.

You have been asked by your president to prepare and present a decision memorandum to respond to this proposal. We are your team of technical and policy advisors, available to answer questions and provide data to help you prepare the memo; what would you like to know to prepare your draft decision memo?

Scenario 4: Developed Country Unilateral Response

You are a cabinet member for a large developed country. Global climate mitigation efforts have been under way for years, with mixed results. While global average warming has been held to 2°C over preindustrial levels, the regional impacts have varied dramatically. Your country has been particularly hard hit, with higher temperature rise, extended drought across your agricultural areas, and a series of natural disasters that have been made more intense and sometimes more frequent by climate change, affecting your major population centers. Your government has fully mobilized its resources and policies to counter the impacts, but global conditions are predicted to worsen for decades at least before they get better. It is becoming clear that even with full commitment of resources you will not be able to avoid catastrophic negative impacts across your population.

A consortium of domestic business and academic entities has drafted a proposal to implement a stratospheric aerosol injection program (spraying large quantities of inorganic particles, e.g., sulphur dioxide, into the upper layer of the atmosphere where they could reflect a small fraction of sunlight back into space). Based on the best-known science and modeling, they project that such a program can not only lead to a meaningful reduction in global average temperature but, if implemented to their specifications, may forestall further impacts while reversing some of the disproportionate impacts that your country has experienced. This kind of solar geoengineering effort has been debated in world forums for years but has been stymied by lack of consensus about risk and governance. The domestic proponents have done a detailed deployment analysis, showing that the cost of full-scale deployment is within reasonable means for your country and is actually a fraction of the projected cost of continued environmental adaptation efforts.

You have been asked by the president to prepare and present a decision memorandum to respond to this proposal. We are your team of technical and policy advisors, available to answer questions and provide data to help you prepare the memo. What would you like to know to prepare your draft?

Scenario 5: Global Coordinated Effort

You are the head of a national delegation to a multinational body. The world has reached net zero emissions target. Nevertheless, based on best model projections, global average temperatures will continue to increase, peaking in several decades.

A group of fellow member nations have submitted a proposal for a comprehensive solar geoengineering program of marine cloud brightening and stratospheric aerosol injection, with a goal of slowing the rise in global average temperature. The proposal is for the program to be administered and monitored by a committee of the multinational body.

You have been asked to prepare a policy position for your nation to support debate of the solar geoengineering proposal. We are your team of technical and policy advisors, available to answer questions and provide data to help you prepare the memo. What would you like to know to prepare your policy position? If the best scientific assessment of the proposed solar geoengineering program indicates that it is likely to have widely varying regional effects, with significant secondary impacts to local temperatures, cloud cover, rainfall, and biomass, how would your position change? What is the information required to identify and compensate for these varying regional secondary impacts?

APPENDIX D

Biographical Sketches of the Committee Members

CHRISTOPHER B. FIELD, Chair, (NAS) is the Perry L. McCarty Director of the Stanford Woods Institute for the Environment and Melvin and Joan Lane Professor for Interdisciplinary Environmental Studies. His research focuses on climate change, ranging from work on improving climate models, to prospects for renewable energy systems, to community organizations that can minimize the risk of a tragedy of the commons. Dr. Field was the founding director of the Carnegie Institution's Department of Global Ecology, a position he held from 2002 to 2016. He was co-chair of Working Group II of the Intergovernmental Panel on Climate Change (IPCC) from 2008 to 2015, where he led the effort on the IPCC Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation (2012) and the Working Group II contribution to the IPCC Fifth Assessment Report (2014) on Impacts, Adaptation, and Vulnerability. His widely cited work has earned many recognitions, including election to the National Academy of Sciences, the Max Planck Research Award, and the Roger Revelle Medal. Dr. Field's A.B. is in biology from Harvard University (1975). His Ph.D. is in biology from Stanford University (1981). For the National Academies, Dr. Field served as a member of the Board on Environmental Studies and Toxicology, and he has recently served on the Advisory Board for the Gulf Research Program, the Committee to Review the Draft Climate Science Special Report, and the 2017–2027 Decadal Survey for Earth Science and Applications from Space.

WILLIAM W. L. CHEUNG is a Professor and Canada Research Chair in Ocean Sustainability and Global Change at the Institute for the Oceans and Fisheries at the University of British Columbia (UBC). His main research areas include understanding the responses and vulnerabilities of marine ecosystems and fisheries to global change, exploring solution options to meet climate challenges in the ocean, and examining trade-offs in managing and conserving living marine resources. His works cut across multiple disciplines, from oceanography to ecology, economics and social sciences, and range from local to global scales. Dr. Cheung has published more than 150 peer-reviewed publications, including papers in leading international journals. Dr. Cheung is actively involved in international and regional initiatives that bridge science and policy. For instance, currently, he is a member of the Core Writing Team for the Synthesis Report in the IPCC's Sixth Assessment and a coordinating lead author for the IPCC Special

Report for the Oceans and Cryosphere in the Changing Climate. He was a Coordinating Lead Author of the Intergovernmental Platform on Biodiversity and Ecosystem Services (IPBES) and Global Biodiversity Outlook. He serves as Associate Editor for *Global Change Biology and Frontiers in Ecology and the Environment* (ESA Journal), and member of the editorial board of *Fish and Fisheries*, *Fisheries Oceanography*, and *Frontiers in Marine Sciences*, and as scientific advisors in a number of international and local organizations. Dr. Cheung obtained his B.Sc. in biology (1998) and M.Phil. (2001) from the University of Hong Kong. He worked for WWF Hong Kong for 2 years, after which he completed his Ph.D. in resource management and environmental studies at UBC (2007). From 2009 to 2011, he was Lecturer in Marine Ecosystem Services in the School of Environmental Sciences, University of East Anglia.

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MARION HOURDEQUIN is a Professor of Philosophy at Colorado College, where her research focuses on ethics and justice in relation to climate change and climate engineering; the social and ethical dimensions of ecological restoration; and environmental ethics. She has published work in a variety of journals, including *Environmental Ethics*; *Environmental Values*; *Ethics & the Environment*; *Ethics, Policy, & Environment*; *Science, Technology, & Human Values*; and *Ethical Theory and Moral Practice*. She is the author of *Environmental Ethics: From Theory to Practice* (Bloomsbury, 2015) and editor, with David Havlick, of *Restoring Layered Landscapes* (Oxford, 2016). Dr. Hourdequin is Vice President of the International Society for Environmental Ethics, and she currently serves as an Associate Editor for the journal *Environmental Values* and on the Editorial Board of *Environmental Ethics*. She earned her Ph.D. in philosophy at Duke University

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JAMES W. HURRELL joined Colorado State University faculty in September 2018 as the Scott Presidential Chair in Environmental Science and Engineering and a professor in the Department of Atmospheric Science. Dr. Hurrell is a former director of the National Center for Atmospheric Research (NCAR) in Boulder, Colorado, where he was a Senior Scientist in the Climate and Global Dynamics Laboratory (CGD). He is also the former Chief Scientist of Community Climate Projects in CGD, which includes the Community Earth System Model, and a former director of CGD and the NCAR Earth System Laboratory. Dr. Hurrell spent 1 year as a visiting scientist at the Hadley Centre for Climate Prediction and Research in the United Kingdom. Dr. Hurrell's research has centered on empirical and modeling studies and diagnostic analyses to better understand climate, climate variability, and climate change. He has authored or co-authored more than 100 peer-reviewed journal articles and book chapters, as well as dozens of other planning documents, workshop papers, and editorials. Dr. Hurrell has been extensively involved in the World Climate Research Programme (WCRP) on Climate Variability and Predictability (CLIVAR), including roles as co-chair of the Scientific Steering Group (SSG) of both U.S. and International CLIVAR, Chair of the Scientific Organizing Committee for the WCRP Open Science Conference (2011), and member of several other CLIVAR panels. He is currently a member and an officer of the Joint Scientific Committee of WCRP. Dr. Hurrell also has served the International Geosphere-Biosphere Programme as a member of the Global Ocean Ecosystem Dynamics SSG and the CLIVAR-PAGES (Past Global Changes) working group. Dr. Hurrell has been involved in assessment activities of the IPCC and the U.S. Climate Change Science Program. He has served on several National Research Council panels, and he has provided briefings and testimonies to both the U.S. Senate and the House of Representatives on climate change science.

ANDREW LIGHT is on leave as University Professor of Philosophy, Public Policy, and Atmospheric Sciences at George Mason University and Distinguished Senior Fellow in the Climate Program at the World Resources Institute in Washington, D.C. He is currently serving as Acting Assistant Secretary and Principal Deputy Assistant Secretary for International Affairs at the U.S. Department of Energy. From 2013 to 2016 he served as Senior Adviser and India Counselor to the Special Envoy on Climate Change and Staff Climate Adviser in the Secretary of State's Office of Policy Planning in the U.S. Department of State. In this capacity, he served on the senior strategy team for the UN climate negotiations, Director of the U.S.-India Joint Working Group for Combating Climate Change, and Chair of the Interagency Climate Working Group on the Sustainable Development Goals, among other duties. In recognition of this work, Dr. Light was awarded the inaugural Alain Locke Award for Public Philosophy from the Society for the Advancement of American Philosophy in March 2016 and, with the larger State Department team working on Paris, a Superior Honor Award from the U.S. Department of State in July 2016 for "contributions to the U.S. effort that made the 21st Conference of the Parties to the UN Framework Convention on Climate Change in Paris, where the landmark Paris Agreement was concluded, a historic success." In his academic work, Dr. Light is the author of more than 100 articles and book chapters, primarily on the normative dimensions of environmental policy, especially on climate change, restoration ecology, and urban sustainability, and he has authored, co-authored, and edited 19 books, including *Environmental Values* (2008), *Controlling Technology* (2005), *Moral and Political Reasoning in Environmental Practice* (2003), *Technology and the Good Life?* (2000), and *Environmental Pragmatism* (1996).

ALBERT LIN is a Professor of Law at the University of California (UC), Davis School of Law, where he specializes in environmental and natural resources law and also teaches evidence. His research interests include toxic torts and the relationship among emerging technologies, the environment, and law. Prior to joining the UC Davis faculty in 2003, Professor Lin was a trial attorney for the Environment and Natural Resources Division of the U.S. Department of Justice. He is also the author of *Prometheus Reimagined: Technology, Environment, and Law in the 21st Century* (University of Michigan Press, 2013) and the co-author of a widely used environmental law casebook. He received his J.D. from the University of California, Berkeley School of Law (1996), his M.P.P. from the Harvard Kennedy School (1995), and his B.S. in biology from Emory University (1992).

DOUGLAS MacMARTIN is a senior research associate in the Sibley School of Mechanical & Aerospace Engineering at Cornell University, and also a Visiting Researcher in Computing + Mathematical Sciences at the California Institute of Technology. Prior to joining Caltech in 2000, he led the active control research and development program at United Technologies Research Center. His primary research focus is on solar climate engineering (geoengineering), working to help develop the knowledge base to support informed future societal decisions. This includes using design principles to assess what outcomes are possible from different strategies, simulating projected climate impacts of those strategies, how to assess and manage uncertainty, as well as supporting ongoing efforts to develop governance. His research is supported by NSF and by the Cornell Atkinson Center for Sustainability (through multiple philanthropic donors). Dr. MacMartin's research interests also include applying engineering dynamics and feedback analysis to study climate dynamics more broadly, as well as control design for the Thirty Meter Telescope project. He joined the steering committee for the Geoengineering Modeling Research Consortium in late 2020, and will be a chair of the 2022 Gordon Research Conference on Climate Engineering. In 2017 he testified in the US Congress at a hearing on geoengineering, and has provided numerous briefings including to the UN Environment Program in 2018. He received his bachelors' degree in engineering science from the University of Toronto in 1987, and masters and Ph.D. degrees in aeronautics and astronautics from MIT in 1990 and 1992, respectively.

ROBERT McHENRY is the Chief Executive Officer of Bright Silicon Technologies, an optical microdevice manufacturing company. He is an expert in advanced technology system engineering and development, particularly with complex policy context. Mr. McHenry's prior affiliations include the Palo Alto Research Center (PARC) from 2012 to 2020, where he held a number of roles including leading its Energy Technology Program and publicly funded research and development business, and serving as corporate Chief Operating Officer. From 2007 to 2012, Mr. McHenry served as a Defense Advanced Research Projects Agency (DARPA) program manager, formulating and leading complex maritime and aerospace system demonstration programs that established new technological and policy approaches for highly autonomous platforms. Prior to DARPA he ran a defense technology development consultancy, and he started his career as a nuclear submarine officer in the U.S. Navy. Mr. McHenry holds an M.S. in nuclear engineering from the Massachusetts Institute of Technology, and a B.S. in marine engineering from the U.S. Naval Academy.

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Ricke recently served as a research associate in the Sibley School of Mechanical and Aerospace Engineering at Cornell University and a fellow at the Carnegie Institution for Science. Her publications on solar geoengineering have included physical science on the regional climate effects, economic analysis of the strategic incentives created by geoengineering impacts, and foreign policy analysis of the international relations implications of solar geoengineering. Her research develops methods for accounting for uncertainty and heterogeneity in both the effects of climate change and in preferences for how to address them. She has analyzed uncertainty associated with phenomena including ocean acidification's effects on coral reefs, the warming effect from an emission of carbon dioxide today, the social cost of carbon, and decadal climate variability's influence on international climate agreements. Dr. Ricke received her B.S. in Earth, atmospheric, and planetary science from the Massachusetts Institute of Technology and her Ph.D. in engineering and public policy from Carnegie Mellon University.

LYNN M. RUSSELL is Professor of Climate, Atmospheric Sciences, and Physical Oceanography at Scripps Institution of Oceanography, University of California, San Diego, where she has led the Climate Sciences Curricular Group since 2009. Her research focuses on the processes that control atmospheric aerosols and their cloud interactions. Dr. Russell's work uses both modeling and measurement studies of atmospheric particles and their chemical composition, and she has studied marine aerosols, flux and entrainment in the marine boundary layer, terrestrial biogenic particles, combustion emissions, and feedbacks between climate and particle sources. She completed undergraduate degrees at Stanford University and received her Ph.D. in chemical engineering from the California Institute of Technology for her studies of marine aerosols. Her postdoctoral work as part of the National Center for Atmospheric Research Advanced Studies Program investigated aerosol and trace gas flux and entrainment in the marine boundary layer. She served on the faculty of Princeton University in the Department of Chemical Engineering before accepting her current position at Scripps in 2003. Dr. Russell has been honored with young investigator awards from the Office of Naval Research, the National Aeronautics and Space Administration, Dreyfus Foundation, the National Science Foundation, and the James S. McDonnell Foundation, and she received the Kenneth T. Whitby Award from the American Association for Aerosol Research (AAAR) (2003) for her contributions on atmospheric aerosol processes. She was elected as a fellow of AAAR in 2014 and of the American Geophysical Union in 2017. Dr. Russell also served as a member of the National Academy of Sciences' Committee on Geoengineering Climate: Technical Evaluation and Discussion of Impacts, which produced two reports including *Climate Intervention: Reflecting Sunlight to Cool Earth* in 2015.

AMBUJ D. SAGAR is the Vipula and Mahesh Chaturvedi Professor of Policy Studies and the founding Head of the School of Public Policy at the Indian Institute of Technology

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PAUL O. WENNBERG (NAS) is R. Stanton Avery Professor of Atmospheric Chemistry and Environmental Science and Engineering and the Director of Ronald and Maxine Linde Center for Global Environmental Science at the California Institute of Technology. His research has improved our understanding of stratosphere and troposphere composition and anthropogenic impacts on climate, ozone depletion, and air quality. His laboratory has developed state-of-the-art in situ laboratory, airborne, and ground-based instrumentation. These instruments have participated in numerous field campaigns across the world. Dr. Wennberg's laboratory has also been at the center of the development of space- and ground-based measurement of greenhouse gases by remote sensing. He has helped to create the Total Carbon Column Observing Network (TCCON) that is used as the ground-based standard for measurement of greenhouse gas column abundance. Dr. Wennberg earned his B.A. in chemistry from Oberlin College in 1985 and his Ph.D. in physical chemistry from Harvard University in 1994. He was elected into the National Academy of Sciences in 2017 as a member of the geophysics section.

APPENDIX E

Acronyms and Abbreviations

AIE	aerosol indirect effect
AOD	aerosol optical depth
CAA	Clean Air Act
CBD	Convention on Biological Diversity
CCAC	Climate and Clean Air Coalition to Reduce Short-Lived Climate Pollutants
CCN	cloud condensation nuclei
CCT	cirrus cloud thinning
CDR	carbon dioxide removal
CLIVAR	Climate and Ocean—Variability, Predictability, and Change
CLRTAP	Convention on Long-Range Transboundary Air Pollution
CO_2	carbon dioxide
CPT	Climate Process Team
CWA	Clean Water Act
DECIMALS	Developing Country Impacts Modelling Analysis for Solar Radiation Management
DOE	U.S. Department of Energy
EIS	environmental impact statement
ENMOD	Convention on the Prohibition of Military or Any Other Hostile Use of Environmental Modification Techniques
EPA	U.S. Environmental Protection Agency
FAA	Federal Aviation Administration
FACE	Free-Air CO_2 Enrichment
FDAAA	Food and Drug Administration Amendments Act
FDAMA	Food and Drug Administration Modernization Act
FIREX-AQ	Fire Influence on Regional to Global Environments and Air Quality
GAO	U.S. Government Accountability Office
GeoMIP	Geoengineering Modeling Intercomparison Project
GEOSS	Group on Earth Observations
GHG	greenhouse gas

GLENS	Geoengineering Large Ensemble
GT	gigaton
IAC	InterAcademy Council
IAM	integrated assessment model
IAP	InterAcademy Partnership
IAP2	International Association for Public Participation
ICH	International Council for Harmonisation of Technical Requirements for Registration of Pharmaceuticals for Human Use
ICMJE	International Committee of Medical Journal Editors
ICTRP	International Clinical Trials Registry Platform
INP	ice nucleating particle
IP	intellectual property
IPCC	Intergovernmental Panel on Climate Change
IR	infrared
ISC	International Science Council
ISSCR	International Society for Stem Cell Research
LBA	Large-Scale Biosphere-Atmosphere Experiment in Amazonia
LC/LP	London Convention and London Protocol
LES	large eddy simulation
MCB	marine cloud brightening
MLS	Microwave Limb Sounder
MSPES	Multi-Site Public Engagement with Science–Synthetic Biology
NASA	National Aeronautics and Space Administration
NCAR	National Center for Atmospheric Research
NDC	nationally determined contribution
NEPA	National Environmental Policy Act
NGO	nongovernmental organization
NIH	National Institutes of Health
NOAA	National Oceanic and Atmospheric Administration
NPP	net primary production
NSF	National Science Foundation
NSTC	National Science and Technology Council
ODA	Ocean Dumping Act
OECD	Organisation for Economic Cooperation and Development

OSTP	Office of Science and Technology Policy
POC	pocket of open cells
R&D	research and development
RCP	Representative Concentration Pathway
RF	radiative forcing
RRI	responsible research and innovation
SAI	stratospheric aerosol injection
SCAR	Scientific Committee on Antarctic Research
SCoPEx	Stratospheric Controlled Perturbation Experiment
SDGs	United Nations Sustainable Development Goals
SG	solar geoengineering
SPICE	Stratospheric Particle Injection for Climate Engineering
SRM	solar radiation management
SRMGI	Solar Radiation Management Governance Initiative
SSP	Shared Socioeconomic Pathway
TRIPS	Trade-Related Aspects of Intellectual Property Rights
UN	United Nations
UNCLOS	UN Convention on the Law of the Sea
UNEA	UN Environment Assembly
UNEP	UN Environment Programme
UNESCO	UN Educational, Scientific and Cultural Organization
UNFCCC	UN Framework Convention on Climate Change
USDA	U.S. Department of Agriculture
USGCRP	U.S. Global Change Research Program
UT	upper troposphere
UV	ultraviolet
WCRP	World Climate Research Programme
WHO	World Health Organization
WIPO	World Intellectual Property Organization
WMO	World Meteorological Organization
WMRA	Weather Modification Reporting Act