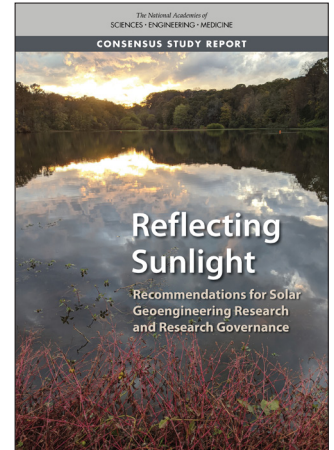




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## Reflecting Sunlight: Recommendations for Solar Geoengineering Research and Research Governance



Climate change is creating impacts that are widespread and severe—and in many cases irreversible—for individuals, communities, economies, and ecosystems around the world. Without decisive action and rapidly stabilizing global temperature, risks from a changing climate will increase in the future, with potentially catastrophic consequences.

Meeting the challenges of climate change requires a portfolio of options. The centerpiece of this portfolio should be reducing greenhouse gas emissions, along with removing and reliably sequestering carbon from the atmosphere, and pursuing adaptation to climate change impacts. Concerns that these options together are not being pursued at the level or pace needed to avoid the worst consequences of climate change have led some to suggest the value of exploring additional response strategies, including solar geoengineering.

While solar geoengineering could potentially help reduce surface temperatures and ameliorate some risks posed by climate change, it could also introduce an array of potential new risks—for instance, those related to critical atmospheric processes, aspects of regional climate, or numerous environmental, social, political, and economic factors that can interact in complex ways. This report provides an update to *Climate Intervention: Reflecting Sunlight to Cool Earth* (NRC, 2015) regarding the understanding of three proposed solar geoengineering strategies (see Figure 1) and makes recommendations for how to establish

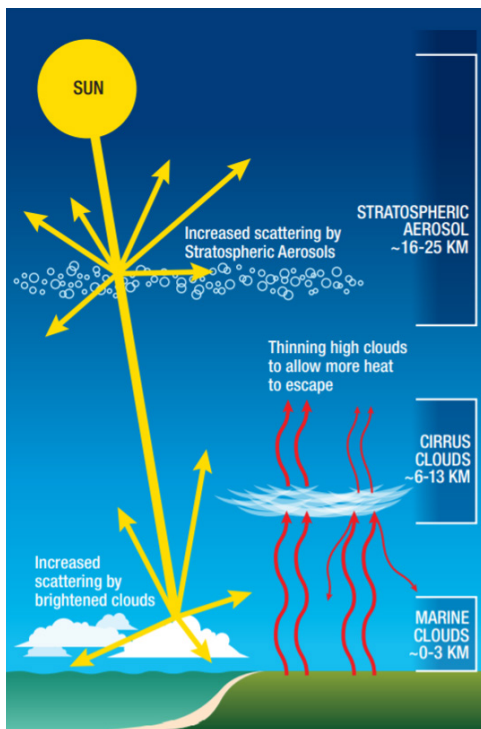
a research program, a research agenda, and mechanisms for governing this research.

### CURRENT LANDSCAPE FOR SOLAR GEOENGINEERING RESEARCH AND RESEARCH GOVERNANCE

There is currently no coordinated or systematic governance of solar geoengineering research. Solar geoengineering research to date is ad hoc and fragmented, with substantial knowledge gaps and uncertainties in many critical areas. There is a need for greater transdisciplinary integration in research, linking physical, social, and ethical dimensions. Research to understand the potential magnitude and distribution of solar geoengineering impacts—on ecosystems, human health, political and economic systems, and other issues of societal concern—is in a particularly nascent state.

While research to date has answered some important questions about solar geoengineering, scientific understanding remains limited. Research on the efficacy and impacts of the three solar geoengineering strategies considered suggests the following:

**Stratospheric Aerosol Injection (SAI).** Substantial modeling and empirical evidence (using volcanic eruptions as a natural analog) indicate that SAI can induce cooling at a global scale; but significant uncertainties remain regarding the cooling potential



**FIGURE 1. SOLAR GEOENGINEERING STRATEGIES**

Solar geoengineering refers to attempts to moderate warming by increasing the amount of sunlight that the atmosphere reflects back to space or by reducing the trapping of outgoing thermal radiation. This study considers the following solar geoengineering strategies:

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

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

**Cirrus cloud thinning (CCT)** is a strategy for modifying the properties of high-altitude ice clouds, increasing the atmosphere's transparency to outgoing thermal radiation.

and with regard to the amount of injected aerosols, location, and type, and regarding the effects of an increased aerosol burden on atmospheric chemistry, transport, and resulting regional and local effects on climate. Such uncertainties contribute to uncertainty in climate response and resulting impacts around the world.

**Marine Cloud Brightening (MCB).** Adding aerosols to marine clouds can increase cloud reflectivity in some circumstances, as is observed in studies of ship tracks. However, limited understanding of aerosol/cloud interactions leads to significant uncertainty regarding where and by how much cloud albedo can be modified and whether feedback processes will mask or amplify some of the effects. Key processes occur at scales too small to include directly in global climate models, and these process uncertainties will need to be reduced in order to develop reliable large-scale climate impact projections.

**Cirrus cloud thinning (CCT).** The efficacy of CCT is currently unknown due to very limited understanding of cirrus cloud properties and the microphysical processes determining how cirrus may be altered. Existing climate model simulations of CCT have yielded contradictory results.

## PROPOSED FRAMEWORK FOR RESEARCH AND RESEARCH GOVERNANCE

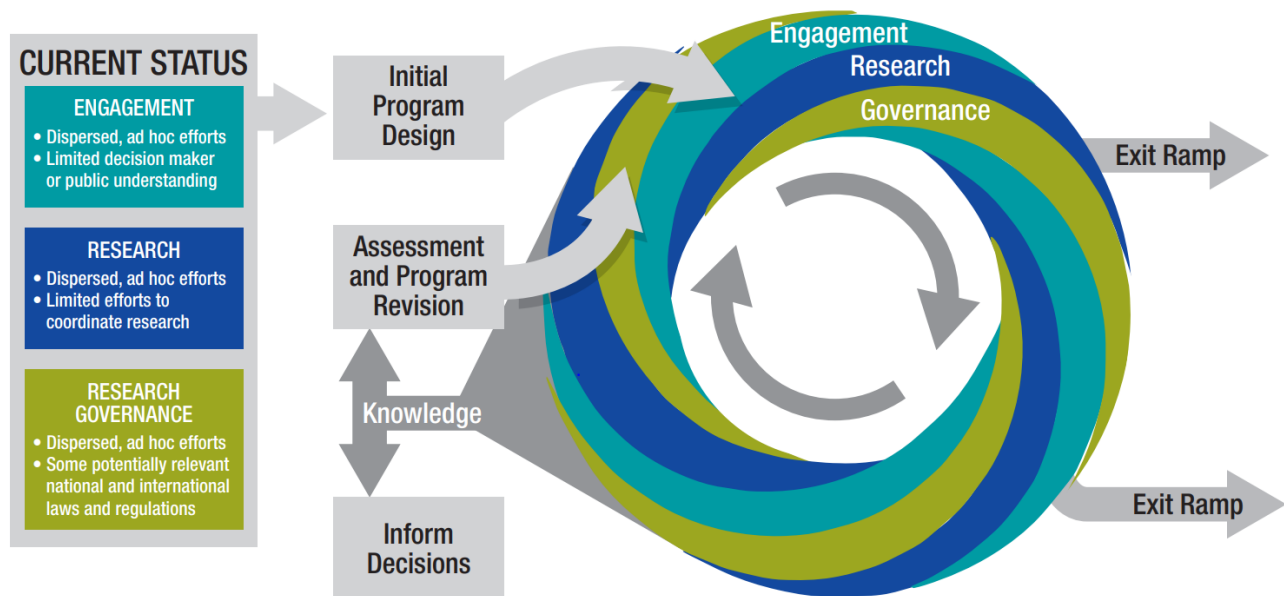
Given the urgency of the risks posed by climate change, this report calls upon the United States both to implement a robust portfolio of climate mitigation and adaptation strategies and to establish a national solar geoengineering research program. This program

should be a minor part of the overall U.S. research portfolio related to climate change, and it should focus on advancing understanding of options for responding to climate change risks and developing policy-relevant knowledge, rather than advancing a path for deployment.

A transdisciplinary domestic research program, established in coordination with other countries, can help build the foundation of scientific insights and information that will help decision makers and stakeholders faced with choices about possible future implementation of solar geoengineering. To this end, the committee envisions an integrated framework (see Figure 2) that would enable research governance and research activities to evolve hand-in-hand, with ongoing mechanisms for stakeholder engagement and input. A research program needs to be sufficiently flexible to allow for improvements and adjustments as our understanding grows.

Building an effective, transdisciplinary research program will require coordination across multiple agencies, national laboratories and cooperative institutes and coordination with other countries. The U.S. Global Change Research Program, charged with coordinating global change research across the federal science agencies, is the most logical entity for orchestrating a solar geoengineering research program.

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



**FIGURE 2.** Schematic of solar geoengineering research and research governance environment. The stepwise, iterative nature of this framework is paramount.

## GOVERNANCE FOR SOLAR GEOENGINEERING RESEARCH

The recommended national solar geoengineering research program should operate under robust research governance, and should support the development of international governance mechanisms. The goals of research governance include advancing and coordinating appropriate research, facilitating inclusive and equitable public and stakeholder engagement, and addressing physical risks together with social, ethical, and legal concerns.

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

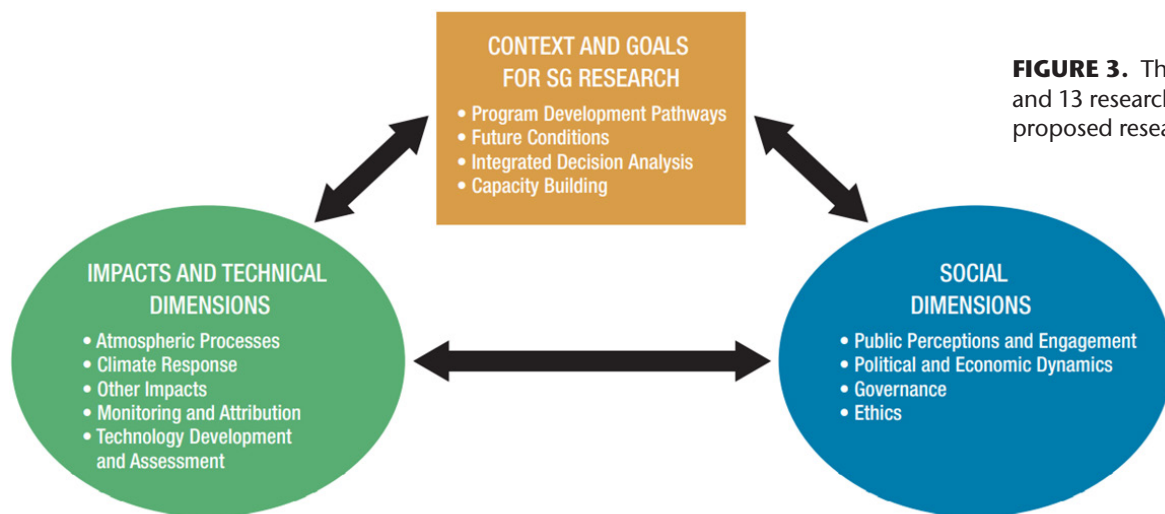
## AN INTEGRATED AGENDA FOR SOLAR GEOENGINEERING RESEARCH

The research agenda for the U.S. solar geoengineering research program should encompass a diverse array of 13 “research clusters”. As the boundaries among these different topics are often blurred, with many questions that cut across different types of research, the committee organized research needs under three broad categories (see Figure 3):

- **Context and goals for solar geoengineering research**, which includes research on the goals and social context for solar geoengineering research, developing modeling scenarios, strategies for decision making under uncertainty, and the capacity needed for all countries to engage meaningfully on this issue.
- **Impacts and technical dimensions**, including the properties of injected reflective particles and their interactions with clouds and atmospheric processes, possible climate outcomes and subsequent impacts on ecological and societal systems, technical requirements for advancing these technologies, and advancing monitoring and attribution capabilities.
- **Social dimensions**, including research on public perceptions of and engagement with solar geoengineering; domestic and international conflict and cooperation; effective governance of solar geoengineering; and integration of justice, ethics, and equity considerations into work on this issue.

## Considerations for Outdoor Experiments

Limited outdoor experimentation could help advance the study of certain atmospheric processes that are critical for understanding solar geoengineering. Such activities, however, are controversial, with significant likelihood for public concerns and objections. If subject to appropriate governance and oversight, outdoor experimentation could feasibly be pursued in a balanced manner that is sufficient in scale to acquire critical observations not available by other means, but small enough in scale to limit impacts.



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

### Funding Considerations for Solar Geoengineering Research

Implementing the recommended research and research governance will require dedicated resources. To help inform planning for a national research program, the report offers guidelines for shaping a budget for the program, including suggestions that funding for solar geoengineering research should not shift the focus from other important global change research. A reasonable initial investment for this program is within a range of \$100-200 million total over 5 years. A program of this size would be sufficient to advance all the research topics identified, but represent a small fraction of the national budget for climate-change research.

### CONCLUDING THOUGHTS

The recommendations in this report focus on an initial, exploratory phase of a research program. The program might be continued or expand over a longer term, but may also shrink over time, with some or all elements eventually terminated, if early research suggests strong reasons why solar geoengineering should not be pursued. The proposed approaches to transdisciplinary research, research governance, and robust stakeholder engagement are different from typical climate research programs and will be a significant undertaking; but such efforts will enable the research to proceed in an effective, societally responsive manner.

## COMMITTEE ON DEVELOPING A RESEARCH AGENDA AND RESEARCH GOVERNANCE APPROACHES FOR CLIMATE INTERVENTION STRATEGIES THAT REFLECT SUNLIGHT TO COOL EARTH

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**For More Information . . .** This Consensus Study Report Highlights was prepared by the National Academies of Sciences, Engineering, and Medicine based on the Consensus Study Report *Reflecting Sunlight: Recommendations for Solar Geoengineering Research and Research Governance* (2021). The study was sponsored by the BAND Foundation, the Christopher Reynolds Foundation, the Department of Energy, the MacArthur Foundation, the National Academy of Sciences' Arthur L. Day Fund, the National Aeronautics and Space Administration, the National Oceanic and Atmospheric Administration, and the V. Kann Rasmussen Foundation. Any opinions, findings, conclusions, or recommendations expressed in this publication do not necessarily reflect the views of any organization or agency that provided support for the project. Copies of the Consensus Study Report are available from the National Academies Press, (800) 624-6242; <http://www.nap.edu> or via the Board on Atmospheric Sciences and Climate web page at <http://www.nationalacademies.org/basc> or the Committee on Science, Technology, and Law webpage at <https://www.nationalacademies.org/cstl/committee-on-science-technology-and-law>.