CONGRESSIONALLY MANDATED RESEARCH PLAN AND AN INITIAL RESEARCH GOVERNANCE FRAMEWORK RELATED TO SOLAR RADIATION MODIFICATION

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About This Report

This Research Plan was prepared in response to a requirement in the joint explanatory statement accompanying Division B of the Consolidated Appropriations Act, 2022, directing the Office of Science and Technology Policy (OSTP), with support from the National Oceanic and Atmospheric Administration (NOAA), to provide a research plan for "solar and other rapid climate interventions."

The Congressional directive also requests that OSTP develop a "research governance framework to provide guidance on transparency, engagement, and risk management for publicly funded work in solar geoengineering research." An initial Research Governance Framework is included in part I of this report. This initial framework provides important context for the Research Plan. While key concepts in the framework, such as transparency and international cooperation, are reflected in the Research Plan, the Research Plan itself does not focus on issues of research governance.

This document focuses on atmospheric-based approaches to solar radiation modification (SRM), specifically stratospheric aerosol injection (SAI) and marine cloud brightening (MCB), following the recent and extensive 2021 National Academies of Sciences, Engineering, and Medicine (NASEM) report, *Reflecting Sunlight: Recommendations for Solar Geoengineering Research and Research Governance*.[1] Also following the approach of the 2021 NASEM report, this Research Plan mentions cirrus cloud thinning (CCT), even though this works by increasing outgoing thermal radiation and hence is not strictly speaking SRM. There is relatively little work to date on CCT, and this Plan's treatment of it reflects that paucity of knowledge.

This Research Plan does not consider space-based approaches to SRM (commonly, "mirrors in space"), nor local-scale measures to increase surface reflectance (e.g., "white roofs"). The focus on atmospheric approaches also follows from their greater near-term feasibility relative to space-based approaches, and the greater governance challenges of atmospheric approaches—which inherently have significant trans-boundary impacts—relative to building-scale albedo modification.

Consideration of both societal and scientific dimensions as part of a research agenda is critical to providing decision-makers with the fullest possible scope of understanding. Furthermore, due consideration of these factors may reduce the risk that research is perceived as a step towards inevitable deployment of SRM. Societal dimensions include socioeconomic benefits and risks of SRM relative to those of climate change itself. Examples of societal dimensions include environmental justice, effects on geopolitical stability, implications for other aspects of climate policy (e.g., mitigation and adaptation), tolerance of risks which may not be well characterized, issues of public perception and acceptance, and more. Scientific dimensions include new and continued ground-based, airborne, and space-based observations; improving global modeling of SRM approaches and scenarios; the need for laboratory research and outdoor experiments; the ability to detect global or regional SRM deployments; and development of scenarios for SRM.

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[1] National Academies of Sciences, Engineering, and Medicine. (2021a). *Reflecting Sunlight: Recommendations for Solar Geoengineering Research and Research Governance.* Washington, DC: The National Academies Press. https://doi.org/10.17226/25762

This Research Plan focuses on improving understanding of the potential impacts of SRM, rather than on technologies needed for deployment. Much of this research would contribute to our ability to understand basic climate processes and effects of human greenhouse gas emissions, as well as outcomes of SRM. This Plan draws from the published literature on SRM, research currently underway, and other reports identifying priorities for SRM research. This Plan will require updating as knowledge grows in this dynamic area.

While this Research Plan focuses primarily on *what* research would be performed, it also briefly discusses aspects of *how* that research would be performed, specifically the value of coordination of Federal research and international cooperation in SRM research.

In addition to Federal input from ten agencies, the Research Plan draws from the select engagement with stakeholder groups and the public, including inputs collected through a Request for Comment.[2]

Importantly, the issuance of this report does not signal any Executive Branch policy decision(s) regarding SRM. The report is only a response to Congressional directive. Any future decisions around Federal SRM activities, including SRM research, must be considered in the broader context of scientific and societal factors, Administration priorities, and available resources.

Suggested Citation

OSTP. (2023). Congressionally Mandated Research Plan and an Initial Research Governance Framework Related to Solar Radiation Modification. Office of Science and Technology Policy, Washington, DC, USA.

About the Office of Science and Technology Policy

The Office of Science and Technology Policy (OSTP) was established by the National Science and Technology Policy, Organization, and Priorities Act of 1976 to provide the President and others within the Executive Office of the President with advice on the scientific, engineering, and technological aspects of the economy, national security, homeland security, health, foreign relations, the environment, and the technological recovery and use of resources, among other topics. OSTP leads interagency science and technology policy coordination efforts, assists the Office of Management and Budget with an annual review and analysis of federal research and development in budgets, and serves as a source of scientific and technological analysis and judgment for the President with respect to major policies, plans, and programs of the federal government. More information is available at http://www.whitehouse.gov/ostp.

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[2] White House Office of Science and Technology Policy. (3 March 2023). *Request for Input to a Five-Year Plan for Research on Climate Intervention*. https://www.whitehouse.gov/ostp/legal/

Executive Summary

A program of research into the scientific and societal implications of solar radiation modification (SRM) would enable better-informed decisions about the potential risks and benefits of SRM as a component of climate policy, alongside the foundational elements of greenhouse gas emissions mitigation and adaptation. Such a research program would also help to prepare the United States for possible deployment of SRM by other public or private actors. A research program characterized by transparency and international cooperation would contribute to a broader basis of trust around this issue.

The potential risks and benefits to human health and well-being associated with scenarios involving the use of SRM need to be considered relative to the risks and benefits associated with plausible trajectories of ongoing climate change not involving SRM. This "risk vs. risk" framing, along with cultural, moral, and ethical considerations, would contribute to the necessary context in which policymakers can consider the potential suitability of SRM as a component of climate policy.

By their fundamental nature, the current suite of potential SRM methods would not simply negate (explicitly offset) all current or future impacts of climate change induced by increased atmospheric greenhouse gas concentrations. They would introduce an additional change (an alteration of solar energy at scales determined by the particular SRM method) to the existing, complex climate system, with ramifications which are not now well understood.

A research program aimed at **improving quantification of the effects of potential SRM methods implementation on the Earth system would involve observations, experimentation, and modeling.**

Research would be intended to address knowledge gaps and build understanding to aid decision-making and policymaking. Because such decisions would involve important societal dimensions, **any research program should encompass the societal as well as the scientific dimensions of SRM**, including cross-disciplinary research. Efforts in this area also would help to foster advances in understanding of the human consequences of climate change, independent of SRM.

Any program of research into SRM would be characterized by transparency, oversight, safety, public consultation, international cooperation, and periodic review, as outlined in a research governance framework.

Physical Aspects of Solar Radiation Modification

Observations from instruments on ground-based, airborne, and spaceborne instruments support understanding of the physical processes and outcomes associated with SRM. These include observations related to atmospheric composition (gases and aerosols), aerosol–cloud interactions, chemistry, dynamics, radiation, short-term and long-term trends, and seasonal variability.

Observations from spaceborne platforms (satellites) have a unique role in providing continuous global observations of the background and perturbed atmosphere. **Maintaining key satellite**

measurements is important for SRM research as well as for our broader understanding of Earth system processes.

Key research objectives for improving global modeling of SRM scenarios would include: increase the number and diversity of models that can conduct realistic SRM simulations; include a range of model types from process-resolving models to global climate models; assess the climate response to SRM across multiple global climate models, scenarios, and strategies; perform sensitivity studies to assess the surface cooling effectiveness of various SRM strategies; use global models to study how SRM would affect aspects of climate that drive societal impacts; and assess the risks associated with sudden termination of SRM.

Outdoor experiments would be valuable in combination with model and laboratory studies for understanding the processes involved with potential SRM deployment. Outdoor experiments would benefit from development and testing of aerosol injection technologies, observing systems, and analysis tools.

The ability to detect any global or regional SRM deployments would be of value for decision-making. Verifying a deployment—whether carried out covertly or openly—over the short-and long-term would occur by measuring and monitoring the characteristics of the deployment, while assessing the intended and unintended physical, environmental, and societal outcomes.

An international scientific assessment of the state of understanding of SRM methods would be valuable in establishing a common understanding and frame of reference for what is known and not known regarding this topic. The scope of an assessment, if intended to be of value to decision-makers, should include international and privately funded research, as well as any outdoor experiments conducted to date.

Development of Scenarios for Solar Radiation Modification

Development of a standard set of SRM scenarios would be an important integrating aspect of a comprehensive research program. A set of scenarios should include those carefully designed to produce specific climate outcomes (e.g., “peak-shaving” or cooling the Arctic and/or other regions), as well as those that might be implemented without having been carefully designed. SRM scenario development is an iterative process where scenarios are periodically revised based on updated policy choices, new observations, and improved process-based understanding.

Since SRM is intended to reduce risks associated with climate change**, a research program would most usefully assess risks and benefits associated with SRM scenarios in comparison to risks associated with plausible climate change scenarios not involving SRM.**

Socioeconomic and Ecological Outcomes

Decisions concerning whether and how to deploy SRM should be based upon an understanding of the risks and benefits to human health and well-being of its implementation relative to those anticipated under the current climate change trajectory. Of particular importance is consideration of potential jeopardy to diverse communities and intergenerational equity.

Cultural, moral, and ethical considerations are often overlooked in model-based evaluations and may be equally, if not more, important to different communities. In addition to physical scientists and engineers, philosophers and social scientists are needed to help answer questions related to the human dimensions of climate change and efforts to manage that change through SRM.

There is a potential for adverse outcomes to ecosystems and the services they provide with the implementation of SRM, but the nature and intensity of these outcomes—in comparison to those in scenarios without SRM—remain unclear, particularly over the long time periods anticipated in many scenarios. **Further assessment of outcomes to ecosystems in SRM scenarios relative to those in scenarios without SRM is needed.**

Climate change raises geopolitical risks. SRM deployment could also carry significant geopolitical risks. **Research into the geopolitical ramifications of SRM would be aimed at reducing the likelihood and/or severity of these risks.**

International Cooperation on Solar Radiation Modification Research

If Federal science agencies were to support a large-scale program of SRM research, **they could consider engaging in appropriate international cooperation.** International cooperation could promote knowledge gains, a common international understanding of research needs and results, resource savings, socializing best practices (such as acting with full transparency), and reducing the prospect of irresponsible experimentation and/or deployment.

Cooperation could involve one or more areas of SRM-related research and could take various forms, ranging from modest (e.g., an exchange of experts) to extensive (e.g., an international consortium).

Potential cooperation partners could be engaged based on any number of criteria or perceived benefits, including countries with expertise, available funding, or capacity in a particular area, countries with limited opportunities or capacity in a certain area, and countries with access to particular ecosystems (e.g., the ocean or the Arctic).

Research Coordination

Any large-scale, multi-agency Federal research program into SRM should be coordinated by the U.S. Global Change Research Program. This coordination role is currently mandated by the Global Change Research Act of 1990 and would apply to all Federally funded research into SRM, whether performed domestically or internationally, and whether involving natural or social science. Ongoing research into SRM involving the National Oceanic and Atmospheric Administration (NOAA), the National Aeronautics and Space Administration (NASA), and the Department of Energy (DOE) has been coordinated by the participating agencies.

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I. Initial Research Governance Framework

As outlined in the joint explanatory statement accompanying Division B of the Consolidated Appropriations Act for Fiscal Year 2022, Congress requested that an interagency working group "should establish a research governance framework to provide guidance on transparency, engagement, and risk management for publicly funded work in solar geoengineering research." This document describes an initial approach the Executive Branch could take to establish that framework: Further development and evolution of related policies may be pursued, as appropriate.

The Biden-Harris Administration strongly affirms that climate change is one of the greatest challenges facing the world, particularly those countries and communities most vulnerable to its adverse effects. Immediate, sustained, and effective reductions of global greenhouse gas emissions are required to slow the pace of climate change and reduce the risk of crossing critical and potentially catastrophic thresholds in the global climate system. These reductions must occur while robust adaptation is accelerated and while capabilities in effective and responsible carbon dioxide removal, such as direct air capture and permanent sequestration, are pursued vigorously.

The Administration also recognizes that there is growing interest and investment in research on actions that, together with mitigation measures, could limit temperature increase and thereby help address the risks of climate change, including potential tipping points and overshoot scenarios. For example, academia, philanthropy, and the private sector have examined preliminary applications of climate intervention techniques, such as stratospheric aerosol injection and marine cloud brightening (techniques categorized as "solar radiation modification," hereafter SRM), intended to rapidly limit temperature increase. Alongside the potential benefits of such actions, serious concerns have been raised about the potential outcomes of SRM. These unknowns, and the ever-evolving understanding of complex Earth systems, provide a compelling case for research to better understand both the potential benefits and risks.

The State of Knowledge and Current Executive Branch Action

The risks of inaction to reduce greenhouse gas emissions quickly and significantly and limit warming to 1.5°C above preindustrial levels are increasingly clear. This urgency warrants additional research to evaluate the efficacy, trade-offs, or other relevant considerations of SRM. In some cases, research may need to be undertaken with guardrails that acknowledge relevant concerns, balance the risks and need to address unknowns, and seek to avoid or minimize undesirable outcomes of both such research and climate impacts. The below five-year Research Plan—mandated by Congress—highlights some of the key knowledge gaps and priority topics for potential research. Discussions on SRM research, including the submission of the five-year Research Plan to Congress, should not be interpreted as endorsement of implementation of SRM.

The U.S. Government is engaged in a subset of SRM research activities including modeling, measurements and monitoring, and laboratory research—all of which occur within existing authorizations for Federal science agencies. Several agencies have also for years been conducting background research on fundamental climate processes that are important to understanding climate change, generally, and that research also has relevance to research concerning SRM (e.g., understanding the impact of volcanic forcing and natural analog systems, cloud–aerosol interactions, etc.). Existing research is not a preparatory measure for deployment, and the U.S. Government is not currently engaged in outdoor testing or deployment.

Governing Research Responsibly

In addition to what research to conduct, the Biden-Harris Administration seeks to ensure that how research is conducted meets the high standards it has set in advancing its unprecedented and ambitious climate and clean energy strategies. An interagency group has begun considering the importance of ensuring these high standards as they relate to SRM activities going forward. The following key points describe an initial approach the Executive Branch would take to that framework.

1. The U.S. Government will model responsible behavior through well governed and transparent research programs, including reporting, data sharing, and, as appropriate, regulations or rulemaking.
2. The U.S. Government will encourage other countries and non-Federal entities to share research plans and results, in line with principles of open science and transparency.
3. Federal science agencies[3] commit—and encourage non-Federal entities to commit—to promoting open scientific research aligned with F.A.I.R.E.R. (Findable, Accessible, Interoperable, Reproducible, Equitable, and Responsible) principles of data and data use.
4. The U.S. Government will seek to ensure transparency, oversight, safety, public and Tribal consultation, and periodic review of future research governance standards to allow governance to co-evolve with research findings. New knowledge and capabilities may present unforeseen circumstances that require new guidance and/or governance mechanisms.

International Cooperation

As elaborated in the Research Plan below, there are numerous ways in which the United States might engage in cooperation with international partners and the global scientific community on SRM research, and these can vary according to scope, type, forum, and potential partners for such cooperation.

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[3] The relevant Federal science agencies are the National Oceanic and Atmospheric Administration (NOAA), the National Aeronautics and Space Administration (NASA), the National Science Foundation (NSF), the U.S. Geological Survey (USGS), the Department of Energy, in particular the Office of Science and their National Laboratories (DOE), and the National Institutes of Health (NIH).

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II. Research Plan

Introduction

Solar radiation modification (SRM) is a potential complement to other tools available to address climate change: mitigation of greenhouse gas emissions, removal of carbon dioxide (CO2) from the atmosphere, and adaptation to existing and expected changes in climate. SRM offers the possibility of cooling the planet significantly on a timescale of a few years.[4] Such cooling would tend to reverse many of the negative consequences of climate change, albeit with ramifications which are now poorly understood. Interest in SRM is heightened as greenhouse gases continue to accumulate in the atmosphere and as science tells us more about the risks associated with exceeding global temperature targets.[5] At the same time, deployment of SRM would inevitably involve its own risks, almost all of which are poorly understood and some of which are unknown.

Science tells us that SRM would not simply undo all of the negative consequences of human greenhouse gas emissions. SRM would not ameliorate most of the impacts of ocean acidification, which is primarily driven by rising atmospheric carbon dioxide levels, nor eliminate the tendency for fossil fuel burning to worsen air quality. In addition, limited research suggests that the use of SRM might result in environmental impacts, as well as climate variability and extremes which are distinct from those in any climate without SRM.[6] Finally, SRM might halt but would not result in the rapid reversal of some important manifestations of climate warming, such as loss of land ice and greenhouse gas emissions from thawing permafrost. More fundamentally, greenhouse gases warm the climate by blocking a portion of outgoing longwave radiation that would otherwise be emitted into space. By contrast, SRM cools the climate by reflecting a greater amount of incoming solar (shortwave) radiation back into space. Because these are different physical mechanisms, an environment with SRM would be different from any without it.[7] Improving understanding of these differences would be an important aim of any SRM research program.

Furthermore, SRM would affect other aspects of the physical environment besides climate. Stratospheric aerosol injection (SAI), for example, can alter stratospheric heating, circulation,

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[4] National Academies of Science, Engineering, and Medicine. (2021a). *Reflecting Sunlight: Recommendations for Solar Geoengineering Research and Research Governance.* Washington, DC: The National Academies Press. https://doi.org/10.17226/25762

[5] E.g., Armstrong McKay, D.I., Staal, A., Abrams, J., Winkelmann, R., Sakschewski, B., Loriani, S., Fetzer, I., Cornell, S., Rockström, J., and Lenton, T. (2022). Exceeding 1.5°C global warming could trigger multiple climate tipping points. *Science*, *377*(6611). https://doi.org/10.1126/science.abn7950

[6] Muthyala, R., Bala, G., and Nalam, A. (2018). Regional scale analysis of climate extremes in an SRM geoengineering simulation, Part 1: precipitation extremes. *Current Science*, *114*(5), 1024-1035. https://dx.doi.org/10.18520/cs/v114/i05/1024-1035; Muthyala, R., Bala, G., and Nalam, A. (2018). Regional scale analysis of climate extremes in an SRM geoengineering simulation, Part 2: temperature extremes. *Current Science*, *114*(5), 1036-1045. https://dx.doi.org/10.18520/cs/v114/i05/1036-1045

[7] National Academies of Sciences, Engineering, and Medicine. (2021a). *Reflecting Sunlight: Recommendations for Solar Geoengineering Research and Research Governance.* Washington, DC: The National Academies Press. https://doi.org/10.17226/25762

and chemistry (including accelerating ozone depletion); SRM would likely also affect ecosystem functioning like net primary productivity and more integrative aspects of ecosystems like biodiversity, for example, because SRM may increase the proportion of diffuse rather than direct incoming solar radiation. These effects would be distinct from the impacts of increased greenhouse gases.

When considering these and other environmental and societal consequences and risks associated with scenarios involving SRM, it is essential to assess these in comparison to consequences and risks associated with plausible alternative scenarios—policy scenarios with different mixes of mitigation and adaptation measures, but without SRM. This is known as a "risk vs. risk" analysis. Climate change is already having profound effects on the physical and natural world, and on human well-being, and these effects will only grow as greenhouse gas concentrations increase and warming continues. A statement to the effect that SRM increases or decreases certain risks is meaningful only if it is clear which SRM scenario and which alternative scenario are considered. While it can be useful to compare the risks of increased greenhouse gases alone or in conjunction with SRM to the risks of a preindustrial climate, it is important to keep in mind that a preindustrial climate is not a plausible future scenario.

Societal consequences of the potential use of SRM follow from its real and perceived physical consequences, hence this Plan starts with the research needed to improve understanding of the climatic and other environmental consequences (e.g., effects on atmospheric chemistry) of SRM, and to detect deployment of SRM. This includes observations and modeling as well as laboratory and outdoor experiments. These are the topics of Section A: Physical Considerations of SRM.

This report then introduces the concept of scenarios to guide, coordinate, and integrate many aspects of the SRM research agenda (Section B: Development of Scenarios for SRM). Section B presents scenario development as a primary research activity and outlines three of the most considered scenario strategies (global peak-shaving deployment, regional deployment, and unexpected deployment).

The concept of using scenarios and risk vs. risk analysis to frame SRM research activities is carried into Section C: Socioeconomic Considerations, which discusses research priorities related to impacts on food and water scarcity, human health, migration, environmental justice, ethics, geopolitical security, and other human considerations.

Finally, in Section D: International Cooperation on SRM Research and Section E. Coordination of Federally Funded Research into SRM, the Plan discusses international cooperation on research into SRM, as well as how any Federal SRM research would be coordinated. Conducting any SRM research in an institutional context which fosters transparency, cooperation, and sharing of observations and other research results would be key to building cooperation and trust on this issue.

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Section A. Physical Aspects of Solar Radiation Modification

Summary

Observations from ground-based, airborne, and spaceborne instruments support understanding of the physical processes and outcomes associated with SRM. These include observations related to atmospheric composition (gases and aerosols), aerosol–cloud interactions, chemistry, dynamics, radiation, short-term and long-term trends, and seasonal variability.

Observations from spaceborne platforms (satellites) have a unique role in providing continuous global observations of the background and perturbed atmosphere. **Maintaining key satellite measurements would contribute to SRM research**, as well as broader understanding of Earth system processes.

Key research objectives for improving global modeling of SRM scenarios include: increase the number and diversity of models that can conduct realistic SRM simulations; include a range of model types from process-resolving models to global climate models; assess the climate response to SRM across multiple global climate models, scenarios, and strategies; perform sensitivity studies to assess the surface cooling effectiveness of various SRM strategies; use global models to study how SRM would affect aspects of climate that drive societal impacts; and assess the risks associated with sudden termination of SRM.

Outdoor experiments would be valuable in combination with model and laboratory studies for understanding the processes involved with potential SRM deployment. Outdoor experiments would benefit from development and testing of aerosol injection technologies, observing systems, and analysis tools.

The ability to detect any global or regional SRM deployments would be of value for decision-making. Verifying a deployment—whether carried out covertly or openly—over the short-and long-term would occur by measuring and monitoring the characteristics of the deployment, while assessing the intended and unintended physical, environmental, and societal outcomes.

An international scientific assessment of the state of understanding of SRM methods would be valuable in establishing a common understanding and frame of reference of what is known and not known regarding this topic. The scope of an assessment, if intended to be of value to decision-makers, would include international and privately funded research, as well as any outdoor experiments conducted to date.

Context

This section discusses the physical basis of SRM and identifies a potential research agenda to advance understanding of the processes underpinning SRM and expected SRM deployment outcomes. Similar to the research agenda for advancing the understanding of climate change, the SRM research agenda emphasizes the need to improve understanding of basic physical and chemical processes, advance the capabilities of Earth system models, and support a suite of observational capabilities. Indeed, much of the research needed to better understand SRM would also contribute to our understanding of climate change.

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As defined in the Introduction, the environmental outcomes of SRM should be evaluated using a risk vs. risk approach of comparative analysis to alternatives, including the no-intervention alternative.

State of Understanding: Climate intervention has been a topic of research for several decades. Of a variety of proposed methods (Figure 1), stratospheric aerosol injection (SAI) and marine cloud brightening (MCB) currently have garnered the most interest because of a combination of projected feasibility and estimated cost. Volcanic eruptions, which are known to cool the Earth,[8] are natural analogs for SAI, while ship tracks over the ocean demonstrate the mechanism underpinning MCB. Cirrus cloud thinning (CCT), which cools the surface by allowing more terrestrial (longwave) radiation to escape to space,[9] has been explored using model simulations;[10] there are no known natural analogs. Substantial modeling efforts (e.g., the Geoengineering Model Intercomparison Project (GEOMIP)) have simulated both SAI and MCB in order to explore the various processes involved, and those efforts demonstrate the basic feasibility for cooling Earth's atmosphere within a few years.[11] Model-based studies have identified a number of potential unintended outcomes in the climate system from SAI implementation that would benefit from further research.

Understanding of SRM methods and outcomes, and the ability to accurately simulate SRM scenarios, is aided by international research aimed at improving our understanding of the background atmosphere and the climate system. Similarly, some research aimed primarily at investigating SRM would have broader value for understanding and modeling climate change. For example, focused research is being conducted by the NOAA Earth's Radiation Budget (ERB) program created in response to a Congressional directive to investigate background aerosol and aerosol–cloud processes that affect the reflectivity of the stratosphere and the reflectivity of the marine boundary layer.[12] Of particular importance to the ERB program are changes to the stratosphere from natural events and human influence from rockets, stratospheric aircraft, and intentional perturbations to reduce global temperatures. The ERB program has initiated a number of focused modeling, field observational, and laboratory activities that are relevant to the research agenda for SAI, MCB and CCT discussed below.

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[8] IPCC, 2013: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.* T. F. Stocker, et al. (Eds). Cambridge University Press, Cambridge, UK, and New York, NY, USA, 1535 pp. https://www.ipcc.ch/report/ar5/wg1/

[9] Because it does not work by reflecting sunlight, CCT is not strictly speaking an SRM method; however, we follow the practice of NASEM (2021a) and other recent reports by considering CCT along with SRM methods in this plan.

[10] Tully, C., Neubauer, D., Omanovic, N., and Lohmann, U. (2022). Cirrus cloud thinning using a more physically based ice microphysics scheme in the ECHAM-HAM general circulation model. *Atmos. Chem. Phys., 22*(17), 11455–11484. https://doi.org/10.5194/acp-22-11455-2022

[11] Kravitz, B., MacMartin, D. G., Visioni, D., Boucher, J. O., Cole, J. N. S., Haywood, J., Jones, A., Lurton, T., Nabat, P., Niemeier, U., Robock, A., Séférian, R., and Tilmes, S. (2021). Comparing different generations of idealized solar geoengineering simulations in the Geoengineering Model Intercomparison Project (GeoMIP). *Atmos. Chem. Phys., 21*(6), 4231–4247. https://doi.org/10.5194/acp-21-4231-2021

[12] NOAA Chemical Science Laboratory. (3 March 2023). *Earth's Radiation Budget.* https://csl.noaa.gov/research/erb/

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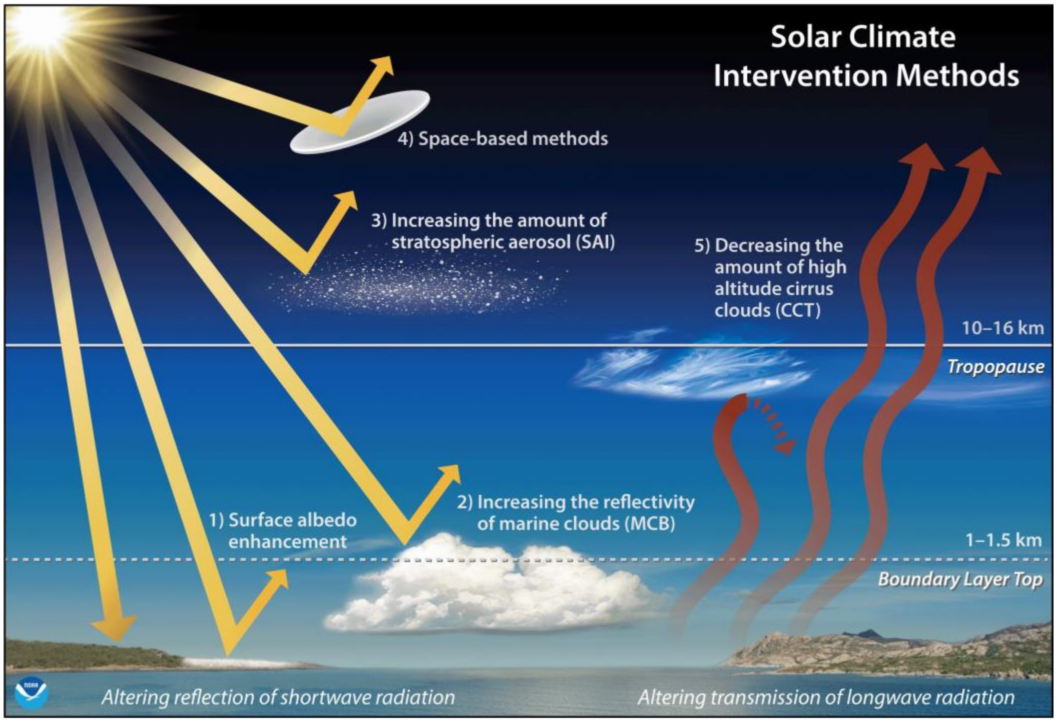

Figure 1. The most widely discussed forms of solar radiation modification increase the quantity of solar radiation reflected back into space, including surface albedo enhancement, marine cloud brightening (MCB), stratospheric aerosol injection (SAI), and space-based methods. In contrast, cirrus cloud thinning (CCT) involves the reduction of cirrus clouds to increase the amount of terrestrial radiation "lost" from the Earth system. All these methods would alter fluxes of both longwave (red) and shortwave (yellow) light. Discussed in this document are the methods that involve injecting material into the atmosphere; increasing albedo using space-based mirrors or changing the Earth's surface are not considered here. Credit: Chelsea Thompson, University of Colorado/CIRES and NOAA Chemical Sciences Laboratory.[13]

Major Gaps: An environmental assessment of SRM methods by international researchers would be a very important approach for sharing, synthesizing, and distilling current SRM knowledge to identify gaps and inform research planning and to translate findings for decision-makers; such an approach is described more in Section D.

The intended and unintended outcomes of SRM implementation depend strongly on the scenario and implementation strategy (e.g., latitudes, altitudes, amounts, and duration). Global climate models have been used to determine the outcomes of certain SRM scenarios and strategies. However, such models are not optimized to represent all the relevant processes associated with SRM deployment.

Atmospheric and ecological observations to validate the models used to estimate SRM effects are also insufficient because of platform availability or instrument limitations. Given these

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[13] Eastham, S., Doherty, S., Keith, D., Richter, J. H., and Xia, L. (2021). Improving models for solar climate intervention research. *Eos, 102*. https://doi.org/10.1029/2021EO156087

shortcomings, together with the uncertainty in reductions in future greenhouse gas (GHG) emissions, analysis of uncertainties in the projections would be valuable; this would involve the use of a variety of new and historical observations and models that may be combined with advanced data analytics (e.g., machine learning) that focus on incorporating multiple scales and weather, climate, chemistry, and biological processes.

A variety of unintended outcomes of SRM are not well understood, and there may be others of which we are not aware. The "known unknowns" include potential changes in precipitation patterns; stratospheric temperatures; ozone amounts; sea-level rise; patterns of climate variability; ocean acidification, productivity, and mixing; terrestrial vegetation; coral reefs; biodiversity; crop production; and ecosystems.[14] Model simulations show that the chemistry of the stratosphere may change, and atmospheric circulations may intensify in ways that may lead to seasonal-scale impacts such as more frequent extreme drought or precipitation events. Evaluating SRM outcomes and their associated risks would involve establishing the climate context of an SRM scenario, where the context includes the outcomes and risks in today's world and those projected for the future without SRM implementation.

Gaps remain in our understanding of how SRM deployments might irreversibly alter the Earth's climate system. The long-term risks of SRM deployments should be evaluated using a risk vs. risk approach, since SRM could potentially prevent or ameliorate some of the irreversible impacts of GHG-induced warming, such as sea-level rise, GHG emissions from thawing permafrost, and the loss of biodiversity.

Research Agenda

Information to understand the physical outcomes of SRM comes from three major areas of science effort: development and use of numerical models, identification and parameterization of processes, and acquisition of atmospheric observations. As shown in **Figure 2**, each category comprises a number of components with some overlap of SAI, MCB and CCT processes. SRM processes and outcomes occur on a range of temporal and spatial scales, similar to climate change processes and outcomes. Spatial scales range from the microphysical (less than a millimeter) to the global scale and have associated timescales that range from sub-second to decades and longer. These spatial scales vary from injection-plume evolution and cloud processes; to regional/meso scales that may alter temperature and precipitation patterns; to synoptic scales that impact weather systems; and finally, to global scales that can potentially alter the strength, variability, and wave mode characteristics of planetary circulations. The components, which are outlined in Figure 2 with their characteristic spatial and temporal scales, help inform the research areas outlined below.

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[14] Zarnetske, P.L., et al. (2021). Potential ecological impacts of climate intervention by reflecting sunlight to cool Earth. *Proceedings of the National Academy of Sciences, 118*(15). https://doi.org/10.1073/pnas.1921854118

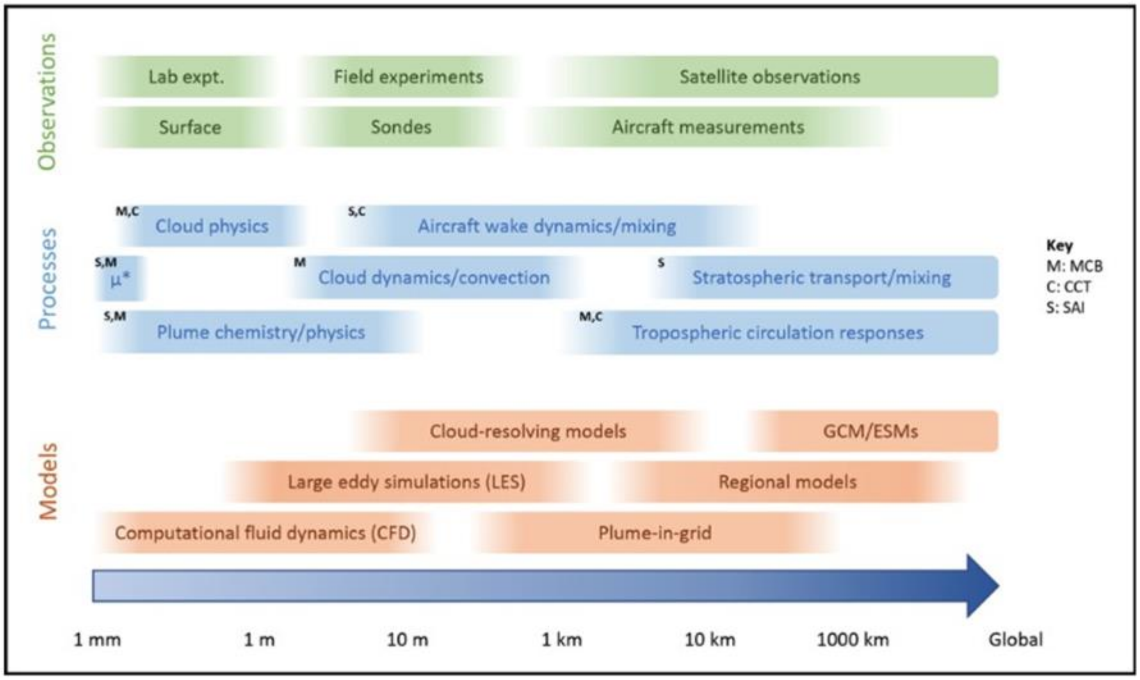

Figure 2. Understanding solar radiation modification involves modeling, process understanding, and observational challenges at multiple spatial scales. Light brown bars span the scales explicitly represented by types of models relevant to SRM. (GCM is global climate model; ESM is Earth system model.) Blue bars span scales of distinct sets of physical atmospheric phenomena that pose key challenges for SRM (μ* indicates aerosol chemistry and microphysics). The SRM methods most relevant to each process are noted in black type. Green bars span physical scales that can be directly observed by different approaches. Source: Eastham et al., 2021.

1. Assessing Solar Radiation Modification Outcomes with Models

Important objectives of an SRM research program would be improving existing models to enhance assessments of SRM outcomes and developing new modeling capacity applicable to specific aspects of SRM. As shown in **Figure 2**, there is a range of scales associated with SRM processes, and no one model resolves the full range of scales. Global models would be used to assess global radiative impacts, while regional and cloud resolving models would assess changes induced by MCB and CCT methods.

Highly idealized modeling studies[15] show that it may be theoretically possible to use SRM to return the global mean surface air temperature to the preindustrial level, though with some changes in regional temperature and precipitation patterns, as well as possible changes in extremes. A robust result comes from the analysis of multiple-model simulations in which a scenario with CO2 quadrupled relative to the preindustrial value (4 X CO2) is compared with another 4 X CO2 scenario with the solar constant reduced to simulate SAI returning Earth's atmosphere to the preindustrial radiative balance, as well as to a preindustrial climate scenario.

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[15] See, e.g., Tilmes, S., Richter, J. H., Kravitz, B., MacMartin, D. G., Mills, M. J., and Simpson, I. R. et al. (2018). CESM1(WACCM) stratospheric aerosol geoengineering large ensemble project. *Bulletin of the American Meteorological Society, 99*(11), 2361–2371. https://doi.org/10.1175/BAMS-D-17-0267.1

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The result shows that with SAI, the changes in regional climate and in climate extremes are smaller than for the 4 X CO2 case yet remain significant relative to preindustrial conditions.[16]

It is imperative to understand the potential changes in the frequency, severity, and causes of extreme events under different SRM scenarios, as well as changes in regional-scale climate. Every climate or Earth system model available today has limitations regarding its representation of key processes relevant to SRM scenarios and the quantitative representation of the intended and unintended outcomes of SRM. Hence, further research into model development within a multi-model and multi-ensemble framework, along with model inter-comparison, would further increase confidence in the modeled outcomes of SRM scenarios. Such studies would allow for a systematic effort to first identify and understand relevant small-scale processes, use high-resolution models to represent those processes, and then enable the creation of accurate parameterizations for global models. These studies would also afford an opportunity to evaluate the completeness of the known processes involved in SRM methods and to discover any previously unknown processes of importance. Improvement in the representation of small-scale processes for SRM analysis purposes would improve aerosol process representation overall, which would also likely improve models used for climate change studies.

SRM, and SAI in particular, has been studied using a limited number of global models, none of which were designed initially for SRM evaluation. In particular, the models don't resolve the microphysical and chemical processes that control the formation and distribution of SRM aerosols, nor any cloud–aerosol interactions. These limitations also affect the fidelity of climate system simulations not involving SRM. Dispersal of multiple plumes of injected aerosols, especially important when considering current SAI deployment scenarios, has not been explicitly resolved or parameterized in global models used for SAI studies. MCB has been examined using large-eddy simulation (LES) and cloud resolving models; these would be needed to properly simulate injection of aerosols into low-level marine clouds.[17] CCT has not been established as a viable SRM method and requires more research using realistic ice microphysics relevant to upper tropospheric clouds. More Earth system models with SRM-simulation capability and more evaluation of model results relevant to SRM would be beneficial.

2. Assessing and Reducing Uncertainty to Improve Projections

A systematic assessment of uncertainty from SRM model experiments would inform policymakers and prioritize the research activities most likely to improve projections of the outcomes of SRM implementation scenarios. This assessment would involve simulations across a hierarchy of models of varying resolution and complexity, comparing results across models of similar resolution and complexity, and comparing model results with observations. Model assessment would focus on increasing confidence and reducing uncertainty in model simulations. Confidence in models to accurately simulate the impacts of a possible SRM deployment can be increased by demonstrating—through comparison to observations—the model's fidelity in reproducing natural and non-natural analogs to SRM-related physical and chemical processes. These include observations of events which are analogs to SRM, as well as observations of

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[16] Curry, C. L. et al. (2014). A multimodel examination of climate extremes in an idealized geoengineering experiment. *J. Geophys. Res. Atmos., 119*(7), 3900–3923. https://doi.org/10.1002/2013JD020648

[17] Wood, R. (2021). Assessing the potential efficacy of marine cloud brightening for cooling Earth using a simple heuristic model. *Atmos. Chem. Phys., 21*(19), 14507–14533. https://doi.org/10.5194/acp-21-14507-2021

physical and chemical processes in the climate system that have particular relevance to SRM. In the case of SAI, process understanding is aided by the natural analogs of volcanic eruptions or pyrocumulonimbus (pyroCb) events in which the plumes of large wildfires reach the stratosphere. The analog for MCB is brightening of areas of marine boundary-layer clouds caused by ship emissions in the open ocean (ship tracks). Detailed, process-level observations of these natural analogs can be used to identify and remedy gaps in the representation of key processes, such as the parameterization of cloud–aerosol interactions, to reduce uncertainty and improve projections.

Confidence in projections of the future can be inferred by comparing results across a suite of models of similar resolution and complexity. Vetting models for accurate representation of processes important for SRM simulations would improve the comparison process. If all models include accurate representations of the key physical and chemical processes, higher levels of inter-model consensus provide higher confidence in the accuracy of the simulations. Among the suite of models being compared, greater weight might be assigned to the models that more accurately represent the relevant processes for the SRM strategy being considered, and thus reproduce relevant observations relatively better. This type of model weighting would need to be done carefully in order to yield improved projections of the future.[18]

Each model would include a host of parameterizations representing, among other things, cloud–aerosol processes that are fundamental to accurately projecting the climate impacts of an SRM deployment. Each of the multiple parameters has a range of possible values that is consistent with observations and theory. Model performance and the range of SRM climate outcomes can be assessed by measuring the sensitivity of model results to changing values of key parameters. These sensitivity studies not only provide an estimate of uncertainty but can also aid in determining combinations of parameter values to improve model projections. Distinct from sensitivity studies, the intrinsic uncertainty of SRM outcomes can be assessed through modeling studies in which the initial conditions of the Earth system simulation are changed slightly to allow various realizations of natural variability to develop.

It is important to point out that additional research does not lead linearly to increasing certainty. In many cases, new discoveries, or more sophisticated representations of physical processes in climate models, lead initially to increased uncertainty. Dramatic enhancement in the certainty of our ability to simulate Earth system processes is a long-range challenge.

3. Observations for Model Validation, Process Understanding, and Monitoring

Model evaluation and improvement involve observations and experiments, as noted above. A focus of the current ERB project is making the observations to allow for model evaluation and improvement. These and related studies and observations are fundamental to improve understanding of the present state of the atmosphere that would be perturbed by SRM methods. Uncertainties associated with aerosol and aerosol–cloud processes and the implications for

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[18] E.g., Wootten, A., Massoud, E., Waliser, D., and Lee, H. (2022). To weight or not to weight: assessing sensitivities of climate model weighting to multiple methods, variables, and domains. *Earth Syst. Dynam. Discuss.* [Preprint]. https://doi.org/10.5194/esd-2022-15; Knutti, R., Sedláček, J., Sanderson, B. M., Lorenz, R., Fischer, E. M., and Eyring, V. (2017). A climate model projection weighting scheme accounting for performance and interdependence. *Geophys. Res. Lett., 44*(4), 1909–1918. https://doi.org/10.1002/2016GL072012

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radiative forcing are still large.[19] In the case of SAI, there are significant differences across models in simulated radiative forcing from aerosol injections that are due to differences in the microphysical models used to represent aerosol processes. There are still significant uncertainties concerning how anthropogenic sulfur emissions at Earth's surface influence the background aerosol layer in the stratosphere.[20] An expansion of stratospheric and tropospheric observations related to key model parameters would be required, especially those related to composition (gases and aerosols), aerosol–cloud interactions, chemistry, dynamics, radiation, short-term and long-term trends, and seasonal variability. In the event of an SRM deployment, sustained regular observations would allow the monitoring of the evolution of the SRM material and its effectiveness.

Ground-based, airborne, and spaceborne platforms and associated instruments would be part of understanding SRM processes and possible deployments. Both types of platforms have made large contributions to Earth science in the troposphere and stratosphere over many decades and can be expected to make large contributions to SRM research going forward (**Figure 3**). Aircraft platforms afford instrument payloads direct access (i.e., *in situ* sampling) to the atmosphere from Earth's surface to the lower stratosphere, which is essential to diagnose and monitor atmospheric composition and the chemical and dynamical processes that control composition. Instruments orbiting in space have the advantage of continuous monitoring of Earth's atmosphere using a variety of remote-sensing methods. To date, instruments on both types of platforms have provided essential data to describe the background atmosphere and associated events and trends and thereby help document the changes brought about by climate change. Aircraft and spaceborne instrumented platforms would likely be essential tools for diagnosing, verifying, and monitoring outdoor experiments and any subsequent implementation of SRM methods.

Satellite measurements have provided stratospheric gas and aerosol measurements with high-altitude resolution for over 40 years. Certain measurement wavelengths, such as in the microwave region, have the advantage that enhancements in stratospheric aerosols from volcanos, wildfires, or SRM deployment do not interfere in the retrieval of trace gases. From U.S. satellites, vertically resolved stratospheric aerosol and ozone measurements with near-global coverage will continue in the foreseeable future from the Ozone Mapping and Profiler Suite (OMPS)-Limb instruments on board the NOAA operational polar-orbiting satellites. The Stratospheric Aerosol and Gas Experiment (SAGE) III/ISS instrument provides water vapor with limited spatial sampling and is expected to continue through the life of the International Space Station (ISS).

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[19] Lee, L. A., Reddington, C. L., and Carslaw, K. S. (2016). On the relationship between aerosol model uncertainty and radiative forcing uncertainty. *Proceedings of the National Academy of Sciences, 113*(21), 5820-7. https://doi.org/10.1073/pnas.1507050113

[20] Lelieveld J., et al. (2018). The South Asian monsoon—pollution pump and purifier. *Science, 361*(6399), 270-273. https://doi.org/10.1126/science.aar2501

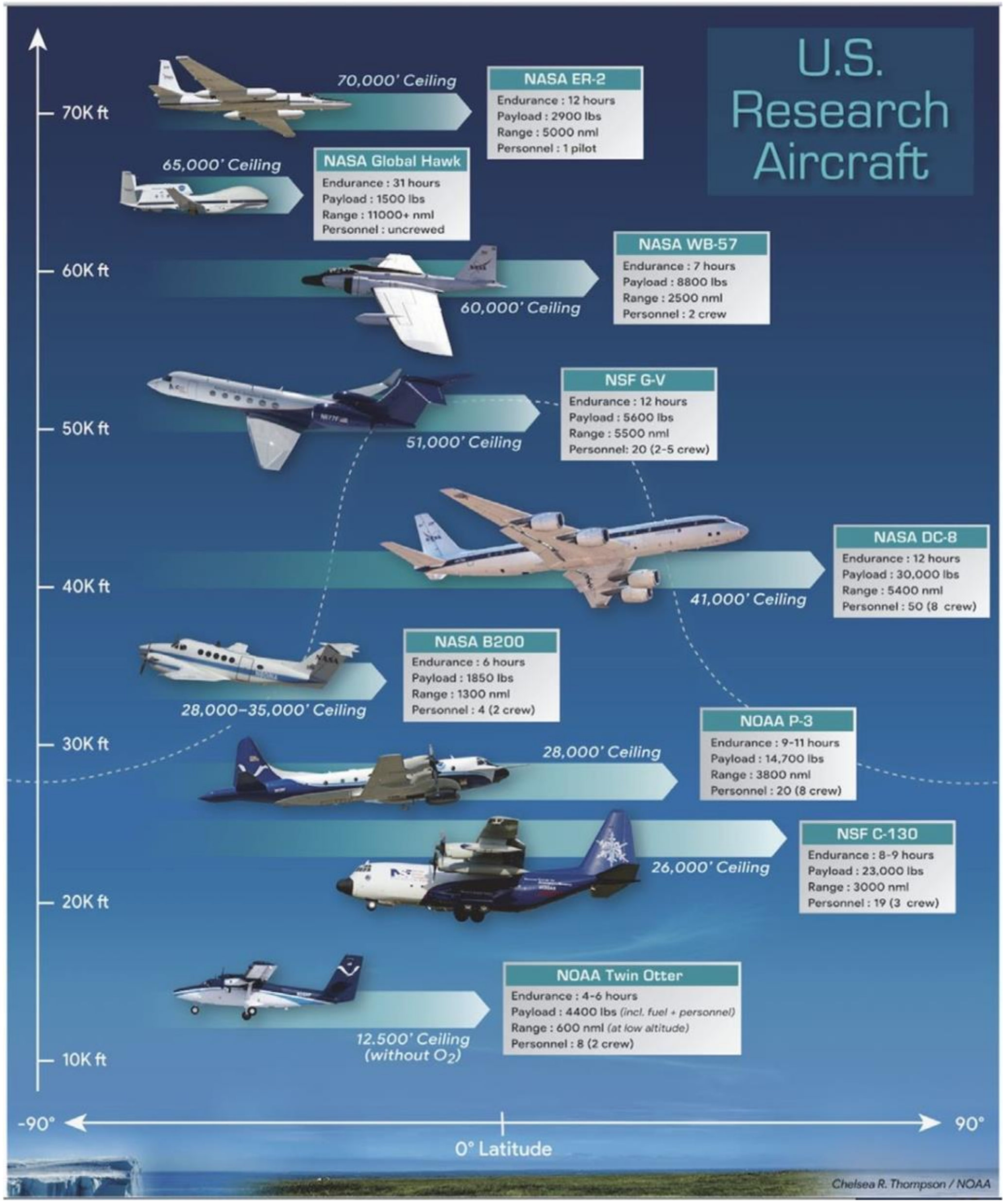

Figure 3. Examples of U.S. research aircraft with nominal performance specifications shown in order of maximum operating altitude vertically and nominal payload horizontally. The dashed line illustrates the approximate tropopause dependence on latitude. The U.S. and international fleet of research aircraft is far larger than shown here. Not shown are a variety of uncrewed low-altitude aircraft that are of potential value to MCB studies. NASA is operating Global Hawk Uncrewed Aircraft Systems (UAS) platforms that are not presently available for atmospheric research. Credit: Chelsea Thompson, NOAA.

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Figure 4. Example launch of a small (weather) balloon launch with a payload of *in situ* instruments for ozone, water vapor, and aerosol measurements. These balloons reach a maximum altitude of 30 km (100,000 ft) and telemeter data to the ground during flight since many payloads are not recovered. Source: NOAA Chemical Sciences Laboratory.

4. Advancing Understanding of Solar Radiation Modification Methods with Small-Scale Outdoor Experiments

For understanding the effectiveness and outcomes of potential SRM deployment, small-scale outdoor experiments would be of value in combination with model and laboratory studies.[21] While improved atmospheric models and expanded observations as described above would improve modeling of SRM deployments, small-scale outdoor experiments would serve to test the completeness and accuracy of SRM modeling. By affording comparisons of observations and modeling of real-world aerosol perturbations, outdoor experiments could provide important new knowledge that cannot be obtained by any other means, despite governance challenges. Observations in small-scale outdoor experiments would be critical for validating and advancing key chemical transport and microphysical aspects of SRM modeling. Of importance for SAI and MCB are, for example, aerosol microphysical processes, plume dispersion mechanics, atmospheric chemistry, atmospheric transport, albedo response, and delivery mechanisms.

While small-scale experiments improve our understanding of the effectiveness and outcomes of SRM deployments, further research and analysis would be needed to understand how a global- or

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[21] National Academies of Sciences, Engineering, and Medicine. (2021b). *Airborne Platforms to Advance NASA Earth System Science Priorities: Assessing the Future Need for a Large Aircraft.* Washington, DC: The National Academies Press. https://doi.org/10.17226/26079

regional-scale deployment would be conducted. For example, different platforms and technology could be required for a large-scale deployment. These activities are outside of the scope of this Research Plan.

Instrumented aircraft platforms and aerosol or aerosol-precursor injection systems would be needed in both SAI and MCB small-scale outdoor experiments. The effort to design, plan, coordinate, and execute these outdoor experiments is a multi-disciplinary, multi-year activity involving scientists, engineers, and technicians and one that spans multiple institutions and agencies.

For SAI experiments, of interest is how aerosols are formed and evolve in the real stratosphere in response to the injection of aerosols or aerosol-precursor gases (e.g., sulfur dioxide). A variety of aerosol materials could be examined. Detecting the radiative signature of the enhanced aerosol population is fundamental to understanding SAI.

For MCB, of interest is how marine boundary-layer clouds respond to injected aerosol(s) over a range of background aerosol and meteorological conditions. Systematically conducting controlled perturbation experiments would allow for building statistical relationships between aerosol perturbations, meteorological conditions, and cloud responses over a range of timescales. Measurement of radiative fluxes inside and outside of the perturbed region under a range of marine stratocumulus conditions would demonstrate the effectiveness of MCB.

The results of SAI and MCB small-scale outdoor experiments would provide dual benefits by substantially accelerating improvements in climate model representations of stratospheric aerosol and cloud-aerosol effects, thereby reducing the uncertainties in estimated aerosol climate forcings. A further benefit might come from enhanced preparedness and capabilities to sample analog events in the troposphere and stratosphere as discussed above.

5. Verifying and Monitoring Potential Solar Radiation Modification Deployment

It would be important to verify and monitor any SRM deployment over the short- and long-term by measuring and monitoring the characteristics of the deployment, and assessing the intended and unintended physical, environmental, and societal outcomes.

Detection of SRM implementation of SAI or MCB methods would require coordination of new and existing atmospheric observations and other information. For SAI, material injected into the stratosphere reflects sunlight, while remaining in the stratosphere for several years on average and spreading over the globe. Routine observations of stratospheric composition and detailed knowledge of stratospheric transport dynamics could allow early detection of large injections of aerosol and identification of injection locations. Hence, high-sensitivity baseline observations of key ranges of aerosol size, altitudes, and latitudes would be required for optimal early detection. Instruments in the United States and other regions operating on the ground, on board research aircraft, and on satellites have capabilities for this targeted detection. Orbiting remote-sensing instruments are especially important in early detection because of their continuous global observations of aerosols and key radiative species in the middle atmosphere (i.e., stratosphere and mesosphere). Observing instruments would also be valuable on short-duration and long-duration uncrewed (UAS) platforms operating in the stratosphere. Atmospheric aerosol and trajectory models would be required to assess the magnitude, location of injection, and future climate impact associated with anomalous aerosol observations in the stratosphere.

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Accurate and globally representative measurements and models of global or regional radiative flux through the atmosphere could also potentially detect an unanticipated, non-public SAI implementation.

Improving the ability to detect these relatively small changes in radiative flux driven by stratospheric composition would also aid in diagnosing and monitoring any publicly announced implementation of SRM.

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Section B. Development of Scenarios for Solar Radiation Modification

Summary

Development of a standard set of SRM scenarios would be an important integrating aspect of a comprehensive research program. A set of scenarios should include those carefully designed to produce specific climate outcomes (e.g., “peak-shaving” or cooling the Arctic and/or other regions), as well as those that might be implemented without having been carefully designed. SRM scenario development is an iterative process where scenarios are periodically revised based on updated policy choices, new observations, and improved process-based understanding.

Since SRM is intended to reduce risks associated with climate change, a research program would most usefully assess risks and benefits associated with SRM scenarios in comparison to risks associated with plausible climate change scenarios not involving SRM.

Context

An important aspect of an SRM research program would be developing a suite of SRM scenarios. Collectively, the scenarios would span the climate intervention scenarios that the international community might choose to analyze in the future. Key aspects of an SRM research program would be assessment of both the climatic and environmental impacts, as well as feasibility of implementation strategies, of specific SRM scenarios. The development of SRM scenarios would provide a process for the physical, biological, environmental, socioeconomic, ethical, and geopolitical aspects of SRM implementation to be considered within a holistic framework. The exploration of a set of scenarios would serve to coordinate and integrate activities across all aspects of SRM research, while ensuring that the knowledge gained improves the assessment of the most relevant intervention scenarios.

The outcomes of an SRM scenario depend on the background climate, level of warming being offset, and the implementation strategy—namely, the type of SRM deployed; the location, scale, and rate of deployment; duration; and other factors.[22]

A well-chosen set of scenarios would span the range of situations that decision-makers might need to consider. Insights gained through examination of a representative set of scenarios would provide improved understanding, which would be helpful in deciding whether and when to implement SRM and in reacting to contingencies. Contingencies that arise during the planning or implementation stages could lead to changes in the scenario objectives and associated strategies, and may require significant analysis to reassess benefits, costs, risks, and uncertainties. Performing research into a well-chosen set of scenarios would necessitate the development of tools and understanding which later might be quickly adapted to assess scenario contingencies.

The development and updating of SRM scenarios would be an integrating activity of a U.S. SRM research program and would support international cooperation and dialogue on SRM matters.

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[22] As stated in NASEM (2021a), “The [SRM] 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 would 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.”

Within the United States, the scenarios would help identify the most pressing research questions related to the physical, biological, environmental, socioeconomic, and geopolitical aspects of SRM methods. Internationally, the scenarios convey the motivation for undertaking research in a transparent and easy-to-understand manner. The scenarios would also serve as a vehicle to engage international partners who might wish to contribute to both the development and understanding of the scenarios.

Ideally, an SRM research program would periodically update the set of scenarios. In practice, therefore, the scenario design process and the broader research program would proceed as a coupled, iterative process in which each activity informs the other. Current understanding would inform the development of an initial set of scenarios; new understanding developed as a result of researching the diverse aspects of these scenarios would then inform the definition of new scenarios, and so on. As understanding and technology matures—and as international conditions evolve—entirely new scenarios might be developed. The cycle of scenario revision and research would allow the SRM research program to evolve while remaining focused and integrated.

All scenarios would be studied and evaluated using the risk vs. risk framework where costs, benefits, risks, and uncertainties of SRM deployment are measured in relation to a non-intervention baseline scenario.

Solar Radiation Modification Research Priorities for Scenario Development

The development and refinement of a suite of SRM scenarios is an important research priority to gain a comprehensive understanding of how SRM might affect the physical environment, as well as human and natural systems, and to maintain a cohesive SRM research program over the long term. At the same time, the design characteristics of SRM scenarios depend—in an iterative process—on the knowledge gained through this research. Specifically, the design of scenarios intended to produce specific climatic or environmental outcomes would require substantial understanding of the functional relationships between SRM strategies and the environmental responses.

An initial research priority for SRM scenario development would be assessing the existing scenarios used in the research community to simulate SRM deployments in contemporary models. A group of experts could be convened to define what constitutes an SRM scenario and conduct workshops and other community activities to ultimately propose a suite of SRM scenarios that takes relevant physical, biological, and socioeconomic research aspects of SRM into consideration, as well as identifying relevant non-intervention baseline scenarios. This SRM Scenario Development Group ideally would involve a dedicated and inter-disciplinary group of scientists and decision-makers with a range of expertise. Given the potential global nature of SRM deployment and its effects, an international process would be preferable to ensure global representativeness of the scenarios. An international process would also reinforce and exemplify the value of international cooperation and transparency on issues related to SRM. A portfolio of scenarios that is developed jointly by the global community as a shared investment would be an aid to SRM policy decisions.

The range of physical science expertise needed for SRM scenario development and refinement would include multiple disciplines in atmospheric and Earth system sciences, such as atmospheric composition, tropospheric and stratospheric chemistry, radiation, dynamics, aerosol composition and microphysics, the global carbon budget, climate system modeling and observation, and integrated assessment models (IAMs). Expertise in possible deployment technologies and strategies would also be needed to avoid wasting effort developing and studying scenarios that are not viable for implementation. At a higher level, understanding the potential long-term implications of SRM deployment requires input from experts in ecosystems, economics, decision processes, public health, social sciences, governance, history, ethics, environmental justice, and political science. Involving a wide range of experts in the scenario development and refinement process would accelerate the evaluation and use of the scenarios in IAMs that are used to develop scenarios of energy, land, emissions, and climate, and in impact models that use information from climate models to assess the implications for people and ecosystems. These IAM and impact model results would provide feedback into the scenario development process.

In accordance with the initial Governance Framework above, an SRM Scenario Development Group would be expected to be transparent in how the scenarios are developed and to solicit public and stakeholder comments on the provisional suite of scenarios and their associated strategies.

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Section C. Socioeconomic and Ecological Outcomes

Summary

The potential risks and benefits to human health and well-being associated with scenarios involving the use of SRM need to be considered relative to risks and benefits associated with plausible trajectories of ongoing climate change not involving SRM. This "risk vs. risk" framing, along with cultural, moral, and ethical considerations, would contribute to the necessary context in which policymakers can consider the potential suitability of SRM as a component of climate policy.

Decisions concerning whether and how to deploy SRM should be based upon an understanding of the risk and benefits to human health and well-being of its implementation relative to those anticipated under the current climate trajectory. Of particular importance is consideration of potential jeopardy to diverse communities and intergenerational equity.

Cultural, moral, and ethical considerations are often overlooked in model-based evaluations and may be equally, if not more, important to different communities. In addition to physical scientists and engineers, philosophers, ethicists, and other social scientists are needed to help answer questions related to the human dimensions of climate change and efforts to manage that change through SRM.

There is a potential for adverse outcomes to ecosystems and the services they provide with the implementation of SRM, but the nature and intensity of these outcomes—in comparison to those in scenarios without SRM—remain unclear, particularly over the long time periods anticipated in many scenarios. Further assessment of outcomes to ecosystems in SRM scenarios relative to those in scenarios without SRM is needed.

Climate change raises geopolitical risks. SRM deployment could also carry significant geopolitical risks. Research into the geopolitical ramifications of SRM would be aimed at reducing the likelihood and/or severity of these risks.

Context

The human consequences of an altered climate, today and in the future, are primary considerations for climate policies. Socioeconomic impacts are those human impacts that encompass both tangible economic and social factors, as well as factors that are difficult or, perhaps, impossible to quantify, such as intergenerational equity, identity, and values. Here the report discusses issues related to the human outcomes of potential deployment of SRM relative to the trajectory of climate change impacts and risks, and outlines research priorities related to the implications for human health and well-being, food and water scarcity, ecosystem services, geopolitical security, human social systems, and equity. Understanding these impacts is crucial to enable informed decisions around a possible role for SRM in addressing human hardships associated with climate change.

This section summarizes key knowledge gaps and research priorities related to potential socioeconomic and ecosystem risks and benefits of SRM, reviews what is known about public perceptions of SRM, and briefly discusses possible institutional approaches to performing research to close key gaps.

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State of Understanding

Research into SRM has been largely focused on natural science-based topics, examining the basic understanding of SRM approaches and their physical outcomes. The 2021 NASEM report, *Reflecting Sunlight*, reported that about 14% of studies on SRM published between 1983 and 2020 addressed the topics of economics, ecosystems and ecology, health, oceans, agricultural impacts, or Arctic impacts.[23] Research into the human dimensions of SRM impacts to date has been ad hoc and fragmented, rather than being the product of a comprehensive strategy; as a result, substantial knowledge gaps and uncertainties exist in many critical areas.[24] Research to understand the potential nature, magnitude, and distribution of SRM impacts on ecosystems, human health and well-being, political and economic systems, and other issues of social concern does not currently provide a sufficient basis for supporting informed decisions with regard to SRM implementation.

Examples of critical open questions regarding the potential of SRM to ameliorate adverse climate-driven human impacts may include to what extent could SRM:

- preserve human life;
- reduce climate-induced stress on ecosystems and biodiversity;
- preserve the reliability and nutritional value of agricultural regions;
- minimize water scarcity;
- reduce the risk of housing, insurance, and other market failures;
- bolster the weakest links in global and national supply chains;
- reduce climate-induced geopolitical stress in areas susceptible to political strife and potential conflict;
- preserve the integrity and function of physical infrastructure so it does not fail under climate stress;
- ensure continuation of ecosystem services and natural capital dividends; and
- improve sustainability by meeting current needs without compromising the ability of future generations to meet their own needs.

Depending on how it would be used, SRM holds the potential for a range of human impacts, from adverse to beneficial and real to perceived. Large historical volcanic eruptions can serve as natural analogs to understand the potential human impacts of SRM—in particular, stratospheric aerosol injection (SAI) scenarios—separately from the effects of increased atmospheric greenhouse gases. As would be the case for human deployments of SRM, the effects of volcanic eruptions and other proxies depend on the specifics of the event in question, and the outcomes of one event do not necessarily apply to others. As an example of one large event, the 1815 Tambora eruption cooled the Earth by 0.7°C and led to a "year without summer" (1816), altered

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[23] National Academies of Sciences, Engineering, and Medicine. (2021a). *Reflecting Sunlight: Recommendations for Solar Geoengineering Research and Research Governance.* Washington, DC: The National Academies Press. https://doi.org/10.17226/25762

[24] Ibid.

precipitation patterns,[25] disrupted monsoons,[26] and led to flooding that provoked crop failure, famine,[27] and the outbreak of disease.[28] Understanding these and other potential negative impacts of SRM is as important as understanding potential benefits. While limited work has been done to examine how SRM may alter precipitation patterns, net primary production, and other aspects of the physical environment, very little has been done to connect these changes to ensuing human outcomes.

The adverse human impacts of continued global warming have been extensively studied,[29] though much remains to be learned. However, as noted in Sections A and B, SRM would not simply reverse the effects of human GHG emissions. Regional differences and spatial heterogeneity in impacts, in particular, between a climate with SRM and a climate without SRM at the same global temperature may be significant. The current understanding of relationships between projected global temperature increases and resulting human impacts cannot be assumed to apply directly to future climate conditions altered by SRM. Adding further uncertainty is the potential for climatic conditions at a new equilibrium to differ considerably from those experienced during transient warming. Land areas warm more quickly than oceans, leading to the potential for higher temperatures over land during transient warming prior to eventual redistribution of heat as equilibrium is approached.[30] It is unclear how SRM may affect this response and the associated impacts to socioeconomic and ecological end points.

Avoiding climate tipping points has provided a rationale for SRM research and potential deployment, and a recent synthesis suggests that important tipping point thresholds may be crossed at 1.5°C of global warming.[31] Even so, there are significant gaps in our ability to forecast the timing of such tipping points, some of which would unfold over timeframes as long as centuries. Challenges remain in our ability to understand the extent to which near-term SRM

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[25] Kandlbauer, J. et al. (2013) Climate and carbon cycle response to the 1815 Tambora volcanic eruption. *J. Geophys. Res. Atmos., 118*(12), 12,497– 12,507. http://doi.org/10.1002/2013JD019767

[26] Gao, C., Gao, Y., Zhang, Q. et al. (2017). Climatic aftermath of the 1815 Tambora eruption in China. *J. Meteorol. Res., 31*, 28–38. https://doi.org/10.1007/s13351-017-6091-9

[27] Oppenheimer, C. (2003). Climatic, environmental and human consequences of the largest known historic eruption: Tambora volcano (Indonesia) 1815. *Progress in Physical Geography: Earth and Environment. 27*(2), 230-259. https://doi.org/10.1191/0309133303pp379ra

[28] Ibid.

[29] Masson-Delmotte, V. et al. (2018). *Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty.* https://doi.org10.1017/9781009157940.001; Pörtner, H.-O. et al. (2022). *Climate Change 2022: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. https://www.ipcc.ch/report/ar6/wg2/

[30] King, A.D., et al. (2020). Global and regional impacts differ between transient and equilibrium warmer worlds. *Nature Climate Change, 10*(1), 42-47. https://doi.org/10.1038/s41558-019-0658-7

[31] E.g., Armstrong McKay, D.I., Staal, A., Abrams, J., Winkelmann, R., Sakschewski, B., Loriani, S., Fetzer, I., Cornell, S., Rockström, J., and Lenton, T. (2022). Exceeding 1.5°C global warming could trigger multiple climate tipping points. *Science, 377*(6611). https://doi.org/10.1126/science.abn7950

deployment or other responses to climate change can effectively address climate tipping points with such long-term socioeconomic and ecological outcomes.[32]

Major Gaps to Inform Research Topics

There is far more research concerning SAI compared to marine cloud brightening (MCB) and cirrus cloud thinning (CCT) in the climate intervention literature. Reflecting this, the discussion below focuses strongly on SAI. Technical challenges associated with projecting extreme events in future climates limit our ability to quantitatively assess the human risks associated with extreme events in future climate scenarios with and without SRM. Although changes in mean climatic conditions are important, the rate of adaptation (e.g., water storage, flood defense, water sanitation) to new extreme event frequencies is highly variable, and is typically implemented at local, not national levels, and is a key factor in determining human outcomes.

Key Solar Radiation Modification Knowledge Gaps Related to Health and Well-Being: An impetus for research into SRM is to understand its potential to alleviate adverse human impacts related to health and well-being. Increased morbidity and mortality due to extreme heat is the most direct impact of a warming climate,[33] and is perhaps the health impact most likely to be ameliorated by implementing an SRM strategy.[34] Health endpoints related to air quality are more complex than direct heat impacts and have been studied more for SAI scenarios than for MCB and CCT. SAI is expected to result in changes in temperature and sunlight that would affect atmospheric chemistry and thus ground-level formation of ozone and particulate matter (PM) compared to conditions without SAI. Substantial regional variation confounds succinct description of impacts. Increases in ozone formation caused by higher temperatures are expected to be reduced with SAI. However, some work suggests those potential health benefits may be offset by the impacts of increased exposure to particulate matter from injected aerosols and changes in radiative forcing.[35] Health impacts due to wildfire smoke exposure may also be reduced, although some areas may see increased wildfire and smoke exposure risk.[36] Limiting temperature increases by SRM may reduce health impacts related to waterborne disease driven

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[32] Sillmann, J., et al., 2015. Climate emergencies do not justify engineering the climate. *Nature Climate Change, 5*(4): 290-292. https://doi.org/10.1038/nclimate2539

[33] Sarofim, M.C., S. Saha, M.D. Hawkins, D.M. Mills, J. Hess, R. Horton, P. Kinney, J. Schwartz, and A. St. Juliana, 2016: Ch. 2: Temperature-Related Death and Illness. *The Impacts of Climate Change on Human Health in the United States: A Scientific Assessment*. U.S. Global Change Research Program, Washington, DC, 43–68. http://dx.doi.org/10.7930/J0MG7MDX

[34] Raymond, C., et al. (2020). The emergence of heat and humidity too severe for human tolerance. *Sci. Advances, 6*(19). https://doi.org/10.1126/sciadv.aaw1838

[35] Eastham, S.D., et al. (2018). Quantifying the impact of sulfate geoengineering on mortality from air quality and UV-B exposure. *Atmospheric Environment. 187*, 424-434. https://doi.org/10.1016/j.atmosenv.2018.05.047

[36] Burton, C., Betts, R. A., Jones, C. D., and Williams, K. (2018). Will fire danger be reduced by using Solar Radiation Management to limit global warming to 1.5 °C compared to 2.0 °C? *Geophys. Res. Letts., 45*, 3644-3652. https://doi.org/10.1002/2018GL077848

by extremes in temperature[37] and precipitation,[38] although simulations of SAI suggest the potential for increased risk in some regions.[39,40] Further research, particularly with models appropriate to the spatial scales necessary to accurately attribute health impacts, would be informative.

Well-being includes livelihood, mental health, and additional aspects that are affected by increasing temperatures and other climate impacts.[41] Implementation of SRM may reduce mental health impacts related to increasing temperatures, but it is unclear how an SRM scenario of any type may affect eco-anxiety given the potential for adverse outcomes of deployment and cessation of SRM. Well-being is linked to social trust,[42] and better understanding is needed regarding how trust may be affected by SRM implementation.[43] Concerns about livelihood—a measure of a community's quality of life—are paramount, as even temporary climatic disruptions can have long-lasting consequences: Dust Bowl towns in the United States that experienced outward climate-driven migration still have not fully recovered nearly 100 years later. These communities, on average, continue to suffer lower economic growth, per capita income, and education rates.[44]

Climate change is increasingly identified as a main driver for human migration, although confidence in these projections is low.[45] The many factors that drive migration and uncertainties in physical science and human behavior make it difficult to accurately project total numbers of climate migrants in a hypothetical climate with and without SRM. Wage effects and cost of living will influence the spatial distribution of climate-driven resettlement. Current statistical

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[37] Beard, C.B., R.J. Eisen, C.M. Barker, J.F. Garofalo, M. Hahn, M. Hayden, A.J. Monaghan, N.H. Ogden, and P.J. Schramm, 2016: Ch. 5: Vector-Borne Diseases. *The Impacts of Climate Change on Human Health in the United States: A Scientific Assessment.* U.S. Global Change Research Program, Washington, DC, 129–156. http://dx.doi.org/10.7930/J0765C7V

[38] Trtanj, J., L. Jantarasami, J. Brunkard, T. Collier, J. Jacobs, E. Lipp, S. McLellan, S. Moore, H. Paerl, J. Ravenscroft, M. Sengco, and J. Thurston, 2016: Ch. 6: Climate Impacts on Water-Related Illness. *The Impacts of Climate Change on Human Health in the United States: A Scientific Assessment.* U.S. Global Change Research Program, Washington, DC, 157–188. http://dx.doi.org/10.7930/J03F4MH4

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[40] Carlson, C.J., Colwell, R., Hossain, M.S., et al. (2022). Solar geoengineering could redistribute malaria risk in developing countries. *Nat Commun, 13*, 2150. https://doi.org/10.1038/s41467-022-29613-w

[41] Lawrance, E., et al. (2021). The impact of climate change on mental health and emotional wellbeing: current evidence and implications for policy and practice. Briefing Paper No 36, Grantham Institute, London. https://doi.org/10.25561/88568

[42] Helliwell, J.F., H. Huang, and S. Wang. (2016). New evidence on trust and well-being. National Bureau of Economic Research, Working Paper 22450. https://www.nber.org/papers/w22450

[43] Cairns, R. (2016). Climates of suspicion: ‘chemtrail’ conspiracy narratives and the international politics of geoengineering. *The Geographical Journal, 182*(1), 70-84. https://doi.org/10.1111/geoj.12116

[44] Lustgarten, A. (2020). Climate Change Will Force a New American Migration, Propublica, available: https://www.propublica.org/article/climate-change-will-force-a-new-american-migration; Arthi, V. (2018). “The Dust Was Long in Settling”: Human Capital and the Lasting Impact of the American Dust Bowl. *The Journal of Economic History, 78*(1), 196-230. https://doi.org/10.1017/S0022050718000074

[45] Kaczan, D.J. and J. Orgill-Meyer. (2020). The impact of climate change on migration: a synthesis of recent empirical insights. *Climatic Change, 158*(3), 281-300. https://doi.org/10.1007/s10584-019-02560-0

relationships that link climate to productivity, wages, and cost-of-living are developed from historical data that may not apply to future climate conditions with or without SRM deployment.

Food and Water Systems: Food production is heavily concentrated geographically and is increasingly vulnerable to the impacts of climate change.[46] Extreme events including prolonged dry spells and excessive rain reduce crop yields. Excessive heat destroys crops and kills livestock. Warming and drought are projected to result in substantially increased likelihood of multi-breadbasket crop failures as soon as 2030.[47] Food insecurity in Central America's dry corridor is rising and export commodities are decreasing due to a lack of water that threatens continued livelihood in the region.[48]

It is unclear how the combination of limited temperature increases and increased CO2 concentrations expected with SAI implementation may affect crop yields and nutritional value. SAI approaches could worsen soil acidity, with impacts to food production, compared to warming at Representative Concentration Pathway 8.5 (RCP8.5) levels without SAI in some regions due to acidic deposition (e.g., the Pacific Northwest, southern Greenland, the Himalayas, and polar regions).[49] The impacts of sunlight scattering could have negative effects on crop growth that harm nutrition and negate the benefits of limiting temperature increases using SAI.[50] SRM would not address ocean acidification or its implications for ocean ecosystems.[51] These potential impacts emphasize the value of understanding the outcomes of SRM for ecosystems, including managed ecosystems (e.g., agriculture, aquaculture, forestry), more fully.

Evidence from volcanic eruptions is suggestive that asymmetric SAI deployment alters hydrological cycles,[52] can weaken Indian summer monsoons, and reduce Sahelian precipitation

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[46] Gowda, P., J.L. Steiner, C. Olson, M. Boggess, T. Farrigan, and M.A. Grusak, 2018: Agriculture and Rural Communities. In *Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II* [Reidmiller, D.R., C.W. Avery, D.R. Easterling, K.E. Kunkel, K.L.M. Lewis, T.K. Maycock, and B.C. Stewart (Eds.)]. U.S. Global Change Research Program, Washington, DC, USA, pp. 391–437. https://doi.org/10.7930/NCA4.2018.CH10

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[50] Proctor, J., et al. (2018). Estimating global agricultural effects of geoengineering using volcanic eruptions. *Nature, 560*(7719), 480-483. https://doi.org/10.1038/s41586-018-0417-3

[51] Russell, L. M., Rasch, P. J., Mace, G.M., Jackson, R. B., Shepherd, J., Liss, P., Leinen, M., Schimel, D., Vaughan, N. E., Janetos, A. C., Boyd, P. W., Norby, R. J., Caldeira, K., Merikanto, J., Artaxo, P., Melillo, J., and Morgan, M. G. Ecosystem impacts of geoengineering: a review for developing a science plan. *AMBIO, 41*, 350-69. http://doi.org/10.1007/s13280-012-0258-5

[52] Cheng, et al. (2022). Changes in Hadley circulation and intertropical convergence zone under strategic stratospheric aerosol geoengineering. *npj Clim Atmos Sci, 5*, Article 32. https://doi.org/10.1038/s41612-022-00254-6

to contribute to drought and subsequent humanitarian disaster.[53,54] Overall, relative to the RCP8.5 scenario, CCT and SAI scenarios alleviate dryland expansion, while specific implementations of MCB are expected to expand the spatial extent and severity of drylands.[55] Changes in amount and/or timing of precipitation can have substantial impacts on the ability of existing water infrastructure to manage water resources, with adverse outcomes for cities, agriculture, and other water consumers. Most importantly, tested scenarios in all simulations highlight the regional nature of impacts from SRM deployment.

Ecosystem Services: Beyond the fundamental needs of food and water, healthy ecosystems provide substantial and often unrecognized services to people and societies. Changes in the environment due to climate change and other human-driven stressors result in changes in the ability of ecosystems to provide those services. The ongoing Holocene extinction event is likely driven largely by human-driven stressors, resulting in loss of biodiversity in terrestrial and marine environments throughout the Earth at a rate unprecedented in human history.[56] Biodiversity and ecosystem health are fundamental to the Earth's natural cycles (e.g., water, carbon, nitrogen, phosphorus) that are the foundation of core societal systems.[57] Implementing SRM is expected to limit the risks to biodiversity associated with higher temperatures but is also expected to affect the characteristics of solar radiation and potentially cloud cover (associated with changing precipitation patterns) without impacting higher CO2 levels. These changes could have significant effects on vegetation and ecosystem health broadly, leading to unknown impacts to biodiversity, particularly when combined with other anthropogenic stressors (deforestation, urbanization, chemical use, etc.).[58]

Threats to ecosystem services abound. Ecosystem services such as pollination[59] and nutrition[60] are in rapid decline. Drier and warmer climates will increase the risk that Pacific Northwest forests will fail to regenerate following fires, resulting in reduced ability of the forests to provide

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[53] Haywood, J., Jones, A., Bellouin, N. et al. (2013). Asymmetric forcing from stratospheric aerosols impacts Sahelian rainfall. *Nature Clim Change, 3*, 660–665. https://doi.org/10.1038/nclimate1857

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[55] Park, C.E. et al. (2019). Inequal Responses of Drylands to Radiative Forcing Geoengineering Methods. *Geophys. Res. Letts. 46*(23), 14011-14020. https://doi.org/10.1029/2019GL084210

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[57] Marselle, M.R. et al. (2019). Review of the Mental Health and Well-being Benefits of Biodiversity. In Marselle, M., Stadler, J., Korn, H., Irvine, K., Bonn, A. (Eds), *Biodiversity and Health in the Face of Climate Change*. Springer, Cham. p. 175-211. https://doi.org/10.1007/978-3-030-02318-8

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[59] Osterman, J. et al. (2021). Global trends in the number and diversity of managed pollinator species. *Agriculture, Ecosystems & Environment. 322*, 107653. https://doi.org/10.1016/j.agee.2021.107653

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clean water, habitat, timber, and carbon sequestration.[61] Wetlands provide water purification and storage, carbon sequestration, flood mitigation, nutrient cycling, and habitats that support biodiversity, all of which are threatened by a warming climate.[62,63]

The extent to which SRM can mitigate these risks and the impacts of SRM on ecosystem services is unclear. SRM is expected to reduce the GHG-driven increase in global temperature and alter precipitation patterns compared to scenarios without deployment of SRM but would not directly affect increases in atmospheric CO2 concentrations.[64] Species and ecosystems (including microbes, insects, and larger flora and fauna and their interactions) have evolved in response to stable ranges of temperature and precipitation patterns, solar input, and CO2 levels. Both a changing climate and SRM will alter temperature and precipitation ranges and patterns, with results for ecosystems and their provision of goods and services that require further investigation.

Changes in ecosystems may also affect decarbonization strategies. The reduced temperature increase due to SRM deployment might indirectly reduce future atmospheric GHG concentrations compared to a non-SRM scenario by lessening temperature-driven carbon cycle feedbacks that would otherwise be expected to result in higher GHG emissions from natural sources.[65] It is important to recognize that aggressive decarbonization strategies may also affect ecosystems and ecosystem services through changes in land use for low-carbon energy and increased extraction of materials used in low-carbon energy systems.

Ecosystem services also encompass cultural, recreational, and other non-extractive services that can be more difficult to quantify. SRM may provide some benefits to these services, for instance by reducing the magnitude of sea level rise and risks to low-lying cultural heritage sites.[66,67]

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[61] Halofsky, J.E., D.L. Peterson, and B.J. Harvey. (2020). Changing wildfire, changing forests: the effects of climate change on fire regimes and vegetation in the Pacific Northwest, USA. *Fire Ecology. 16*(1), 4. https://doi.org/10.1186/s42408-019-0062-8

[62] Kingsford, R.T., A. Basset, and L. Jackson. (2016). Wetlands: conservation's poor cousins. *Aquatic Conserv: Mar. Freshw. Ecosyst.*, *26*(5), 892-916. https://doi.org/10.1002/aqc.2709

[63] Barbier, E.B. (2017). Marine ecosystem services. *Current Biology. 27*(11), R507-R510. https://doi.org/10.1016/j.cub.2017.03.020

[64] Park et al. (2019). Inequal Responses of Drylands to Radiative Forcing Geoengineering Methods. *Geophys. Res. Letts. 46*(23), 14011-14020. https://doi.org/10.1029/2019GL084210

[65] Canadell, J. G. et al. (2021). Global Carbon and other Biogeochemical Cycles and Feedbacks. In *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [Masson-Delmotte, V. et al. (Eds)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 673–816, doi:10.1017/9781009157896.007

[66] Ferguson-Bohnee, P. (2015). The Impacts of Coastal Erosion on Tribal Cultural Heritage. *Forum Journal, 29*(4), 58-66. https://ssrn.com/abstract=2742326

[67] Reimann, L. et al. (2018). Mediterranean UNESCO World Heritage at risk from coastal flooding and erosion due to sea-level rise. *Nature Communications, 9*(1), 4161. https://doi.org/10.1038/s41467-018-06645-9

Previous research has raised concerns about possible shifts in sky coloration from SAI, and resulting psychological impacts, which would merit study.[68,69]

Key questions regarding ecosystems and biodiversity include improving understanding of how the unprecedented environments of both a warming climate and a climate with increased CO2 and moderated temperatures (as would occur with SRM implementation compared to climate scenarios without SRM) affect net primary production of natural and managed ecosystems. Nearly all research to date has evaluated the responses of ecosystems and ecosystem services based on projected temperature–CO2 combinations in the absence of SRM. Understanding how these different conditions can affect the biodiversity and functionality of ecosystems is foundational to understanding how SRM and alternative strategies may affect ecosystem services relative to other climate response strategies.

Research could improve understanding of ecosystem sensitivities and responses to expected climate and atmospheric conditions under a range of SRM scenarios. Social science research could also help us understand the cultural, psychological, and other non-extractive services provided by ecosystems under conditions associated with continued warming, aggressive decarbonization, and SRM.

Other major research topics include understanding the impacts of SRM on ocean ecosystems and the potential for impacts to algae and subsequent outcomes for marine food chains, aquatic ecosystems, and their ability to support multiple environmental goods and services (water quality, extreme weather protection, biodiversity, cultural resources, and commercial and recreational fishing). Underlying the marine ecosystem response to any SRM scenario are the effects on ocean acidification, which will not be directly affected by SRM, and marine net primary production (NPP), a research area where initial studies suggest relatively little to moderate effects.[70,71] In this arena, models could consider SRM with and without atmospheric CO2 reductions from GHG mitigation or CO2 removal efforts.

A major gap in current understanding is the ecological consequences of a rapid return to temperature levels corresponding to cumulative carbon emissions relative to termination shock, should efforts to maintain artificial radiation management techniques cease.

Environmental Justice: The communities most vulnerable to the climate crisis are often those who contribute least to the climate crisis.[72] In these communities, health, income, and other factors frequently limit access to resources. They disproportionately suffer from the adverse impacts of climate change. Environmental justice extends beyond disproportionate vulnerability and impact and includes the fair treatment and meaningful involvement of all people regardless

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[68] Robock, A. (2008). 20 Reasons Why Geoengineering May Be a Bad Idea. *Bulletin of the Atomic Scientists*, *64*(2), 14-59. https://doi.org/10.2968/064002006

[69] Kravitz, B., D.G. MacMartin, and K. Caldeira. (2012). Geoengineering: Whiter skies? *Geophys. Res. Lett., 39*, L11801. https://doi.org/10.1029/2012GL051652

[70] Tilmes, S. et al. (2020). Reaching 1.5 and 2.0°C global surface temperature targets using stratospheric aerosol geoengineering. *Earth Syst. Dynam., 11*(3), 579-601. https://doi.org/10.5194/esd-11-579-2020

[71] Dagon, K., and D.P. Schrag. (2019). Quantifying the effects of solar geoengineering on vegetation. *Climatic Change, 153*(1), 235-251. https://doi.org/10.1007/s10584-019-02387-9

[72] Althor, G., Watson, J. and Fuller, R. (2016). Global mismatch between greenhouse gas emissions and the burden of climate change. *Sci Rep, 6*, 20281. https://doi.org/10.1038/srep20281

of race, color, national origin, or income, with respect to the development, implementation, and enforcement of environmental laws, regulations, and policies. Achieving environmental justice means that all persons and communities enjoy the same degree of protection from environmental and health hazards, and equal access to the decision-making processes to have a healthy environment in which to live, learn, and work.[73]

In the United States, frontline communities—those that experience the "first and worst" consequences of climate change—are largely low-income communities of color, immigrants, migrants, and people who speak languages other than English. These communities often have less access to health care, air conditioning, and greater exposure to the cumulative impacts of pollution and other stressors. They often live and work in locations that are more susceptible to climate-related harms, and generally have less adaptive and resilience capacity. SRM could potentially reduce these disparities by limiting the severity of temperature-driven impacts to the most vulnerable,[74] but there are important caveats to consider in the context of environmental justice. Differential risk and physical impacts are only one aspect. Cultural, moral, and ethical considerations are often overlooked and may be equally, if not more, important to different communities. These overlooked considerations are often missing from model-based evaluations.[75] Finally, if the potential requirement for SRM were that it would be maintained on timescales of decades, if not centuries, intergenerational equity is another dimension to be understood and considered, in the context of both SRM and alternative strategies without SRM.[76]

The potential for SRM to limit warming may reduce the inequities associated with a warming climate. The potential for SRM to exacerbate social inequities also needs to be analyzed, particularly as such inequities relate to fairness and involvement in decision-making.[77] These include the potential for climate impacts that could result from premature SRM cessation,[78] which would most likely be experienced more severely by frontline communities. The potential benefits to frontline communities of SRM could be reduced if it is used as a substitute for, or reduces, mitigation through emission reductions, although the environmental justice outcomes may depend to some extent upon where emissions are reduced. For example, enabling increased use of fossil energy in developing countries could enhance energy justice, although this could further the air quality impacts in those countries, which are likely to be worse for frontline communities.

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[73] Environmental Protection Agency. (6 March 2023). *Environmental Justice.* https://www.epa.gov/environmentaljustice

[74] Horton, J., and Keith, D. (2016). Solar geoengineering and obligations to the global poor. In C.J. Preston (Ed.), *Climate Justice and Geoengineering: Ethics and Policy in the Atmospheric Anthropocene*. Rowman and Littlefield, London, UK, pp. 79–92. https://keith.seas.harvard.edu/files/tkg/files/horton_and_keith_2016.pdf

[75] McLaren, D. P. (2018). Whose climate and whose ethics? Conceptions of justice in solar geoengineering modelling. *Energy Research & Social Science. 44*, 209-221. https://doi.org/10.1016/j.erss.2018.05.021

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[77] Gardiner, S., and McKinnon, C. (2020). The Justice and Legitimacy of Geoengineering. *Critical Review of International Social and Political Philosophy*, *23*(5), 557-563. https://doi.org/10.1080/13698230.2019.1693157

[78] Baatz, C. (2016). Can We Have It Both Ways? On Potential Trade-Offs Between Mitigation and Solar Radiation Management. *Environmental Values, 25*(1), 29-49. https://doi.org/10.3197/096327115X14497392134847

In model simulations of projected climate with stylized SRM emission scenarios from the Geoengineering Model Intercomparison Project (GeoMIP), the harms of warming and the benefits of cooling both accrue disproportionately in warmer and poor, more populous countries. While local-scale spatial distributions are model-dependent, the potential of SRM to reduce inter-country inequality, as measured by per-capita GDP, is consistent.[79,80] Even given a reduction in inequality of physical and health impacts, it remains unclear how to determine a fair distribution of benefits and burdens for SRM deployment, particularly given the potential significant non-physical outcomes. While there are indications that SRM could advance environmental justice efforts, there remain significant gaps in our understanding of how its research and potential deployment would affect environmental justice across and within countries and communities.

Specific research needs related to environmental justice include improving understanding of regional and community differences in

- food and water scarcity, disease, and air quality and their potential to affect human health;
- inequities and how they may vary across generations; and
- projected economic growth and productivity.

Infrastructure Services: Nearly all physical infrastructure in use today was designed based on the assumption of an unchanging, recent climate. Human-caused climate change means that existing infrastructure may be ill-suited to today's climate and future climates, and therefore be unreliable. The Fourth National Climate Assessment outlines climate change effects on infrastructure services, water, energy, buildings, transportation, etc.[81] Since infrastructure design and reliability are sensitive to climate extremes and seasonal patterns, a research topic is how SRM might affect infrastructure reliability, the need to replace infrastructure, and infrastructure design. The resultant insights, if discernable, could in turn inform the need for and design of climate adaptation measures, inclusive more resilient housing, and insurance markets.

Geopolitical Considerations: The cooling effects of SRM could lessen the tendency of climate change impacts like food scarcity, water scarcity, and migration to exacerbate geopolitical stresses, but could introduce other changes to weather patterns that cause problems and create separate geopolitical tensions. A research program would investigate the geopolitical risks associated with SRM in comparison to the geopolitical risks associated with current climate change trajectories.

An unexpected SRM deployment might incur significant geopolitical outcomes. A research program could assess the factors that might lead to an unexpected deployment; evaluate the

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[79] Kravitz et al. (2021). Comparing different generations of idealized solar geoengineering simulations in the Geoengineering Model Intercomparison Project (GeoMIP). *Atmos. Chem. Phys., 21*(6), 4231-4247. https://doi.org/10.5194/acp-21-4231-2021

[80] Harding, A. R., Ricke, K., Heyen, D. et al. (2020). Climate econometric models indicate solar geoengineering would reduce inter-country income inequality. *Nat Commun, 11(227).* https://doi.org/10.1038/s41467-019-13957-x

[81] USGCRP, 2018*: Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II* [Reidmiller, D.R., C.W. Avery, D.R. Easterling, K.E. Kunkel, K.L.M. Lewis, T.K. Maycock, and B.C. Stewart (Eds.)]. U.S. Global Change Research Program, Washington, DC, USA, 1515 pp. https://doi.org/10.7930/NCA4.2018

international community's capabilities in managing such an event; and might yield suggestions on how to deter, prevent, identify, and respond to such an event. A lack of country-level dialogue, governance bodies, and research norms might increase the possibility that state or non-state actors could move independently to develop and deploy SRM technologies.[82] This elevates urgency around assessing the geopolitical outcomes of unilateral or multilateral SRM deployment and identifying optimal international frameworks for cooperation, monitoring, deterrence, and response.

Research would investigate the challenges with multilateral SRM deployment, such as building consensus and creating a measurement, monitoring, and verification system designed to measure SRM deployments and their impacts to human and natural systems.

Multilateral SRM deployment scenarios, such as peak-shaving, would likely require decades of SAI, and a host of natural, economic, and political events could interfere—maybe in risky ways—with a long-term SRM deployment. A research program would identify and analyze the most impactful deployment scenarios, then evaluate potential international processes and structures to prevent the realization of natural, economic, and political interferences.

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[82] National Intelligence Council. (2021). *Climate Change and International Responses Increasing Challenges to US National Security Through 2040*. NIC-NIE-2021-10030-A. https://www.dni.gov/files/ODNI/documents/assessments/NIE_Climate_Change_and_National_Security.pdf

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Section D. International Cooperation on Solar Radiation Modification Research

Summary

If the United States were to pursue SRM research, **it would be in our interest to engage in appropriate international cooperation.** International cooperation could promote, e.g., knowledge gains, a common international understanding of research needs and results, resource savings, socializing best practices (such as acting with full transparency), and reducing the prospect of irresponsible experimentation and/or deployment.

Cooperation could involve one or more areas of SRM-related research and could take various forms, ranging from modest (e.g., an exchange of experts) to extensive (e.g., a full-blown international consortium).

Potential cooperation partners could be engaged based on any number of criteria or perceived benefits, including countries with expertise, available funding, or capacity in a particular area; countries with limited opportunities or capacity in a certain area; and countries with access to particular ecosystems (e.g., the ocean or the Arctic).

Introduction

This section addresses various aspects of international cooperation on SRM research that could be considered by the U.S. Government. It does not address options for international cooperation regarding the more political function of decision-making on potential climate intervention deployment.

This section begins with reasons for potential cooperation (the “why”) and proceeds to consider the subject matter of potential cooperation (the “what”), the forms of potential cooperation (the “how”), and the types of potential international partners (the “who”). It notes the desirability of conducting any international cooperation in this area with full transparency in order to model good behavior for others and to build confidence, particularly among those who might otherwise be suspicious of research activities.

Potential Benefits of International Cooperation

There are several reasons why the U.S. Government might consider partnering with other countries on one or more areas of SRM research.

In the broadest sense, were the United States to pursue a large-scale program of SRM research, it would presumably be in our affirmative interest to begin to build a common international understanding of research needs and results. Were there ever a need to seriously consider deploying climate intervention, whether proactively or reactively—or a need to respond to its deployment or imminent deployment by someone else—it would be desirable to have a shared empirical basis to inform thinking and promote evidence-based decision-making.

Further, developing a norm of cooperation and related transparency, as well as taking steps to socialize best practices for conducting research, could help reduce the prospect of irresponsible experimentation and/or deployment.

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More specific reasons could include, e.g.:

- The U. S. Government could gain knowledge—e.g., if another country's researchers were looking into the same problem or had capabilities unavailable within the United States.
- The U.S. Government could share knowledge with interested researchers/countries.
- Cooperation could accelerate results, which would be particularly important if the research had an urgent timeframe.
- Cooperation could result in cost savings, either because it involved a deliberate cost-sharing arrangement or because it promoted efficiency (e.g., in the case of avoiding redundancy or overlap).
- Cooperation with the United States could afford opportunities not otherwise available to researchers from other countries, particularly developing countries, including access to U.S. innovation hubs and facilities (e.g., national laboratories).
- Cooperation could help build and/or maintain relationships between researchers as well as countries. It could be particularly important to cooperate with developing countries.
- Cooperation could help promote a well-designed U.S. research program as a model for other countries.
- Cooperation could help reduce the stigma that might be associated with such research—i.e., that it can only be accomplished in service of the interests of more economically advanced countries.

Scope of Potential Cooperation

International cooperation might involve any one or more of the topics that may be identified as part of a U.S. Government research program (science, technologies, etc.).

With respect to any given topic(s), cooperation might relate to, e.g., the identification of needed research; the norms governing the conduct of research; the carrying out of research itself (e.g., observations, computer modeling, laboratory studies, field research, workshops); and/or the assessment of research results.

Cooperation on SRM could usefully involve an international assessment of scenarios and strategies and their associated consequences. For example, it might document and expand the scientific foundation for SRM scenarios and implementation strategies and provide a comprehensive analysis of their intended and unintended consequences for climate and the physical environment broadly. Such an assessment would support future research activities by identifying where knowledge and understanding seem sufficient and where significant gaps remain.

Cooperation would not need to be limited to SRM research per se, but could also include related research and assessment, e.g., fundamental atmospheric research that could improve overall climate modeling; comparative risk assessment (e.g., including the climate risks, such as tipping points, for which SRM might be a potential response); and climate intervention in the context of various climate risk management strategies.

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Potential Approaches to Cooperation

As with the reasons for cooperation and topics for cooperation, there are many options regarding "how" cooperation might be carried out.

In terms of the **type** of cooperation:

- At the more modest end of the spectrum, it could involve inviting foreign scientists into a U.S. research project (e.g., to enable access to high-performance computing capabilities for scientists from countries where they might otherwise not have such access), or having U.S. scientists join another country's research project.
- At the opposite end of the spectrum, it could entail a full blown, self-selected international consortium involving sustained collaboration on a wide range of research areas, as well as on associated modalities, e.g., cost sharing, data sharing, etc.

As elaborated below, another type of cooperation would involve the creation of an open international database that researchers would be encouraged to use to record their activities, data, and results.

In terms of the **forum** for cooperation:

- Bilateral cooperation would not generally raise the issue of creation of a forum.
- Multilateral cooperation might take place through an existing forum/process (e.g., the World Meteorological Organization's World Climate Research Program) or pursuant to a new arrangement(s) created for this purpose.

A one-size-fits-all approach would not be necessary, i.e., the "how" might differ depending upon the "what." The U.S. Government might pursue a modest form of cooperation with respect to one research question or type of research and a more extensive cooperative arrangement with respect to another. Alternatively, cooperation on the conduct of research might take place in numerous forms, while a single international forum might be tasked with the scientific/technological assessment of research.

Potential Partners

Potential cooperation partners might include, e.g.:

- countries with researchers already working on a topic of interest to the United States;
- countries with researchers having expertise in a particular research topic;
- countries with available funding;
- countries whose researchers have limited opportunities, e.g., certain developing countries;
- countries with frontline communities, particularly developing countries, who are most affected by the impacts of climate change (e.g., small islands, etc.) and/or the potential impacts of SRM;
- countries with particular industries relevant to conducting research;
- with respect to field research, countries with access to particular geographical features or ecosystems (e.g., the ocean or the Arctic region), dependent upon particular weather systems (e.g., monsoons), or geographically isolated (to isolate the effects of research); and/or

- all countries, as would be the case if one or more issues—or an across-the-board assessment—were taken to a global forum.

In some cases, the U.S. Government might choose to put constraints on potential partners, such as limiting cooperation to, e.g., countries committed to strong mitigation action—lest it appear that research on SRM would somehow be at the expense of mitigation—and/or countries with a strong commitment to acting transparently.

Cooperation might also focus on climate intervention as a security-related response to extreme climate impacts. Of note is the May 14, 2022 G7 Foreign Ministers' Communiqué, which, in the context of "climate, peace and security," recognized that exceeding tipping points could lead to destabilization of different regions, further recognized the need for further scientific study, and underscored "the urgency for immediate and comprehensive scenario planning as a crucial element of a preventive and climate-sensitive foreign and security policy, as well as for building the capacity to respond to the outcomes of such events should they occur."[83]

Transparency

To the extent that the U.S. Government were to engage in SRM research, it would be important for such research to be as transparent as possible, whether carried out with international cooperation or not. Such transparency would include reporting of past, ongoing, and planned research activities as well as ensuring that all data, tools, and software used were available, accessible, and understandable to all.

Transparency related to international cooperation could be pursued through creation of an international database of research activities, data, and results, recognizing that there may be overlap between intervention-specific research and climate research more generally. Alternatively, such a database could be created by the United States, with the option to accept international submissions.

In either event, being fully transparent about such research activities could help encourage others to be transparent about their activities.

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[83] G7 Foreign Ministers. (2022, 14 May). G7 Germany 2022 Foreign Ministers' Communiqué. https://www.g7germany.de/resource/blob/997532/2039866/59cf2327ee6c90999b069fca648a2833/2022-05-14-g7-foreign-ministers-communique-data.pdf?download=1

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Section E. Coordination of Federally Funded Research into Solar Radiation Modification

Any large-scale, multi-agency Federal research program into SRM would be coordinated by the U.S. Global Change Research Program (USGCRP). This coordination role is mandated by the Global Change Research Act of 1990 and would apply to all Federally funded research into SRM, whether performed domestically or internationally, and whether involving natural or social science work.

The Federal government conducts or funds limited research into SRM. Congress has directed NOAA to fund SRM research as part of its Earth's Radiation Budget Program for the last several years. This supports several observational and modeling activities in NOAA, NASA, and with partner organizations (e.g., the University Corporation for Atmospheric Research, NOAA Cooperative Institutes, and academia). NOAA and NASA are cooperating on sampling the lower stratospheric aerosol layer in the Stratospheric Aerosol processes, Budget and Radiative Effects (SABRE) mission using the NASA WB-57 high-altitude research aircraft. NOAA and DOE co-organized a workshop in Fiscal Year 2022 to evaluate the research needs that can inform SRM.

Indirect funding of SRM research is distributed across the Federal Government's research enterprise through establishing and supporting capabilities needed to "model, analyze, observe, and monitor atmospheric composition,"[84] and "climate impacts and the Earth's radiation budget."[85]

These capabilities range from satellite observations to laboratory experiments, to modeling, to data management and reporting.

The Global Change Research Act of 1990 established USGCRP to "provide for development and coordination of a comprehensive and integrated United States research program which will assist the Nation and the world to understand, assess, predict, and respond to human-induced and natural processes of global change." USGCRP is an active organization with broad representation across the Federal global change research agencies, some of whom are already conducting basic research relevant to understanding important processes linked to SRM. The mandate, capabilities, and scope needed to coordinate Federal research in SRM exist within the USGCRP. Therefore, USGCRP is the best-suited entity to lead any needed coordination of Federally funded SRM research.

Of particular interest in research coordination will be the needed investments in social sciences, and the coordination/integration of that research with the natural sciences. The USGCRP 2022–2031 Strategic Plan suggests this approach by stating that the Program will coordinate research into "how human systems may respond to and be affected by alternative adaptation, mitigation, and intervention actions."[86]

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[84] From the Congressional language mandating this report: https://docs.house.gov/billsthisweek/20220307/BILLS-117RCP35-JES-DIVISION-B.pdf

[85] Ibid.

[86] USGCRP. (2022). *The U.S. Global Change Research Program 2022–2031 Strategic Plan*. U.S. Global Change Research Program, Washington, DC, USA. https://www.doi.org/10.7930/usgcrp-2022-2031-strategic-plan

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In addition to USGCRP, other interagency coordination bodies would be relevant. The U.S. Group on Earth Observations (USGEO), the National Science and Technology Council (NSTC) Subcommittee on Ocean Science and Technology (SOST), and the Interagency Council for Advancing Meteorological Services (ICAMS) have strong connections to relevant natural science research work in the relevant agencies but have traditionally focused less on social science research. Other socioeconomic research forums do exist. For example, engagement with the Climate Security Advisory Council (CSAC) provides connections to the national security community, which would likely be important to provide insight into the potential for international outcomes of specific SRM scenarios.