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

JUNE 2023

THE WHITE HOUSE

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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.

[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

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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.

[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.

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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

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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.

[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

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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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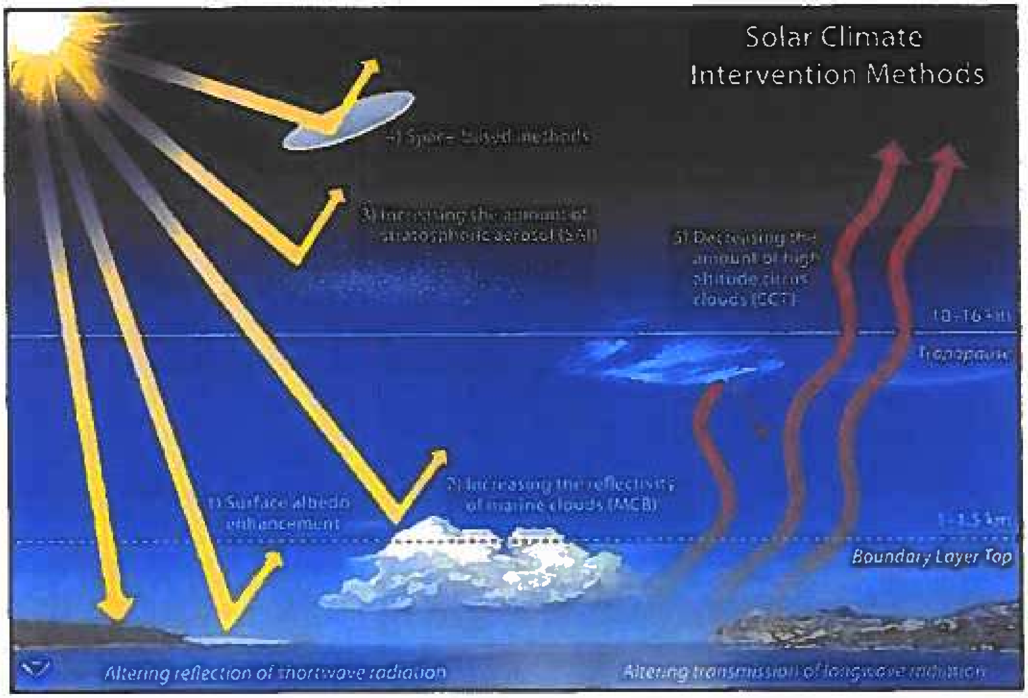

Figure 1. The most widely discussed forms of solar radiation modification increase the quantity of solar radiation reflected back into space, including surface albedo enhancement, marine cloud brightening (MCB), stratospheric aerosol injection (SAI), and space-based methods. In contrast, cirrus cloud 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

[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.

[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