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Near-term Climate Risk and Intervention

A Roadmap for Research, U.S. Research Investment, and International Scientific Cooperation

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A SilverLining Report

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About This Report

Current impacts and escalating risks of climate change require strong and decisive action to reduce greenhouse gas emissions. They also highlight the urgency of research to enhance safety for human and natural systems, especially for those most vulnerable. This report builds on information in *Ensuring a Safe Climate: A National Imperative for Research in Climate Intervention and Earth System Prediction* (SilverLining 2019) and *Near-term Climate Risks and Sunlight Reflection Modification: A Roadmap Approach for Physical Sciences Research* (Springer 2022) to describe the potential for climate interventions to reduce the near-term risks and impacts of climate change.

This report focuses primarily on the physical sciences research required to provide policymakers, the public, and other stakeholders with information for analysis and decision-making. As such, it does not provide an extensive treatment of governance or other non-science considerations but builds on the principles described in a series of papers by international climate law experts Sue Biniaz and Daniel Bodansky: *Solar Climate Intervention: Options for International Assessment and Decision-Making* (C2ES and SilverLining 2020) and *Climate Intervention: The Case For Research* (C2ES and SilverLining 2020).

Climate research requires advanced technologies and expertise that are concentrated in the United States and other developed countries. U.S. federal science agencies currently provide the primary scientific support for many international environmental agreements and scientific and environmental monitoring programs. U.S. scientific institutions and government bodies have also taken steps forward, in both research and policy, on climate intervention. As such, this report emphasizes U.S. research. It builds on recommendations from the National Academies of Sciences, Engineering, and Medicine's 2015 and 2021 reports on approaches for and research on solar climate interventions as well as on a directive from the U.S. Congress to develop a plan for research to inform an assessment of near-term climate risk and climate intervention in 5 years in order to make recommendations for U.S. research designed to support global cooperation, governance, and decision-making.

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Executive Summary

Escalating climate threats demand better information on climate risks and impacts and an expanded portfolio of responses to ensure safety in the next few decades, including for the world's most vulnerable people. The magnitude of these threats warrants an ambitious effort to improve projections of near-term climate risks and impacts and to assess the potential for climate interventions to reduce disaster risks.

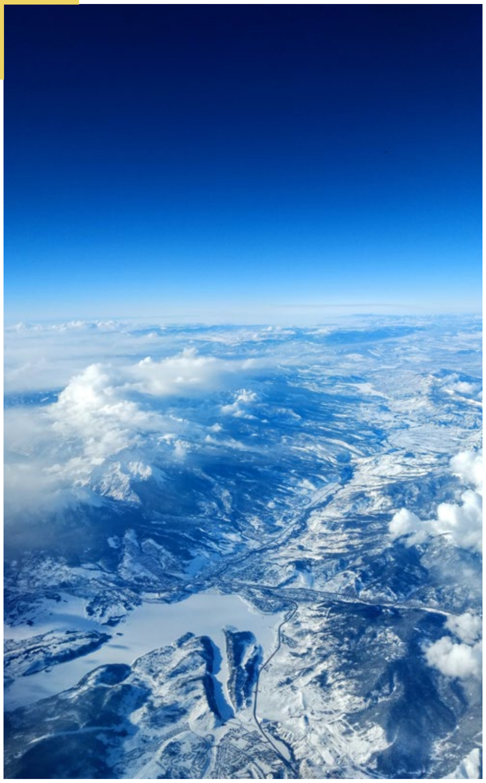
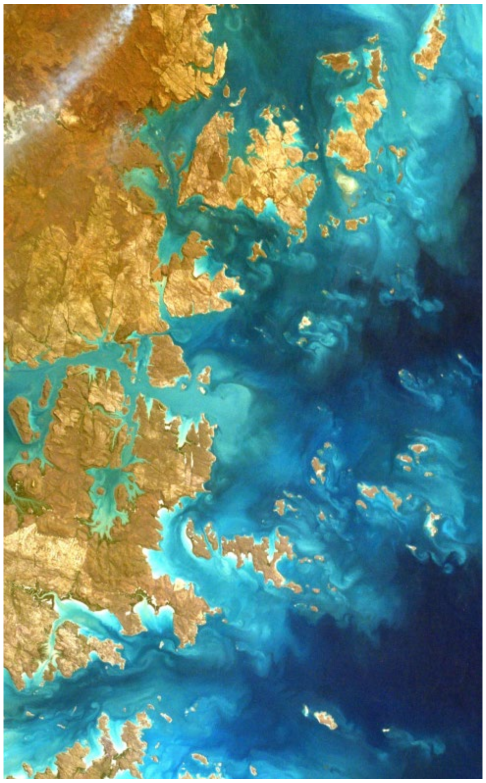
Climate change is causing devastating impacts on communities and ecosystems around the world, posing grave threats to public health, economic security, and global stability. Natural systems are approaching thresholds for catastrophic changes, with the potential to accelerate climate change and impacts beyond humans' ability to adapt.

While reducing emissions continues to be crucial, no level of emissions reduction can counter the warming effects of greenhouse gases (GHGs) that are already in the atmosphere. Addressing the short and decreasing window available for reducing heat in the climate system is an urgent priority. If we do not address this problem, there are significant risks of catastrophic changes over the next few decades. The current portfolio of solutions is unlikely, even in the most optimistic scenarios, to sufficiently reduce warming within that timescale. International cooperation on a 5-year roadmap for research on near-term climate risk and rapid climate interventions and a $13 billion funding program from the U.S. government can provide the tools and resources needed to evaluate the best next steps to promote near-term climate safety.

Near-term Climate Risks and Interventions

Interventions in the climate system to reduce warming by increasing the reflection of sunlight from clouds and particles (i.e., aerosols) in the atmosphere may provide options for protecting the safety of the world's people and the stability of its natural systems while society transitions to a sustainable future.

Of the many factors that influence warming and cooling in the atmosphere, the effects of sunlight reflection by clouds and particles is one of the largest but least understood. Efforts to reduce environmental impacts from particulate emissions may lead to rapid warming through the loss of climate-cooling particles, but observations and scientific understanding are not currently sufficient to evaluate this.


U.S. and International Reports on Solar Climate Intervention Research

To address the need for information on the potential effects of the most prominent form of solar climate intervention—increasing the reflection of sunlight by dispersing particles in the stratosphere—on the ozone layer, the Scientific Assessment Panel of the Montreal Protocol on Substances that Deplete the Ozone Layer (i.e., the Montreal Protocol) included a full chapter on the topic in its *2022 Scientific Assessment on Ozone Depletion*. The first dedicated chapter on solar climate interventions in a United Nations (UN)-sanctioned assessment, it includes the most recent and thorough assessment of scientific research on stratospheric climate intervention available today.

To address the need for information on the potential for solar climate interventions to reduce near-term climate risks, the U.S. Congress directed the National Oceanic and Atmospheric Administration (NOAA) and other federal science agencies to provide a 5-year plan on the research required to support a substantive scientific assessment "of solar and other rapid climate interventions in the context of near-term climate risks and hazards." (H.R.4505—117th Congress (2021–2022).

Responding to the UN Intergovernmental Panel on Climate Change's latest report underscoring the need for all available options to respond to climate change, including the utilization of some "Climate Action Technologies and Measures," the World Meteorological Organization and UN Environment Programme, in collaboration with the UN Secretary-General's office, convened a Meeting of Experts to articulate what is known and what work will be required to enable an informed view about solar climate intervention and its management in the future.

Both pending reports are anticipated for release in early 2023.

> **"To bring global temperatures down quickly, the only button that we can push—that we know about—is solar climate intervention. There are many uncertainties, which is why scientists should be studying the issue carefully in an international forum, like the Montreal Protocol or the UN's Intergovernmental Panel on Climate Change."**
>
> David Fahey, Co-Chair of the Scientific Assessment Panel of the Montreal Protocol and Director of the Chemical Sciences Laboratory, NOAA

There is a growing need for better information and an expanded portfolio of options to promote the safety of communities and the sustainability of natural systems with respect to near-term climate changes. **The magnitude of climate risks and impacts warrants an ambitious effort both nationally and internationally to better understand and predict near-term climate impacts and risks and to assess solar and other promising climate interventions.**

International Imperatives

While demand for better information on near-term climate risks and interventions is rising, climate research globally (as opposed to energy and other research related to reducing emissions) has been broadly subject to inadequate levels of activity and funding for several decades. It must now be made more commensurate with its importance to public welfare, environmental sustainability, economic security and global stability.

Research takes time, and there is a need to define and deliver against ambitious but achievable goals within a set time frame—a "roadmap" for research—to protect people and natural systems in the coming decades. A well-structured roadmap spanning the range of required disciplines designed to a shared set of objectives and goals, such as proposed herein, can accelerate progress and foster a truly open and global collaboration and exchange of information on near-term climate risks and interventions. While there are startups and others who are beginning to sell products or make claims about climate interventions, they lack sufficient information and capabilities for monitoring and mechanisms for governance. This highlights the need and urgency for robust public research.

The global community should consider it a matter of urgency to better understand and respond to catastrophic near-term climate risks. Imperatives for these efforts should be to:

- **Reduce climate disaster risks** for people and ecosystems, with an emphasis on the most vulnerable communities and natural systems, focusing on the risks within the 30- to 40-year time horizon in which the climate is projected to continue to warm.
- **Monitor and avoid tipping points** for catastrophic changes in major natural systems and economic sectors.
- **Undertake concerted research to support scientific assessment of near-term climate risks and interventions in 5 years**, including rapid improvement in climate observation and prediction and open, peer-reviewed scientific research on specific climate interventions that includes, as needed, small-scale field experiments.
- **Support science-based governance and decision-making** on near-term climate risks and solar climate interventions that include mechanisms for robust, independent scientific assessment.
- ***S*upport international scientific cooperation on near-term climate risk and intervention,** including expansion of activities in the World Meteorological Organization, its Global Atmosphere Watch (GAW) Programme, the Montreal Protocol Scientific Assessment Panel, and the Intergovernmental Panel on Climate Change (IPCC).
- **Provide robust support for research capacity and equitable participation** from vulnerable and developing countries in the Global South.

U.S. Imperatives

U.S. imperatives for climate safety, security, and economic leadership demand better information on, and an expanded portfolio of options for, responding to near-term climate risks. U.S. scientific research also plays a central role in supporting international climate and environmental science and governance for the rest of the world.

A coordinated U.S. scientific research effort structured around a 5-year roadmap could deliver a robust scientific assessment of the potential for solar and other promising climate interventions to reduce near-term climate risks. It could also facilitate expanded international participation in research to support more effective and equitable decision-making, including for those most affected by climate change.

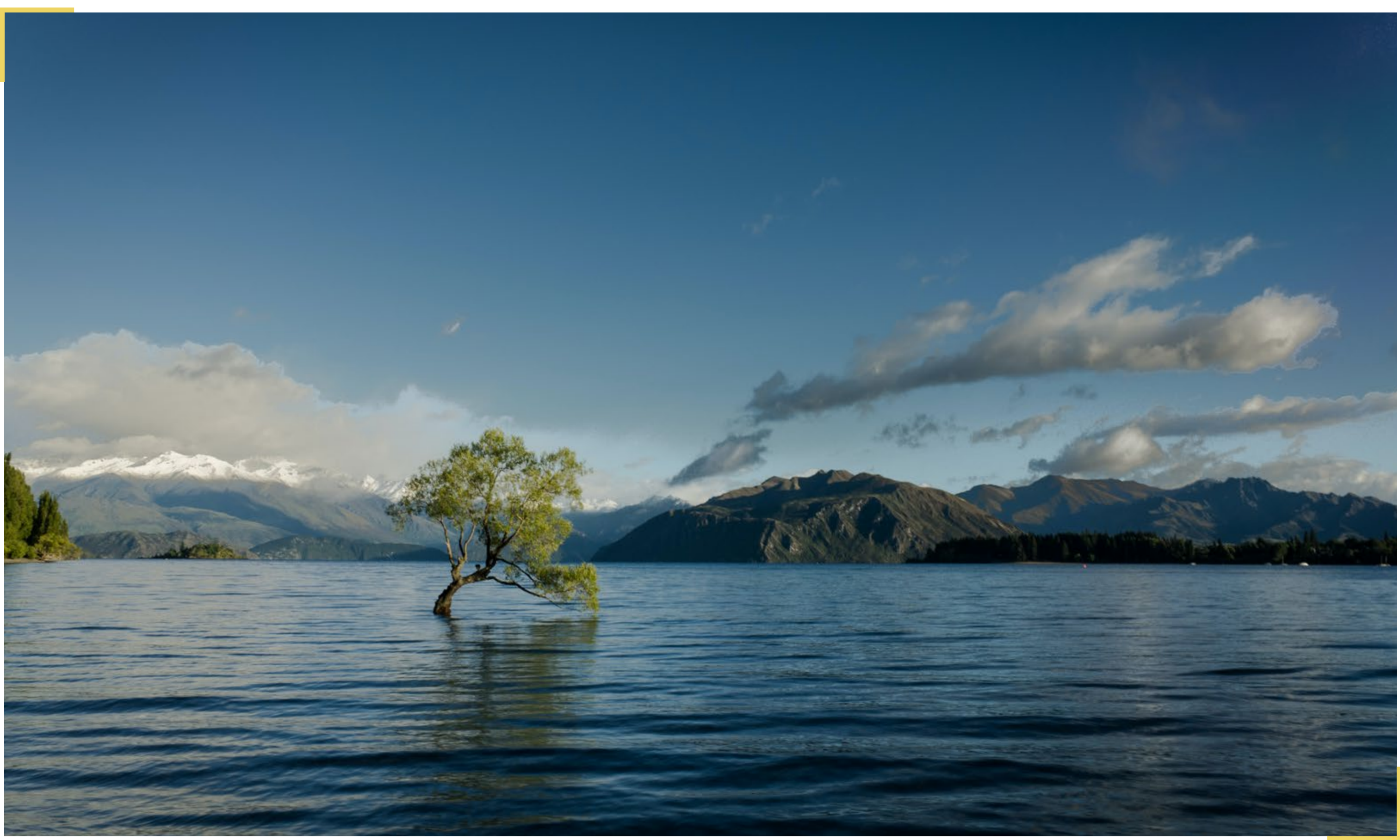
Given this, the United States should undertake a national **Climate Safety Initiative** to generate and assess information on the potential for climate interventions to reduce catastrophic near-term climate risks and support international cooperation on scientific research and decision-making on climate intervention. Specific actions should include:

- **Execute an ambitious 5-year roadmap of research** to support scientific assessment of near-term climate risks and rapid climate interventions in order to:
    - Rapidly accelerate improvements in climate prediction and risk analysis.
    - Rapidly expand observations of the atmosphere and critical natural systems.
    - Deliver the research required to assess approaches for increasing the reflection of sunlight from the atmosphere and any other promising climate interventions.
    - Develop an early warning system and the capabilities to identify and prevent breaching tipping points in major natural systems, including a concerted effort on polar systems.
    - Accelerate adoption of advanced technologies (high-performance computing, cloud computing, autonomous platforms, etc), and expansion of the technology workforce for climate research.
- **Provide $2.6 billion per year in new funding for U.S. federal climate research** (see the appendix for details on specific research activities and associated projected costs) over the next 5 years to support the research and observations required to assess near-term climate risk and intervention, with investments centered in observation and projection of influences on the atmosphere and their effects on climate.
- **Establish a mandate for monitoring, reporting, modeling, and projecting the composition of the atmosphere,** including GHGs, aerosols, and other climate-impacting substances, from the lower atmosphere to the stratosphere. This includes developing expansive capabilities for high-fidelity observations, such as:
    - Developing and operating global networks of, and data and scientific capabilities for, atmospheric observing instruments installed on commercial aircraft and ships.
    - Developing and operating a sustained capability for observation of the composition of the stratosphere, including long-range, high-payload platforms.
- **Support the expansion of international cooperation on solar climate intervention in intergovernmental bodies,** including the Montreal Protocol Scientific Assessment Panel, the World Meteorological Organization (including the GAW and the World Climate Research Programme), the Inter-American Institute of Global Change, and other intergovernmental scientific bodies.
- ***S*upport international scientific cooperation on research in near-term climate risks and climate interventions,** including substantial financial and technical resources for research in vulnerable and developing countries.

Recommendations for Key Stakeholders

Beyond government and intergovernmental institutions, other key stakeholders play critical roles in supporting improved knowledge, international cooperation, and effective and equitable decision-making on near-term climate risk and intervention. For example:

- **The research community** can collaboratively build and refine roadmaps for research, foster diverse and international collaboration, participate in scientific assessment processes, support strong scientific independence and integrity practices, and take special care in accurately communicating findings.
- **The technology sector** can accelerate progress by engaging with research programs, underwriting projects to facilitate the adoption of advanced technologies (e.g., cloud computing, autonomous sensing), and investing in related areas of innovation.
- **Civil society** can help to center consideration of climate intervention on real-world outcomes for people and natural systems (i.e., disaster risk reduction, sustainable development goals), support science-based governance, demand scientific research, and support the expansion of research capacity and technology access in the Global South.
- **Philanthropists** can fund early research and innovation, Global South research, and science-based governance efforts.
- Finally, **individuals** can demand that policymakers invest in the research, innovation, and science-based decision-making necessary to ensure a safe climate.



CHAPTER I

Introduction

The impacts of climate change are devastating communities and ecosystems in the United States and around the world. Natural systems are reaching points of stress in which they become unsustainable and change irreversibly in ways that accelerate climate change, magnify catastrophic impacts, and are less able to support diverse life.

While reducing emissions continues to be crucial, no level of reduction undertaken now can reverse the warming effect of GHGs that are already in the atmosphere. The Earth is projected to continue to warm for several decades in all of the climate change scenarios considered by the UN's IPCC. This poses catastrophic risks for which society currently lacks adequate responses.

In recent years, scientists have assessed proposed approaches for actively removing GHGs or heat energy from the atmosphere, also known as "climate interventions." As climate-linked disasters escalate, various stakeholders around the world have begun to examine the potential for climate interventions to reduce the worst impacts of climate change.

Among the most rapid are approaches that leverage natural system processes to increase the reflection of sunlight (or release of longwave radiation) from the atmosphere, known as "solar climate intervention" (sometimes called "solar radiation modification" or "solar geoengineering"). While solar climate interventions are promising for their potential to reduce global warming, there is considerable scientific uncertainty around the Earth system processes at the center of these approaches. There is also the potential for significant adverse side effects and differentiated effects in different parts of the world.

Understanding the potential for solar climate interventions to reduce the severe risks of near-term warming requires comparing the benefits and risks of various interventions to those from the projected impacts of climate change. However, underinvestment in research and observation of the climate system, along with the very early state of climate intervention research, means that society currently lacks the information and capabilities to adequately make this analysis.

Given the magnitude of climate risks and impacts, there is an urgent need for an ambitious research effort to promote climate safety, including the exploration and assessment of the potential for climate interventions to reduce near-term climate risks and impacts while society transitions to a sustainable future.

CHAPTER II

Near-term Climate Risks

The magnitude of climate threats demands an urgent focus on the near-term risks facing human and natural systems, including the world's most vulnerable.

Recent studies have shown that carbon dioxide emissions are reaching record highs. As a result, global temperatures continue to rise (see Figure 1).

Reducing the emissions that are the underlying cause of climate warming is urgent and imperative. However, no level of emissions reduction can counter the warming effects of GHGs that are already in the atmosphere. **The Earth's climate will continue to warm substantially through 2050 under all emission scenarios considered by the UN's climate change assessment body, the IPCC** (see Figure 2).

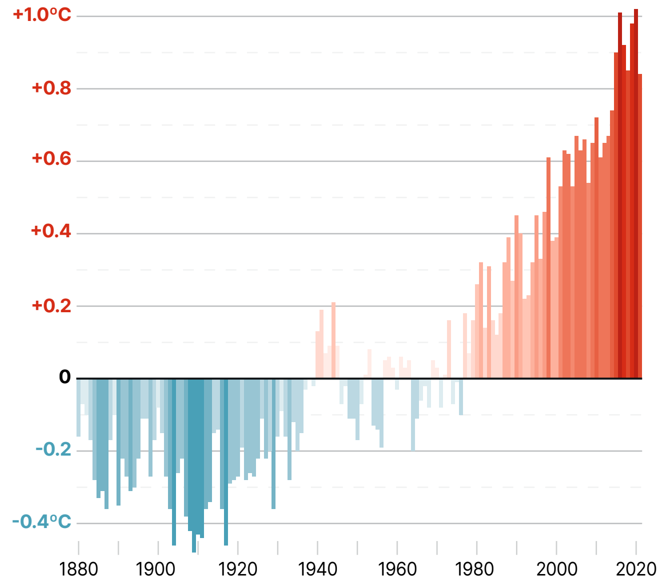
This warming will drive increases in extreme heat, drought, flooding, severe storms, wildfires, infrastructure failure, and loss of species and ecosystems over the next 30–40 years, resulting in significant increases in human mortality, displacement, food insecurity, economic loss, and geopolitical instability (see Figure 3). By 2050, over 1 billion people may be displaced by climate change, mostly in developing countries. Policymakers have not yet developed options or plans for their improved safety.

This ongoing warming also increases the risk of reaching thresholds for major changes in natural systems that could accelerate warming or impacts, often referred to as "tipping points." Recent observations and analytical studies of instabilities in permafrost, ice sheets, terrestrial forests, and ocean and atmospheric circulation systems suggest that these risks are now very significant (see Figure 4). Recent reports from the Organization for Economic Development and others have indicated that these risks now require urgent attention.

FIGURE 1

Global Average Temperature Compared to the Middle of the 20th Century

Global Temperature Anomaly (compared to 1951–1980 average)

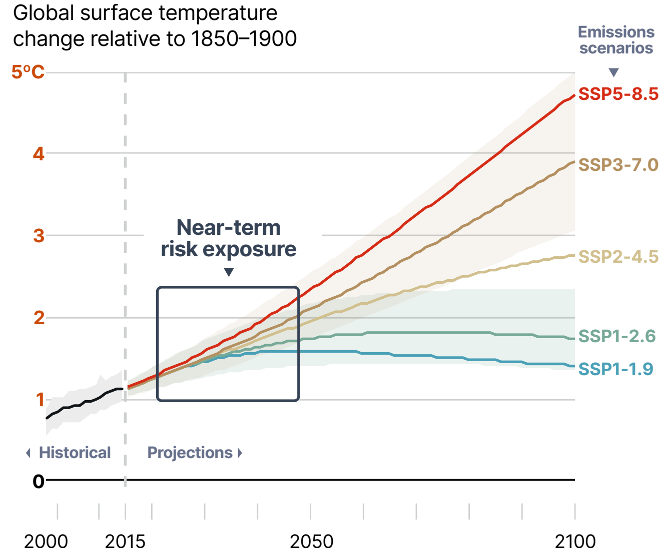


Source: https://www.nytimes.com/2020/04/23/learning/whats-going-on-in-this-graph-global-temperature-change.html

FIGURE 2

Projected Climate Change Under Various Emissions Scenarios

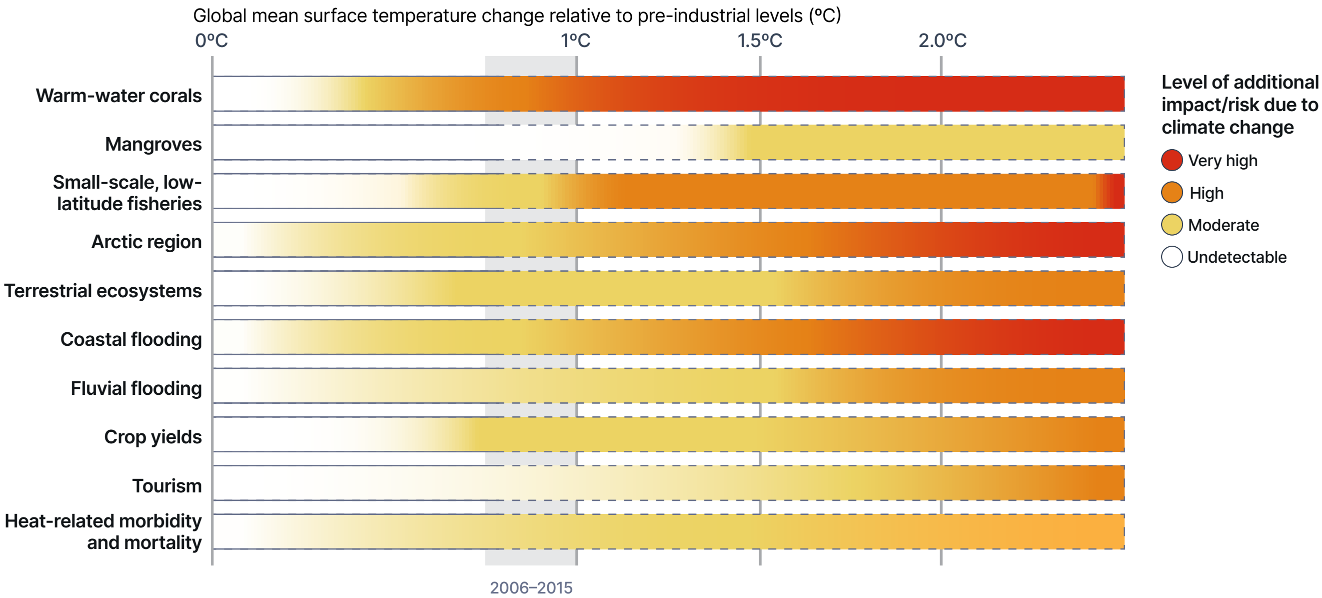
Global surface temperature change relative to 1850–1900



Source: https://www.ipcc.ch/report/ar6/wg1/figures/summary-for-policymakers/figure-spm-8

FIGURE 3

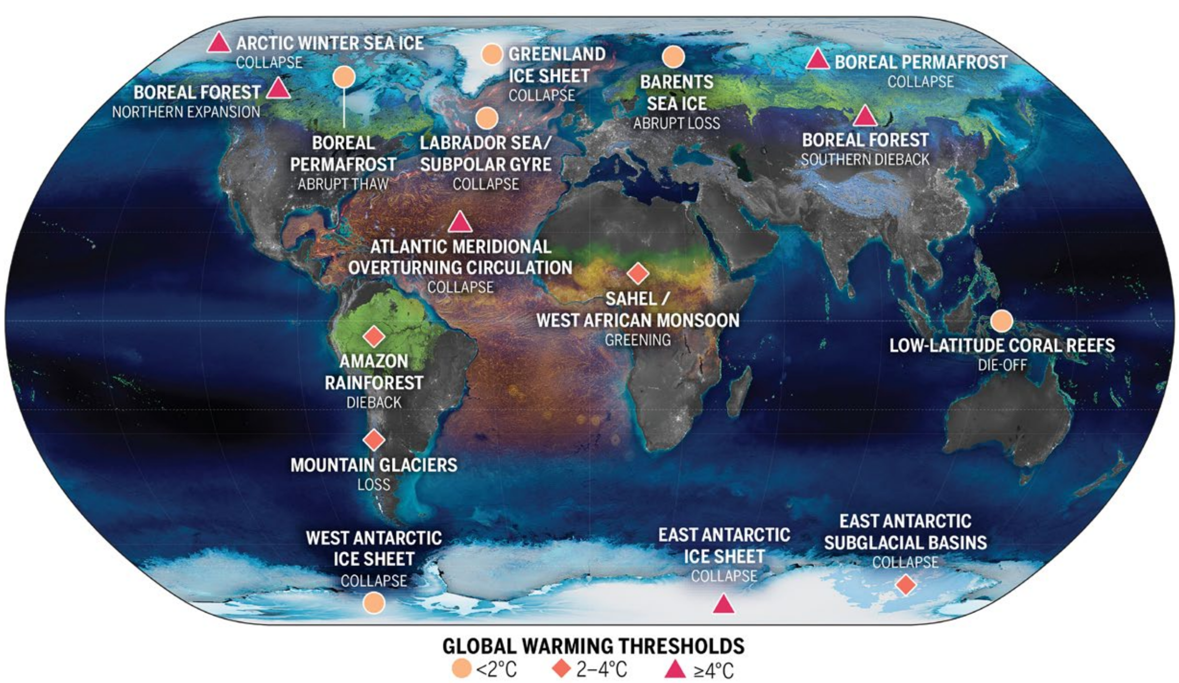
Impacts and Risks for Selected Natural, Managed, and Human Systems



Source: https://www.ipcc.ch/site/assets/uploads/sites/2/2019/02/SPM2.png

FIGURE 4

Climate Tipping Points in the Cryosphere, Biosphere, Ocean, and Atmosphere



Source: https://www.science.org/doi/10.1126/science.abn7950

The Cooling Effects of Particulate Emissions on Climate

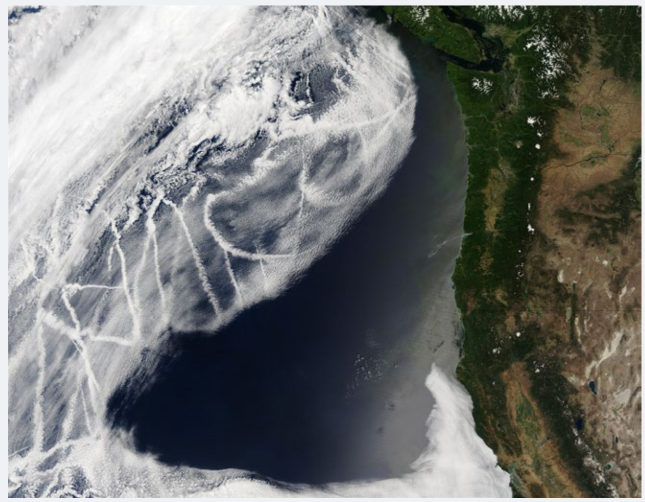
Particles (i.e., aerosols) in the atmosphere generally increase the total amount of sunlight reflected to space by scattering incoming sunlight. Anthropogenic activities produce both GHGs and other particulate matter; while GHGs warm climate, aerosols have a cooling effect both by directly scattering sunlight (i.e., the aerosol direct effect) and indirectly as the aerosols interact with clouds, increasing their brightness and/or their duration (i.e., the cloud–aerosol effect) (see Figure 5). One form of this effect is observed when the particulate emissions from ships influence clouds and create bright trails, also known as "ship-tracks."

The potential global cooling effect of all anthropogenic aerosols is estimated at 0.5–1.1°C (see Figure 6). Thus, these effects are potentially very large while also serving as a large source of uncertainty, making reducing these uncertainties among the highest priorities for climate research, particularly in the context of assessing near-term climate risk.

Particles from emissions produced by human activities are also associated with significant adverse health and environmental effects. Actions are ongoing around the world to substantially reduce them, including recent regulation to substantially reduce sulfate emissions from ships. As the world reduces these particulate emissions, the loss of this cooling "shield" could lead to rapid substantial warming.

FIGURE 5

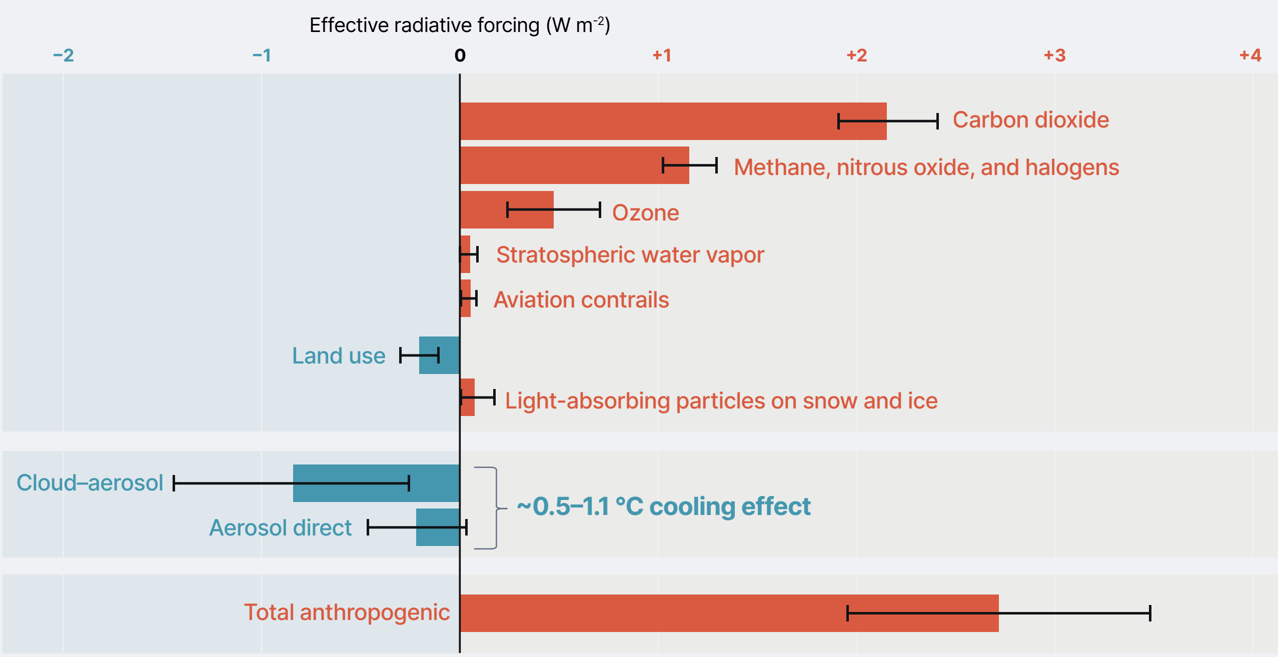
Ship-Tracks Off the Pacific Northwest Coast of the United States



Source: https://visibleearth.nasa.gov/images/66963/ship-tracks-off-the-western-united-states

FIGURE 6

Change in Effective Radiative Forcing from 1750 to 2019



Source: https://www.ipcc.ch/report/ar6/wg1/figures/chapter-7/figure-7-6

CHAPTER III

Climate Intervention

In recent years, scientists have recommended research on approaches to rapidly remove GHGs or heat energy from the atmosphere, also known as “climate interventions.” They may provide options for protecting the safety of the world’s people and the stability of its natural systems.

Understanding the efficacy and risks of climate interventions requires more knowledge of the basic science underpinning these processes than is available today.

While this report focuses on solar climate intervention, which is the leading candidate for rapid reduction of global warming, many of the recommendations herein extend to other nature-based approaches.

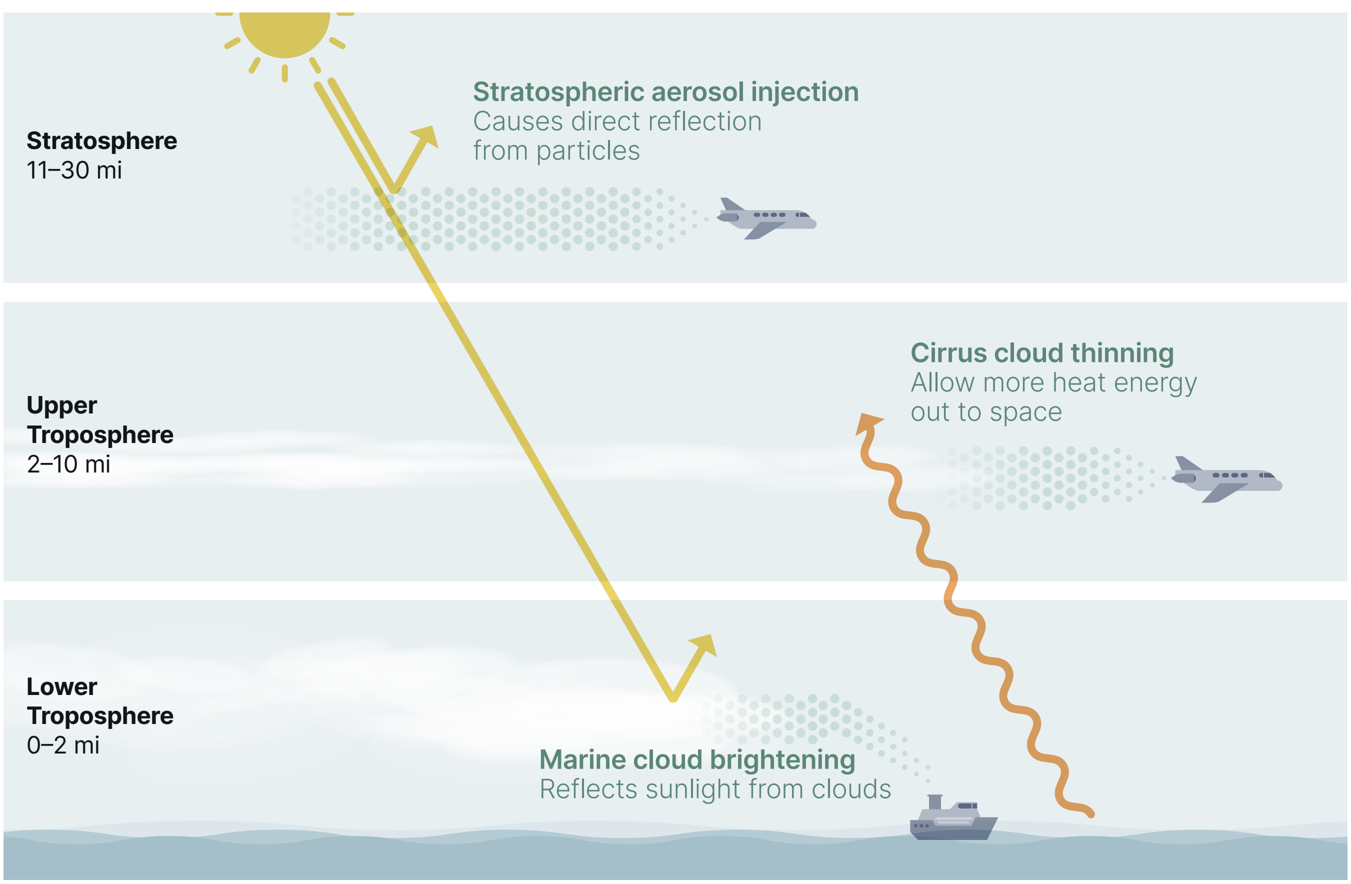
Solar Climate Intervention

Scientific assessments undertaken by the National Academies of Sciences, Engineering, and Medicine (NASEM) and others have identified the most promising approaches for rapidly stabilizing or reducing global temperatures within a few years after development. These approaches would increase the amount of sunlight reflected by particles and clouds in the atmosphere or increase the amount of outgoing long wave radiation from Earth by changing the properties of clouds, phenomena that occur in nature and already play a major role in the regulation of Earth's temperature.

The most promising solar climate intervention approaches include (see Figure 7):

- Dispersing particles in the stratosphere to scatter sunlight directly (i.e., "stratospheric aerosol injection"),
- Dispersing particles into lower troposphere marine clouds to increase their reflectivity (i.e., marine cloud brightening [MCB]), or
- Dispersing particles into cirrus clouds in the upper troposphere to reduce their insulating effect on longwave radiation (i.e., "cirrus cloud thinning").

FIGURE 7
Promising Approaches to Rapid Climate Intervention



Source: SilverLining

These approaches differ in terms of their projected duration, magnitude, potential side effects, and current level of uncertainty. The direct and indirect effects of these approaches are determined by key atmospheric and physical processes, including the effects of particles on clouds, atmospheric chemistry and circulation, and other processes.

Analogous forms of these cooling influences already occur today (e.g., when large volcanoes erupt or particles emitted from burning fossil fuels alter cloud properties). In fact, natural and pollution-linked aerosol influences on the atmosphere and climate are central areas of climate research. Major gaps remain in scientists' understanding of how aerosols influence current and future climate outcomes, making research in solar climate intervention highly overlapping with fundamental climate science research.

For a more complete discussion of these approaches, see chapter 3 in Ensuring a Safe Climate *(SilverLining 2019).*

Governance and Decision-making

Climate interventions have the potential to reduce the impacts of climate change substantially, benefiting the world's most vulnerable people and natural systems. They could also help prevent the acceleration of climate changes and impacts to a point that is beyond humans' ability to counter or adapt.

Reflecting a fundamental precept of international environmental law**, the overarching goals of governance of near-term climate risk and intervention should be safety for the world's people and sustainability for the natural systems that support them.**

Use of climate interventions at scales that significantly impact the environment and climate can and should be heavily debated and governed by society and considered by sanctioned bodies with relevant expertise and decision-making authority. These bodies will need robust information to make sound decisions in the context of the uncertainties, risks, and enormous impacts of climate change.

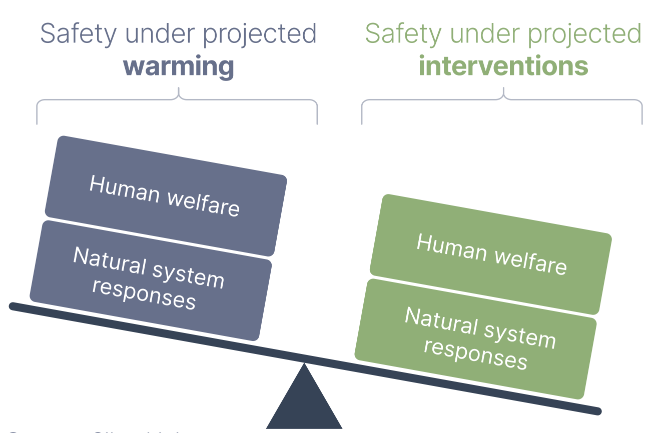
As a result, under any governance regime, **research that does not pose significant and sustained negative environmental impacts should be protected and enabled** in order to provide policymakers with the necessary information to evaluate the risks and benefits of scaled research efforts or deployment.

EVALUATING SAFETY

There is reasonable cause for concern about how different implementations of climate intervention could affect communities, ecosystems, and vital resources and how these effects might be distributed. As a result, it is critical to evaluate the safety of human and natural systems under projected climate change against the safety of possible interventions (see Figure 8). **Scientists and policymakers cannot compare these two "safeties" with the current level of information.**

International bodies currently exist that could both facilitate the production and assessment of policy-relevant science that would inform the international governance of decisions on climate intervention. The world's most successful international environmental framework is the Montreal Protocol. In addition to being responsible for reducing ozone-depleting emissions sufficiently that the ozone hole is now starting to heal, the Montreal Protocol has effectively limited global warming more than any other treaty because many of the same substances that deplete ozone are also very powerful GHGs.

FIGURE 8
Safety of Climate Change Versus Intervention



Source: SilverLining

SCIENCE-BASED APPROACH

Like other successful environmental protection efforts, the Montreal Protocol framework employs three building blocks to ensure decisions about environmental actions are made cooperatively and informed by science:

- Research,
- Science-based decision-making and governance, and
- Scientific assessment.

Science-based decision-making and governance rely on high-quality scientific and technical information generated through research and evaluated by experts to inform decisions and the design of monitoring, reporting, and regulating regimes. In national and international environmental bodies, it is centered in periodic, independent scientific assessment.

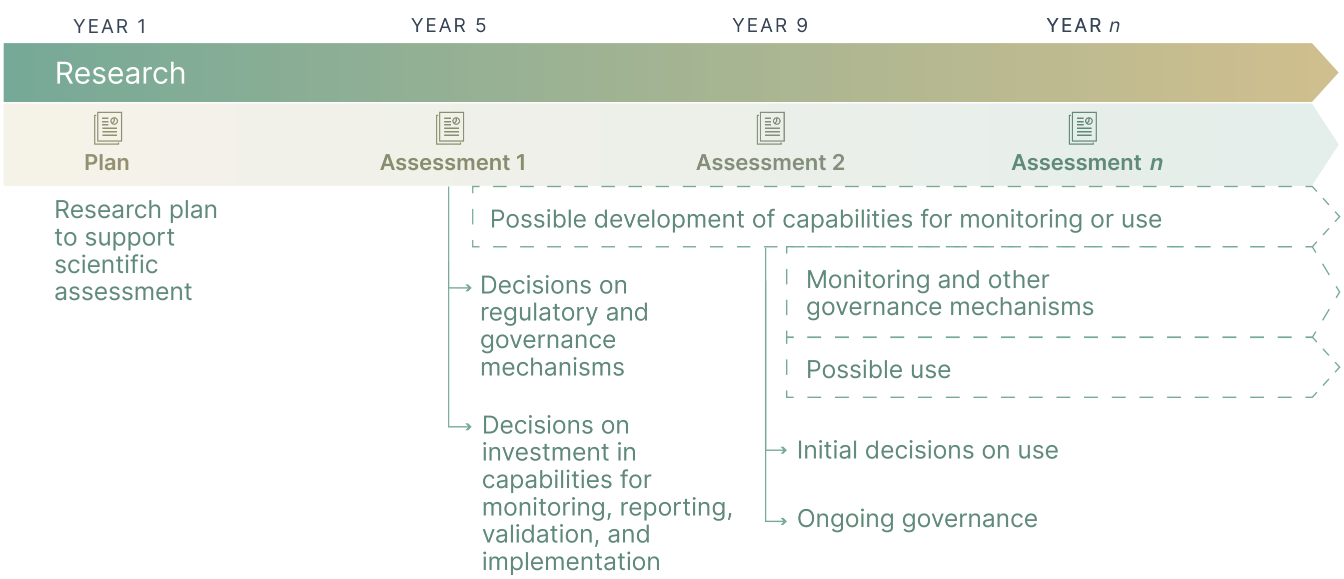
Scientific assessment entails deliberate expert review of a myriad of studies looking at different aspects of the problem under various scenarios to develop a view of broader implications. This process is critical for the healthy development of a research ecosystem and accurate information for policymakers and the public; otherwise, findings from individual studies (e.g., from simplified model simulations) or claims by individual research could lead to inaccurate or incomplete conclusions. Governance regimes developed without robust scientific assessment mechanisms are less effective at informing decisions, minimizing harms, monitoring and regulating activity, and producing successful outcomes.

In the case of near-term climate risks and climate interventions, assessment, decision-making, and governance should address the two safeties. Assessments can inform not only decisions about whether and how to use climate interventions but also in monitoring, reporting, and validation capabilities needed for any potential use, such as those that might occur outside of any international agreement.

Science-based governance of near-term climate risks and interventions depends on developing the substantial body of research needed to inform rigorous and ongoing scientific assessment (see Figure 9).

FIGURE 9

Roadmap for Science-based Governance and Decision-making



Source: SilverLining

An initial assessment is required to support forward decisions on solar climate interventions. It would also reveal the source of significant uncertainties and therefore help with prioritizing the focus areas of future research. The assessment will inform decisions on making the substantial investments that would be required for capabilities for monitoring or intervening in the climate system at scale. It will also inform decisions about regulation of the use of climate interventions and the design of forward governance mechanisms and agreements regarding their use.

For a more complete discussion of governance considerations, see chapter 4 in Ensuring a Safe Climate *(SilverLining 2019).*

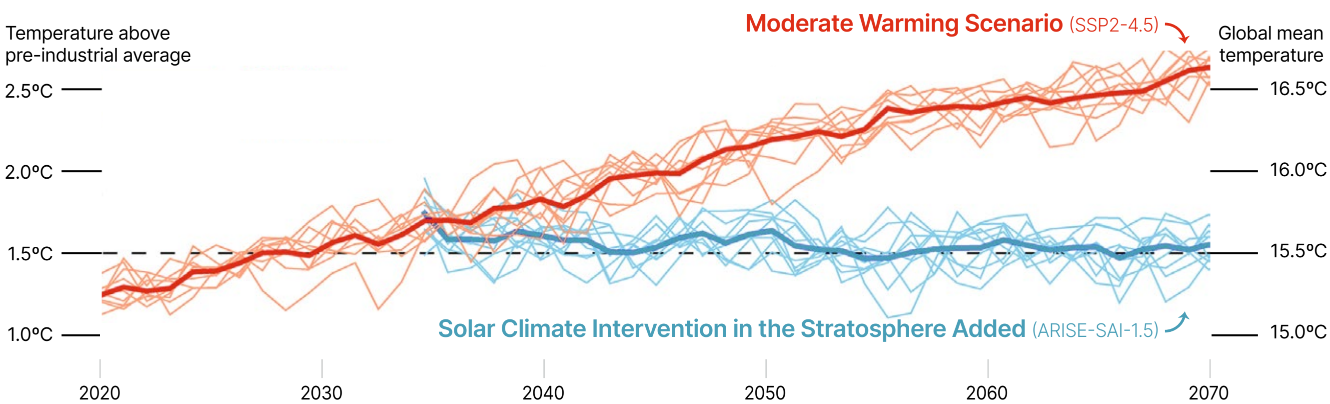
The Nature of Research

Research to inform an assessment of the potential of solar climate interventions to improve the safety of near-term climate risks involves projections and analyses of future climate conditions to compare the likely effects of interventions against the effects of projected warming (see Figure 10). It also includes the identification of possible thresholds for abrupt change or escalating GHGs or warming feedbacks from natural systems (i.e., "tipping points"), such as permafrost (see Figure 11), as potential targets for intervention.

The required body of research is highly interdisciplinary and centered in atmosphere and Earth system sciences. It also requires research in related natural sciences and human systems sciences for studying impacts and other aspects of safety and sustainability.

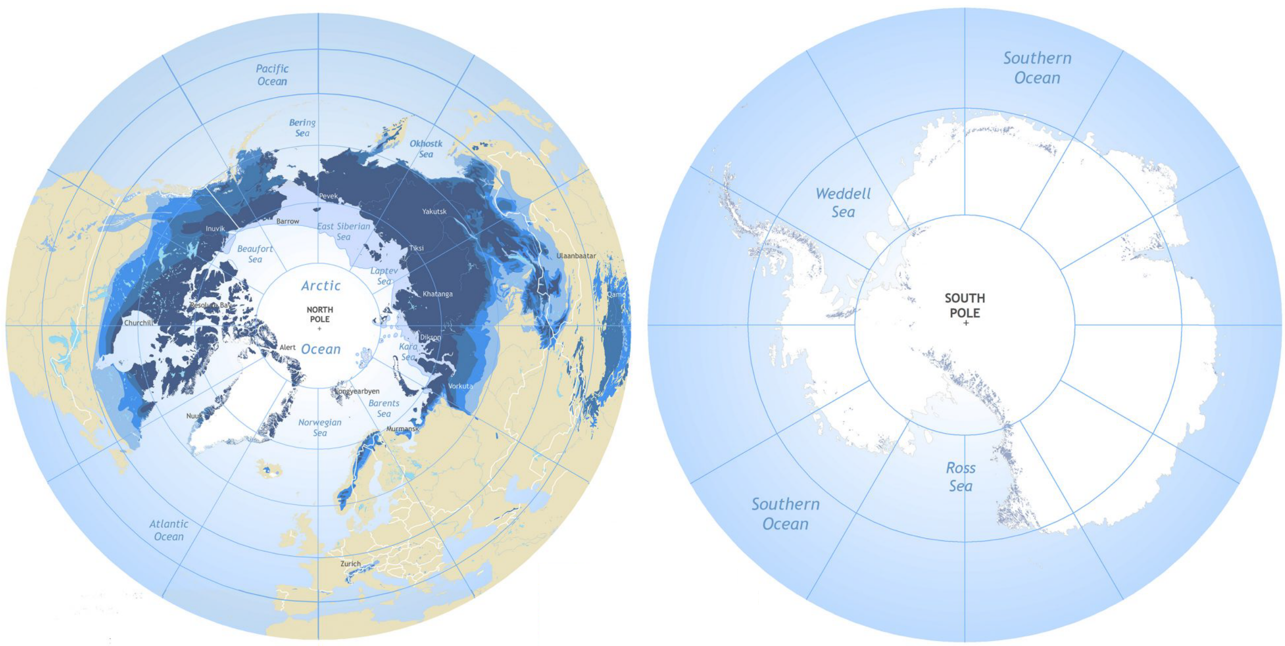
FIGURE 10

Global Mean Temperature Under a Moderate Warming Scenario and with Solar Climate Intervention in the Stratosphere Added



Source: https://gmd.copernicus.org/articles/15/8221/2022/gmd-15-8221-2022.html

FIGURE 11
Global Permafrost Map



Continuous permafrost | Discontinuous permafrost | Sporadic permafrost | Isolated patches | Subsea permafrost

Source: https://www.weforum.org/agenda/2020/02/irreversible-emissions-permafrost-tipping-point

It includes characterization of the atmospheric processes underlying solar climate intervention approaches; their accurate representation in models used to simulate their effects at larger scales; and, based on these models, a large inventory of studies across scales, regions, and human-system interfaces. It also requires substantial improvements in scientific capabilities for climate observation and prediction.

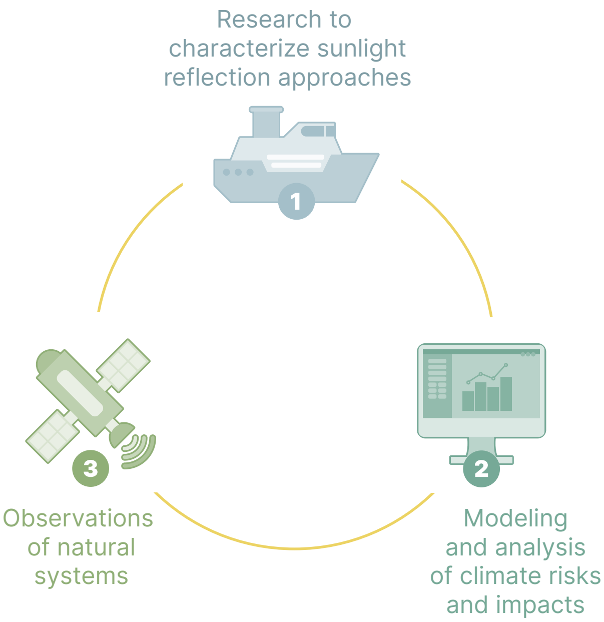
Generating this information requires focused research on specific intervention approaches as well as substantial improvements in scientific capabilities for observation and prediction of closely related natural systems and processes (e.g., atmosphere composition, surface carbon fluxes) and climate in general (see Figure 12).

Characterizing solar climate intervention approaches necessitates research to develop models and analytics tools to project their impacts on the environment. In recent reports by NASEM and others, scientists have stated that this requires small-scale releases of particles into the environment (i.e., field experiments) to study their behavior and the response of the local system in order to develop and refine models of their effects at larger scales.

The small-scale release studies proposed for research are highly distinct from activities that would produce significant or sustained effects on the climate or environment. The Earth system is very large and releases at a scale that would have significant environmental impacts or affect climate would require substantial capabilities development and investment.

FIGURE 12

Near-term Climate Risk and Intervention Research Areas



Source: https://doi.org/10.1007/s10584-022-03446-4

Large-scale releases of material into the atmosphere are also already subject to a variety of regulations related to pollution analogues.

In fact, the mechanisms by which solar climate interventions could be used to cool the Earth's climate are observed in the effects of both natural and anthropogenic emissions. In particular, research would accelerate understanding of some of the largest uncertainties in climate change, such as the effect of particles on clouds and climate. **Thus, much of the required research is dual purpose, with the potential to accelerate both a broad-based understanding of climate as well as manage climate risks.**

Advancing this research is not easy. The Earth system is one of the largest and most complex subjects of analysis of any field of study for humanity. It includes various types of non-linear behavior (e.g., abrupt changes, emergent phenomena) that are not easily or fully represented in climate models and for which analysis can benefit from new and varied analytical and modeling approaches. Effectively analyzing and simulating the climate requires advanced technologies (i.e., high-performance computing, satellites, etc.) operating at massive scales. Because of this, climate research can benefit from the adoption of the most advanced, efficient, and scalable approaches available as well as innovation to push the boundaries of efficiency and scale beyond the current state of the art.

In addition to a large body of research on the physical climate system, research on human systems (e.g., economics, public health) is critical to inform understanding of anthropogenic influences on the climate system, of climate impacts on human systems and communities, and feedbacks between the two. Understanding near-term climate risks and interventions requires both substantial research in these areas as well as ongoing collaboration among physical and social scientists as more information becomes available.

Escalating climate disasters and risks as well as gaps and uncertainties in climate research drive imperatives for the rapid generation of information for the assessment of possible responses, including solar climate interventions. Research takes time, and plans must consider the feasibility of generating research alongside the urgency of demands for findings. Delivering against these demands requires a coordinated plan.

For a more complete discussion of these considerations, see the paper series International Policy on Near Term Climate Risks and Interventions *(Biniaz, Bodansky, and Wanser 2020).*

CHAPTER IV

Roadmap for Research

Given the nature of research on near-term climate risks and solar climate intervention approaches and the time-sensitivity of better information, it is important to develop plans now to significantly reduce key uncertainties in a defined period of time—a roadmap for research.

Roadmaps are integrated, interdisciplinary plans designed to support the coordinated delivery of outputs in a defined time frame. While they have been less common in climate research (where much of the work is undertaken as basic science) than in other more applied fields, like technology and space exploration, there is growing recognition that a forward-planning roadmap approach would be beneficial to climate research in general.

Assessing near-term climate risks and possible interventions requires reconciling the feasibility of generating information with the urgency of policy responses. With escalating major risks to human and natural systems and the climate projected to cross the 1.5°C threshold for safety within a decade, there is considerable urgency. Because significant time is required to generate and analyze information, this report follows the approach directed by the U.S. Congress for a roadmap of research to support scientific assessment of near-term climate risks and solar climate intervention in 5 years.

Research Objectives and Key Questions

A research roadmap for near-term climate risks and solar climate interventions starts with identifying the primary objectives and key questions that support the evaluation of the safety of projected climate change against the safety of solar climate interventions.
This requires evaluating specific climate intervention approaches alongside substantially improved projections for climate and impacts. There are two high-level objectives associated with evaluating these two safeties: the characterization of climate intervention approaches (objective 1) and the projection of the safety of the climate system in a warming world (objective 2). The following explores each objective more closely, along with their associated key questions.

Objective 1: Characterize the key processes associated with climate intervention approaches and represent these processes in models and analyses used to project and quantify the risks of global climate impacts.

Key questions surrounding objective 1 include:

- What are the characteristics of the most optimized releases of particles (e.g., size, distribution, volume) that can be achieved technically? How do aerosol particles evolve, disperse, and influence the local atmosphere under different conditions?
- How can the influences of aerosols introduced through climate intervention versus background aerosols be distinguished under different conditions?
- How much global cooling can be achieved through different implementations of solar climate intervention and in different future climate scenarios?
- What is required to incorporate solar climate intervention processes into global and regional projections of climate under different scenarios for future climate and ranges of natural and anthropogenic emissions?

Objective 2: Evaluate the projected near-term impacts and risks of a range of climate change scenarios without and with intervention.

The key question surrounding objective 2 is, how are regional and global climate impacts altered through different solar climate intervention implementation scenarios and strategies under different future climate scenarios?

This question requires addressing critical gaps in climate research relevant to improved understanding and projection of the atmosphere and climate and the effects of climate interventions such as:

- Reducing uncertainty in aerosol influences on the atmosphere and climate.
- Improving projections of near-term climate impacts and risk analyses with and without intervention.
- Identifying where climate-related risks and impacts are most likely to be influenced by intervention.

Building the Research Roadmap

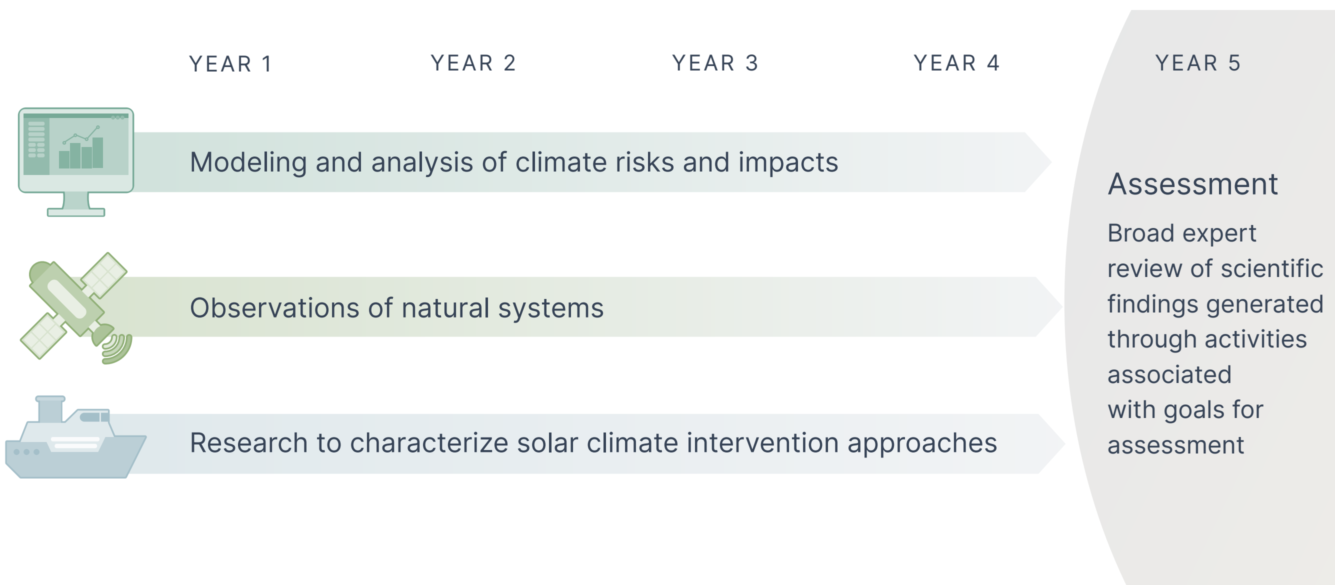
Building the roadmap requires identifying the research activities required to fulfill the primary objectives and answer the key questions along the required 5-year time horizon. This starts with defining high-level areas for research linked to the objectives. Objective 1 translates to the first high-level area for research: research to characterize solar climate intervention approaches. Objective 2 requires two distinct major areas for research and capabilities development: (1) modeling and analyses of climate risks and impacts and (2) observations of natural systems (see Figure 13).

Each area requires advances in research and development to deliver the information required for a robust scientific assessment. Specifying these advances requires identifying relevant categories of research within each of the areas. Importantly, it also requires identifying minimum essential advances or targets for accelerating progress (i.e., "goals") for each category to support requisite research activities in the defined 5-year time frame (see Figures 14 through 16).

From here, researchers in fields relevant to each category can develop priorities and pathways to achieving these goals (i.e., roadmaps) in a framework that facilitates collaboration and coordination within and across categories and disciplines.

FIGURE 13

5-year Research Roadmap to Scientific Assessment



Source: SilverLining

FIGURE 14

Earth System Models and Other Forms of Analysis

Research Category	5-Year Goals
Earth system model development	◆ Improved representation of atmospheric processes associated with climate interventions ◆ Accelerated downscaling and high-resolution modeling efforts ◆ Accelerated advances in the sophistication of dynamically coupled ecosystem models ◆ Accelerated improvements to the representation of abrupt changes (tipping points) and climate feedbacks ◆ Accelerated data assimilation tools and capabilities ◆ Accelerated incorporation of machine learning in study design and analysis ◆ Substantially expanded computing capacity and access including accelerated adoption of cloud computing
Non-model analytical tools and methods	◆ Accelerated application of complex systems and risk analysis methods from other fields
Studies of near-term impacts and risks with and without intervention	◆ Body of global climate model simulations of climate impacts with and without intervention for various scenarios for emissions, intervention, and other climate responses ◆ Body of integrated assessment model studies of impacts with and without intervention to support analysis of biodiversity, human health, energy systems, infrastructure, economic productivity, and global security ◆ Body of studies of natural and anthropogenic analogs to solar climate interventions ◆ Methodology for analysis to identify early warning signals and potential observational metrics for major tipping points ◆ Body of studies on various natural system abrupt change pathways against scenarios for intervention

Source: https://doi.org/10.1007/s10584-022-03446-4

FIGURE 15
Observations of Natural Systems

Research Category	5-Year Goals
Atmospheric observations of high relevance for aerosol-forcing effects/ interventions	◆ Baselines of, and sustained monitoring capabilities for, key aerosol processes and populations across seasons and hemispheres in the stratosphere, upper troposphere, and marine boundary layer ◆ Capabilities for observations of natural system analogs ◆ Sustained observational capabilities adequate to detect significant influences on solar radiation ◆ Sustained aerosol, GHG, and meteorological observations at the ocean surface in targeted regions
GHGs	◆ Sustained observational capabilities sufficient for flux quantification, attribution of sources, and detection of significant changes in feedbacks from natural systems
Global carbon cycle and climate monitoring	◆ Accelerated efforts to eliminate gaps in critical observables ◆ In-situ observations to provide expanded ground-truth sources to support accelerated improvement in satellite information
Other natural systems	◆ Sustained observations sufficient for reducing uncertainties and identifying early warning indicators of abrupt changes in major natural systems associated with climate feedbacks

Source: https://doi.org/10.1007/s10584-022-03446-4

FIGURE 16
Research on Specific Solar Climate Intervention Approaches

Research Category	5-Year Goals
Aerosol generation and dispersal studies	◆ Research-grade aerosol spray generation
Localized processes and outdoor plume studies	◆ Characterization of aerosol processes when introduced into the atmosphere and quantification of uncertainties in responses
Limited-area processes and environmental studies	◆ Models and understanding of chemical and dynamical processes at minimum scale and duration for detecting effects
Analogue and background observational studies	◆ Atmospheric baselines and observations of major analogues
Regional and global model inputs	◆ High-fidelity representation in regional and global models and proof-of-concept simulations
Implementation analysis and operational design tools and methods	◆ Tools and proof-of-concept simulations for evaluating implementation strategies, system design, and operational studies of capabilities

Source: https://doi.org/10.1007/s10584-022-03446-4

Time Dependencies and Critical Path Activities

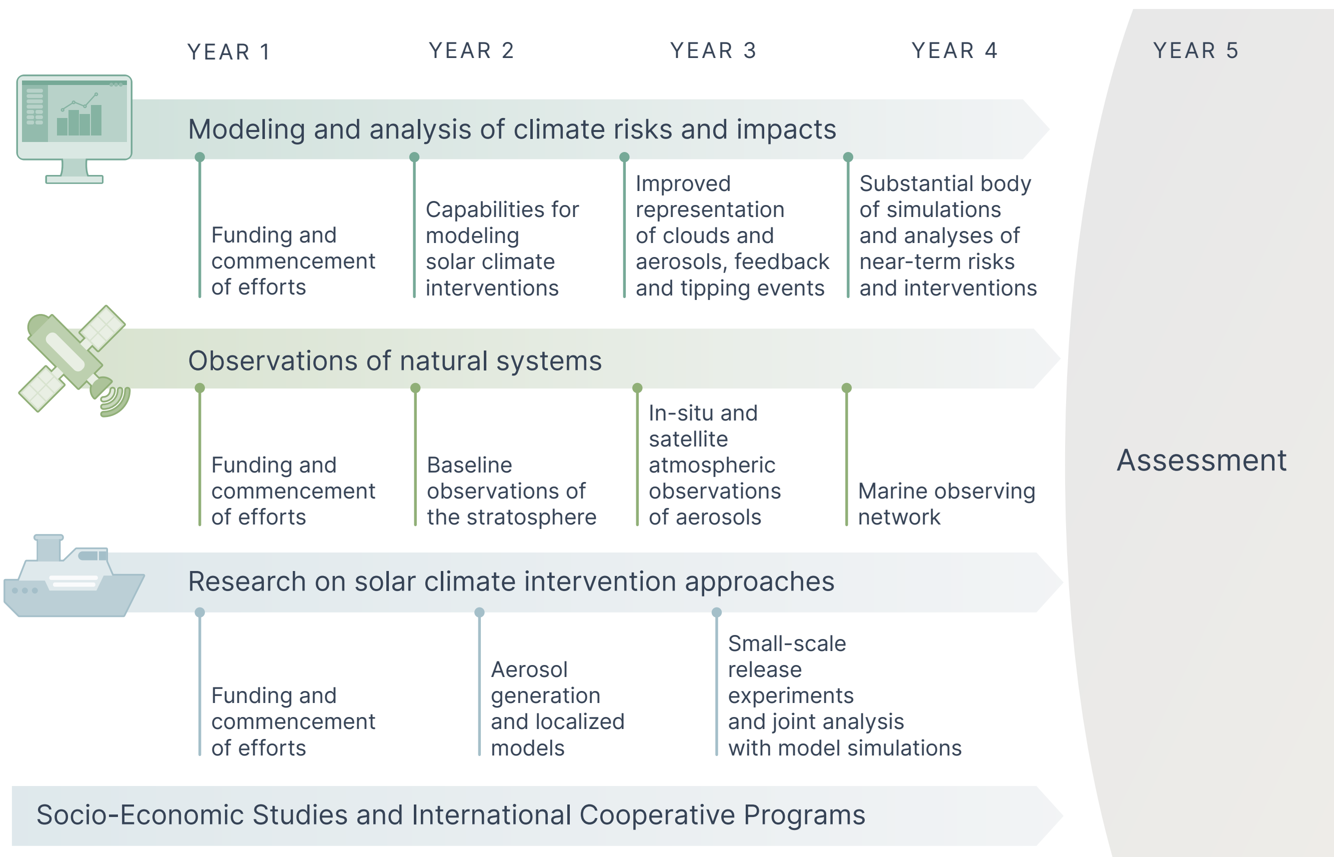
One of the most important aspects of a coordinated research effort is to deliver against the defined 5-year time horizon. A critical part of this process is identifying major time dependencies—milestones in research or capabilities development that must be reached to deliver information or capabilities necessary for other required research or development activities.

There are a number of key critical path activities and time dependencies to deliver a 5-year assessment for near-term climate risks and solar climate interventions. Several are described in Figure 17 and next, illustrating the importance of commencing and successfully executing key activities to be able to deliver information for assessment in the required time frame.

Controlled release experiments require significant technology capabilities and take time and resources to plan, develop, and analyze. A decision must be made early in the roadmap timeline whether an adequate assessment can be made within the period without controlled release experiments and whether required activities can be undertaken within the timeline. Procedures that add uncertainty or delay to the execution of experiments should be considered in the context of the high cost of delay to delivering information and assessment.

FIGURE 17

5-year Research Roadmap to Scientific Assessment



Source: SilverLining

Improved model representation is needed both to simulate climate intervention approaches in global models as well as to develop innovative approaches to incorporate what is learned in smaller-scale, higher-resolution models and from small-scale aerosol release experiments into global models. As such, improvements in modeling capabilities need to be made in advance of when projections are needed, and as the best approaches to some of these issues (i.e., bridging modeling scales) have yet to be identified, this requires significant forward planning.

Atmospheric baselines and monitoring capabilities face major gaps in their ability to characterize the present-day composition of the atmosphere, which is needed to produce baseline simulations, improve models for research and assessment, and monitor significant changes in atmospheric composition from natural or anthropogenic sources. Given that there is also natural variability to baseline properties, these measurements need to be conducted over multiple seasons and years for representative sampling.

Notably, delivering against goals requires prioritizing outcomes and evaluating research plans and activities against their influence on timelines. This may require tradeoffs against consensus practices and engagement processes, and it may prove beneficial for smaller, more focused communities of research to move in concert in some areas.

Designing Research Programs

There are a number of considerations for the design of research programs in near term climate risk and solar climate intervention. A well-structured research roadmap can provide a framework for designing programs around specific cross-sections of goals and activities, such as evaluation of a specific solar climate intervention approach, or the potential for solar climate intervention approaches to reduce the risk of major abrupt change in a certain natural system. There are considerations that cut across all areas of research, most notably technological and analytical innovation and adoption that can accelerate the collection, generation, and analysis of information. And, since the climate system is highly coupled with human systems, there is a substantial body of socio-economic research required to fully project the effects of climate change and inform decisions about climate interventions.

RESEARCH TO CHARACTERIZE CLIMATE INTERVENTION APPROACHES

A roadmap for research to characterize an individual solar climate intervention approach includes activities to deliver against the goals across all relevant categories. Once identified, these activities must be combined into integrated program plans that include interdisciplinary collaboration, synchronized activity, and resource requirements. Costs can then be applied to deliver estimates of funding requirements.

For example, extensive work has been undertaken by the University of Washington Marine Cloud Brightening Program to identify goals and activities for assessment of the effects of MCB. These include the development of a system to deliver the required plume of particles, field experiments to study the local behavior of these particles and their influence on clouds, and extensive modeling and analytical studies. Dozens of researchers from multiple disciplines and institutions work in interdisciplinary collaboration to iterate on requirements and plans. Cost estimates were developed based on active efforts alongside analysis of observational field studies of similar design.

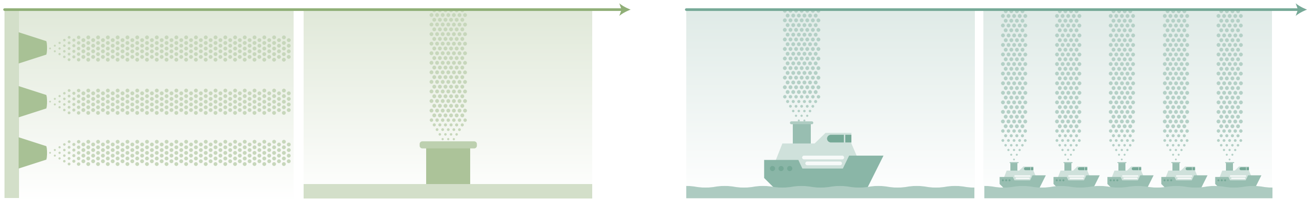
Similar integrated plans are required for other climate intervention approaches. Delivery against these plans requires ongoing coordination across research and development teams over time—a characteristic of applied science programs. A shared roadmap framework can facilitate collaboration and contribution by a broad community of researchers internationally, but substantial applied programs may be required.

FIGURE 18

Marine Cloud Brightening Research Roadmap

Phase 1: Indoor

Phase 2: Field



Aerosol generation and characterization (lab/benchtop studies)

5+ years
$1.5m

Aerosol generation and characterization (full spray system testing and scientific studies)

6–12 months
$3–4m

Single-plume studies in the marine environment

12–24 months
$5m

Limited area field experiment multiple ships/plumes over an area sufficient for studying brightening

6–12 months
$40m

Modeling and Analysis

Studies of effects and impacts at local, regional, and global scales

4 years
$15–20m

Sources: SilverLining, University of Washington.

RESEARCH ON INTERVENTION TO PREVENT MAJOR ABRUPT CHANGES

A roadmap for research to evaluate the potential for solar (or other) climate interventions to reduce the risks of climate change includes the consideration of scenarios for major abrupt changes in natural systems without and with intervention (a modified form of Objective 2).

This requires addressing critical gaps in knowledge and improving capabilities for analysis and projection of relevant natural systems, climate and climate interventions, including:

- Reducing uncertainty in natural system responses to climate change.
- Improving projections of near-term climate impacts and risk analyses with and without intervention.
- Identifying where risks for abrupt changes are most likely to be influenced by intervention.

The roadmap for research on the potential for solar climate intervention to prevent a specific abrupt change combines the activities for a roadmap for near-term climate risk and solar climate intervention with a roadmap of research for improving observation and prediction of the system at risk (ice sheet, permafrost, etc.) and for integrated capabilities and analyses to bring these together (see Figure 19).

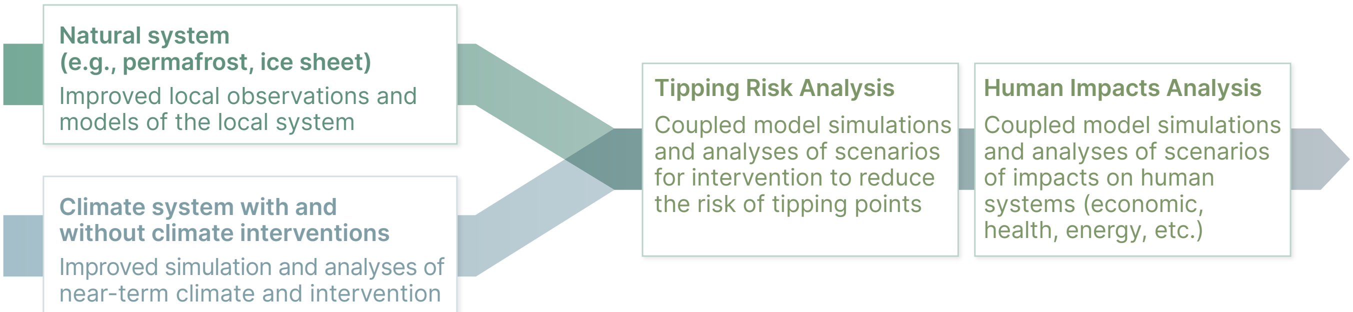
These activities must be coordinated through integrated program plans for interdisciplinary collaboration, coordinated deliverables, resource allocation and funding. **This work has not yet been undertaken for any of the major systems at risk of abrupt change.**

APPLYING ADVANCED METHODS AND TECHNOLOGIES

The climate system is massive and complex, bearing the major analytical challenges found in other complex systems. There are recent and ongoing advances in methods and technologies to understand, monitor, and predict the behavior of complex systems to perform very large-scale computing operations and to gather data from the physical world. These include complex systems studies, portfolio risk management methods,

FIGURE 19

Research on Intervention to Reduce Tipping Point Risks



Source: SilverLining

artificial intelligence and machine learning, hyperscale and cloud computing, autonomous vehicle platforms, and automated and distributed sensing. To be successful, research programs on near-term climate risks and interventions must include collaboration on innovation and adoption of these new methods and technologies.

HUMAN SYSTEMS RESEARCH

There is a need for social sciences research to improve understanding of human system influences on the climate system, the nature of impacts on people, and feedback between the two. For an assessment of near-term climate risks and interventions, this includes reducing uncertainty in the projection of the behavior of energy, industrial, economic, and other human systems and coupled Earth–human system responses.

A well-structured roadmap of physical sciences (i.e., Earth systems) research that facilitates collaboration between physical and social sciences research efforts will accelerate understanding in both fields. Both areas should pursue robust research agendas defined with respect to expertise in relevant fields and oriented toward evidence to reduce uncertainty and promote safety outcomes.

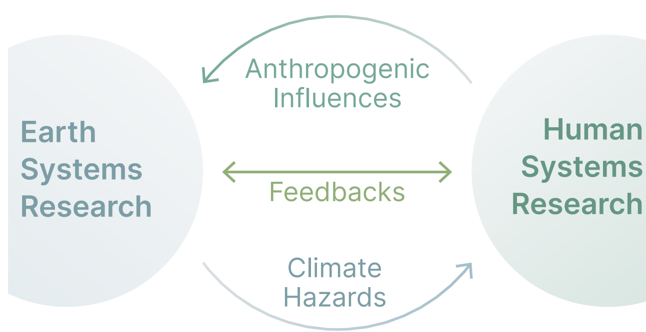
Physical sciences research on Earth systems and hazards can and should be advanced rapidly and independently to improve the information base for human systems studies and as a matter of urgency in informing questions of near-term climate safety (see Figure 20).

A well-structured roadmap for research facilitates the identification of needs (and gaps) in existing knowledge and capabilities for the assessment of near-term climate risks and solar climate interventions. It lays a foundation for collaboration, planning, investment, and the delivery of information for society to help address the urgent problem of near-term climate change.

For additional discussion of these considerations, see Near-term Climate Risks and Sunlight Reflection Modification: A Roadmap Approach for Physical Sciences Research *(Springer 2022).*

FIGURE 20

Collaborative and Independent Human and Earth Systems Research



Source: SilverLining

CHAPTER V

State of Play

Since SilverLining's 2019 report, *Ensuring a Safe Climate: A National Imperative for Research in Climate Intervention and Earth System Prediction* was published, climate linked disasters, slow progress on emissions reductions, and evidence of approaching tipping points have increased dialogue and activity on solar climate intervention and highlighted gaps in understanding of near-term climate risks.

While demand for research and assessment of near-term climate risks and interventions is growing, for many decades, climate research has faced political headwinds and relatively flat funding in most of the world. Solar climate intervention research and research funding have been negligible until very recently. Overall, required scientific research capabilities, resources, and activities face severe gaps.

International Context

Unprecedented climate-linked disasters have occurred in most parts of the world, causing substantial displacement, economic impact, and loss of life. The most impacted countries have demanded more focus on loss and damage and disaster risk, shining a light on information gaps in the prediction and attribution of catastrophic climate events. In 2023, for example, the UN Secretary-General called for creating early warning systems for extreme weather events to cover everyone on Earth within the next 5 years, citing the warming climate and the lack of information available to one-third of the world's population.

Active programs to reduce precipitation extremes (e.g., drought, flooding) by influencing clouds and atmospheric conditions ("weather modification") have emerged and expanded in many countries around the world, including China, Indonesia, Japan, United Arab Emirates (UAE), and the United States. Many center on increasing precipitation to alleviate drought, but some include inducing rainfall off-shore to prevent flooding. They include the UAE's Rainfall Enhancement Program, China's large-scale efforts to increase precipitation, U.S. weather modification efforts across seven states, and a moonshot program in Japan to control and modify weather.

Solar climate intervention research efforts are smaller and more nascent, but there are significant programs at major institutions in many countries including China, the United Kingdom, India, Germany, Switzerland, France, and the United States. Researchers contributing to studies on solar climate intervention number hundreds globally from a diverse array of countries, including many climate-vulnerable countries in the Global South.

In 2022 and 2023, the following developments occured:

- The UN Secretary General and UN Environment Programme convened an expert workshop to provide recommendations on understanding the risks of solar climate interventions. (Its report is pending.)
- The Montreal Protocol Scientific Assessment Panel included the first-ever dedicated chapter on solar climate intervention in an international scientific assessment as part of its *2022 Scientific Assessment of Ozone Depletion* and held a 2-hour briefing on the chapter at its annual Meeting of the Parties.
- The World Climate Research Programme began a process to establish a "lighthouse" effort for international scientific collaboration on solar climate intervention research.
- Numerous panel sessions on the topic were held at the UN climate summit (COP27), including a session on tipping points and climate interventions convened by the UN Climate Change High-Level Champions.
- Over 150 scientists gathered for the Gordon Research Conference on solar climate intervention, and the American Geophysical Union 2022 Fall Meeting (the largest gathering of earth scientists in the world) hosted over 100 scientific presentations and panels on the topic.
- A group of climate activists called for an international "non-use" agreement on solar climate interventions, while prominent climate scientist James Hansen, UN Youth Envoy Joshua Amponsem, and others called for research as a matter of urgency.
- A U.S. start-up offered "cooling credits" for releases from small balloons launched in Mexico. The Mexican government subsequently announced a ban on these activities.

INTERNATIONAL COOPERATION

As climate impacts escalate, the likelihood increases that some countries or actors may engage in climate interventions in response to environmental and/or humanitarian threats or crises. As such, policymakers and other stakeholders face an increased need for information to inform policy and rising demand for mechanisms for governance and decision-making.

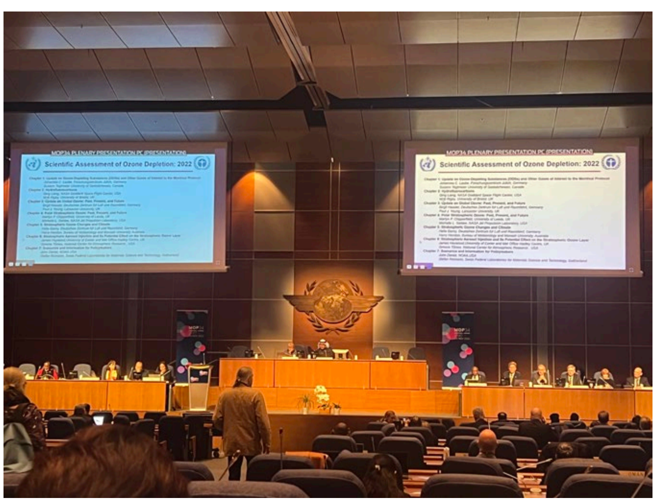
Multiple international assessment and scientific research coordination bodies are well-positioned to play a role in informing and/or assessing near-term climate risks and solar climate interventions.

The most scientifically robust form of international assessment is underway within the Montreal Protocol, where the potential effects of climate intervention in the stratosphere included in its *2022 Scientific Assessment of Ozone Depletion* (see Figure 21). The effort was initiated by a proposal brought forward in 2018 by the following climate-vulnerable countries: the Federated States of Micronesia, Mali, Morocco, and Nigeria. Stakeholders in the Montreal Protocol community have raised the possibility of expanding the work of its scientific assessment panel to include aerosols, which are also entering the stratosphere though aviation.

The IPCC continued to expand coverage of solar climate interventions in its most recent assessment report, *Climate Change 2021: The Physical Science Basis* (IPCC 2021), and some stakeholders in the IPCC community have expressed interest in increasing its coverage of this topic, including the possibility of a dedicated special report. Unlike the Montreal Protocol's regular scientific

FIGURE 21

Montreal Protocol Meeting of the Parties 2022



Source: SilverLining

assessments, IPCC reports are reviewed by governments prior to being finalized. The IPCC process has resulted in some challenges in negotiations between scientists and delegations on the characterization of findings on solar climate intervention.

International cooperation on research is essential to expanding and diversifying the research ecosystem; promoting equitable access to information; developing local expertise for consultation with communities; and supporting cooperative, science-based decision-making. International and intergovernmental research bodies, such as the World Meteorological Organization, and within it, the World Climate Research Programme and the Global Atmosphere Watch (GAW) Programme, perform essential functions in facilitating international collaboration and cooperation and advising intergovernmental bodies and global stakeholders on the atmosphere and climate. These organizations operate with ongoing constraints in funding that make expansion challenging. The GAW, in particular, is underfunded against its remit to monitor and study the composition of the global atmosphere, which is critical in the context of near-term climate risks and solar climate interventions.

CHALLENGE: BARRIERS TO GLOBAL SOUTH RESEARCH

For effectiveness and equity in research and decision-making, it is particularly critical that Global South researchers can participate in research and direct research studies. While there is substantial sophisticated talent in every region of the world, researchers in many countries face funding and technology access constraints that effectively inhibit research on local climate projections and impacts—a major barrier to generating regional and local information on disaster risk, loss, damage, and the effects of climate responses.

While there is generally funding for travel and attendance at meetings associated with various international bodies and functions, there are generally no funds for associated research, and there is no standing fund for developing country researchers to apply for grants to undertake climate research. There are also no funds for the scientific labor associated with scientific assessments (i.e., it is all volunteer, weighing more heavily on less advantaged researchers).

In addition to limited funding, access to technology is also a major barrier to participation in climate research. This is most notable regarding the high-performance computing required to undertake climate projections and impact studies, which is generally only available in developed countries with super-computing facilities. This barrier not only limits the participation of Global South researchers but also the design of studies and, therefore, the nature and level of information available on various regions. For example, down-scaling, an approach to generating high-value information for studying climate impacts, is far more prevalent for developed regions. Similar disparities exist for satellite and other observational data that tends to focus on developed countries that operate these assets. This leads to a "high-resolution" view of the developed world versus other areas.

Solar climate intervention research draws these gaps even more sharply into focus as the emerging community of researchers seeks to improve inclusion. **To expand the global talent pool, promote climate equity, and support international cooperation on near-term climate risk and intervention, gaps in research funding and technology access for Global South stakeholders must be addressed.**

U.S. Context

U.S. federal science agencies provide the primary scientific support for many international environmental agreements and climate and environmental science and monitoring programs. As a result, U.S. research investments play a central role in supporting international governance regimes and open science.

In 2015, NASEM released a pair of reports that reviewed approaches to climate intervention followed by a 2021 study describing considerations for their research and governance. In 2022, the U.S. Global Change Research Program (USGCRP) released its 10-year strategy for research emphasizing climate extremes, tipping points, and risks to human systems, and the U.S. Congress directed federal science agencies to deliver a plan for research to support a scientific assessment of near-term climate risks and solar climate intervention in 5 years.

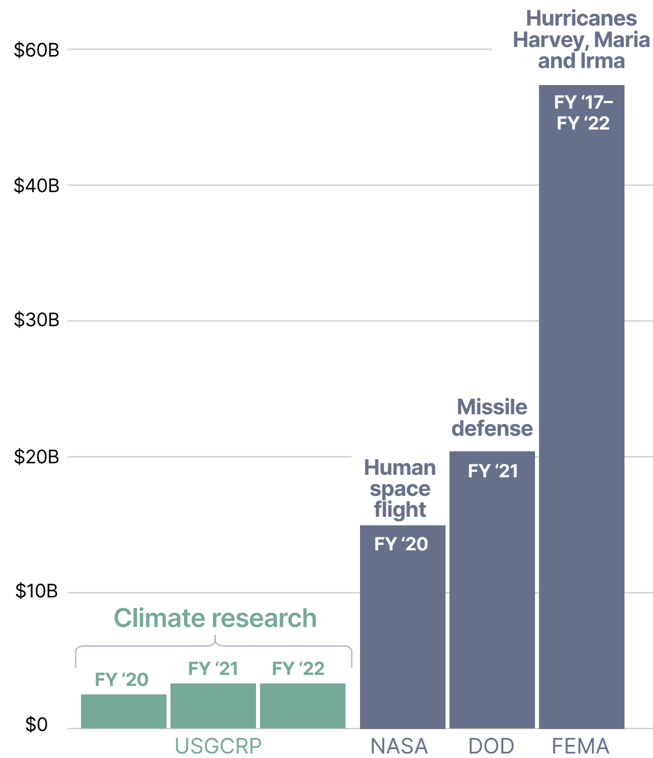
Given this, the analysis and recommendations presented herein focus heavily on addressing gaps in U.S. research capabilities and support for open scientific cooperation among technologically advanced and developing countries.

U.S. CLIMATE RESEARCH

In the United States, funding for climate and atmospheric research has been relatively flat, in real terms, for several decades (see Figure 22).

FIGURE 22

U.S. Climate Research Relative to Other Federal Spending



Source: USGCRP, the National Aeronautics and Space Administration (NASA), Department of Defense (DOD), and Federal Emergency Management Agency (FEMA).

This is not commensurate with major investments in energy transition, other emissions reductions, GHG removal, or disaster response. It is also not commensurate with U.S. federal investments in understanding and exploring areas outside of Earth or defending against or responding to catastrophic threats (see Figure 22).

In fact, the United States has developed plans and/or capabilities for disaster risk management against global catastrophic threats of lower likelihood than global catastrophic climate changes (see Figure 23). For example, the United States is spending over $200 million annually on its program to divert asteroids with the potential to cause catastrophic damage on collision with Earth. The probability of this occurring in the next 50 years is less than 1 in 20,000. Recent reports on the risk of major tipping events in natural systems in the next 50 years are orders of magnitude higher, but there are no current plans or programs to address these catastrophic disaster risks.

As in other publicly supported sectors in the United States, climate research and observation infrastructure investments have been insufficient to maintain services and are below what is needed to meet increasing demand. Many laboratories, observing platforms (e.g., satellites and aircraft), modeling systems, and other facilities are insufficient, aging, and at-risk.

Technological advances that have accelerated progress in other fields, such as automation, machine learning, cloud computing, and statistical sciences, have only recently (and at modest levels) begun to be applied in climate and atmospheric science. This represents a major gap as well as a significant opportunity.

FIGURE 23

Global Catastrophic Disaster Risk Reduction: Comparing U.S. Efforts

Planetary Defense Coordination Office

50-year risk:
1 out of 20,000

U.S. Spending 2022:
~$200M

Yellowstone Supervolcano Mitigation

50-year risk:
1 out of 10,000

planned **~$3.5B**
funded **$0B**

Tipping Points in Major Natural Systems

50-year risk:
>1 out of 10

No plans or specific funding

Source: NASA and USGCRP

Of the 13 U.S. federal agencies with climate-related research programs, those most relevant to solar climate intervention research are NOAA with weather and climate observation and prediction responsibilities, the Department of Energy (DOE) with a focus on the troposphere and Earth system modeling, NASA with stratospheric platforms and Earth system observations, the National Science Foundation (NSF) in building open-source weather and earth system models and fostering community-driven research, the Environmental Protection Agency (EPA) with responsibility for atmospheric emissions and climate analysis, the Office of Naval Research with marine and atmospheric programs, and the Defense Advanced Research Projects Agency with expertise in early mission programs.

There are near-term opportunities for extending programs in these agencies to fund modeling, observations, and small-scale field studies to rapidly increase scientific information and inform decisions about potential investment in larger programs. To support the requirements of near-term climate risk and intervention assessment, these agencies' broader climate research programs require substantial additional investment.

U.S. climate research efforts across multiple government agencies are coordinated through USGCRP, which has successfully delivered rigorous assessments of climate change and projected impacts on U.S. communities and industries. A well-designed scientific research and assessment process managed in a similarly coordinated way might support a broad multi-agency effort executing to deliver robust information for decision-making. If structured around a 5-year roadmap, such as proposed here, this program could produce an effective assessment in the time-sensitive context of escalating climate threats.

CLIMATE-RELEVANT ATMOSPHERIC RESEARCH

Investment in the atmosphere is the weakest of any Earth system domain and has declined in real terms at NOAA, NASA, and NSF. Within atmospheric research, weather forecasting has seen modest but significant support, but climate-relevant atmospheric processes are among the lowest priorities for funding, including for the agencies and institutions with "atmosphere" in their title (e.g., NOAA, NASA, and the National Center for Atmospheric Research). Longer-term and climate-relevant atmospheric processes have lacked both a commercial constituency (e.g., fisheries for ocean, space companies), or local interests (e.g., air pollution). This has contributed to lower awareness of, and political prioritization for, atmospheric programs.

Observation and prediction of the atmosphere is at the center of both weather prediction and projection and prediction of climate change. Yet improvements in predictions are slow, and information is vastly insufficient to support key problems in climate change, like the attribution of sources of GHG emissions, the inventory and behavior of aerosols or the exchanges of gases and aerosols with land and ocean surfaces. Unlike the mandates for local air quality monitoring or chemicals with the potential to deplete the ozone layer, **there is no federal mandate or set of capabilities for monitoring and reporting on the specific composition and health of the atmosphere.**

Substantial increased investment in atmospheric research is imperative for all aspects of understanding and responding to climate change, and essential for evaluating solar climate interventions.

CRITICAL AREAS OF NEED

With respect to near-term climate risks and solar climate interventions, in the United States and internationally, the following are critical areas of underinvestment and need:

- **Aerosol influences on clouds and climate,** including observations, modeling, data analysis, and scientific studies.
- **Terrestrial and marine carbon fluxes**, including observations, modeling, data analysis, and scientific studies.
- **Climate feedbacks and tipping points**, including high-resolution ecosystem models, coupled global climate models, complex systems and artificial intelligence and machine learning analyses, early warning signals, and simulation and analysis of feedbacks and tipping events versus potential interventions.
- **Technology capabilities and workforce**, including computing, software engineering, data science, complex systems and risk analysis, and technology staff to support scientific efforts.

Regarding the three major areas for research on near-term climate risks, there are major gaps in the research and capabilities required to support the goals for 5-year assessment.

Gaps in Observations of Natural Systems

Currently, the United States and the international community lack observations of the stratosphere, marine boundary layer, and exchanges at the ocean and land–surface interfaces (e.g., GHGs, aerosols, water vapor) with sufficient spatial and temporal resolution and accuracy to reduce critical uncertainties in process understanding for predicting climate and weather, detect GHG releases from land and ocean systems, assess and monitor ecosystem health, understand ocean–cloud responses that control climate sensitivity, and, in general, better manage the safety of human and natural systems with respect to weather and climate.

Governments and private organizations have invested in space-based observational capabilities for the atmosphere and climate, but these new investments are currently focused on GHGs, and they are insufficient to maintain continuity. Several long-standing, high-value satellite systems with unique capabilities (e.g., microwave limb sounder instrument, geostationary orbital coverage) are nearing their end-of-life, with no plans for continuity or replacement. This will result in both a loss of continuous data and a loss of coverage for critical measurements of aerosols and other atmospheric constituents and of parts of the planet, including, in particular, the Amazon rainforest region.

There are also significant limitations to the reach, resolution, and specificity of satellite measurements with respect to the atmosphere, some of which can only be addressed by observations taken from within the air or on the surface (“in situ”). These include the specific sources of GHG emissions, visibility below clouds, and many facets of aerosol observation. In fact, in-situ observations are used to inform the algorithms that are applied to raw satellite data to deliver findings. This means that insufficient in-situ data contributes to gaps in satellite information and dampens the value of satellite investments for climate.

To date, outside of surface observing stations on land (concentrated in developed countries), in-situ data on the atmosphere is most often gathered via infrequent ad hoc research campaigns. There are very few sustained observational efforts, and they do not span the breadth and depth of the atmosphere or the scope of required observations for reducing uncertainty in the understanding and projection of influences on climate.

In-situ atmospheric observations benefit from inexpensive disposable platforms (balloons, ocean floats) to carry instruments, but some measurements require long-range, heavy payload, or high-speed platforms. In the United States and globally, these platforms are scarce and aging. For example, to observe the stratosphere, special aircraft are required to reach relevant high altitudes. Of these, there are only five available for research globally (see Figure 24), all four of which are operated by NASA and used by other agencies and research teams who competitively apply for access. These aircraft are aging, and they also do not have

FIGURE 24

WB-57 High-Altitude Research Aircraft for Stratospheric Observations

Source: NOAA/NASA

sustained operational support so they require soft-money grant funding from campaigns to support operations.

To provide sustained coverage of the stratosphere, long-range, high-payload unmanned platforms may also be required. The only platform with proven capabilities is the military's Global Hawk aircraft, which was adapted for use in a highly successful joint NASA and NOAA campaigns (see Figure 25). Early-generation military units are available for adoption for science, but funds and programs have not been available to bring them into use. Emerging new generation "space planes" and high-altitute balloons may be adaptable for these purposes in the future, but are years from production and not currently targeted for science applications.

OPPORTUNITY: PLATFORMS OF OPPORTUNITY

In recent years, scientists in the United States and internationally have started programs to put advanced atmospheric monitoring instruments on commercial ships and airplanes. These limited programs have been proposed for expansion to create large, global networks of observations. While this would require technology improvements, significant and sustained investment, and novel programs, such networks could be built rapidly and inexpensively relative to operating dedicated platforms. The U.S. Congress recently authorized funding for piloting these efforts in NOAA and DOE.

FIGURE 25

NASA Global Hawk "Science Bird"

Source: NASA

Gaps in Earth System Models and Analysis of Climate and Impacts

Global Earth system models, models of natural systems and processes at various scales, and mechanisms for analyzing and assimilating observational data into these models are central to climate research. Highly complex and detailed models are used to study processes and impacts and to make forecasts. More simplified models are used to study the range of possible outcomes and integrated human and earth system responses. In general, there is more demand for research than there is funding or tehnical capacity. In particular, federal research funding favors model studies over model development and support, slowing model improvement, and impairing accessibility and community use.

Models and other analysis tools have important deficiencies with respect to understanding near-term climate risk and intervention, including the representation of clouds and cloud–aerosol effects, the representation of Earth system feedbacks (e.g., GHG release and uptake from natural systems), and the specific chemistry of the atmosphere.

Earth system models do not currently support comprehensive representation of the atmospheric processes associated with solar climate intervention and cannot directly resolve many processes that are key to both representing climate intervention approaches and representing processes that underline current large uncertainties in how human activities are affecting climate (e.g., through cloud–aerosol interactions). In addition, a lack of sufficient computational resources limit how often full model capabilities are used for realistic simulations of the fully interactive Earth system. Model development and enhancement take time and are often built on advancements in modeling at higher resolutions or over smaller domains.

Artificial intelligence and machine learning have great potential to aid in the analysis of data to identify relationships, to characterize processes and for the exploration of future scenarios. Their adoption in climate research is nascent, and impaired by the need for advanced technical skills and computing systems for their execution.

In addition to models and more traditional analysis tools, complex systems and portfolio analysis techniques that are used in other fields are likely to be very valuable for analysis of near-term climate risk and intervention. This work has yet to be undertaken.

OPPORTUNITY: CLOUD-BASED CLIMATE RESEARCH

Climate research is among the most computing-intensive activities in all of science and industry. Even on the world's largest supercomputers, fully featured simulations of the Earth system at high resolution take weeks or months to run and are performed rarely. Supercomputing systems are over-subscribed, and scientists' downscale their proposals based on computing access expectations, slowing the pace of science.

To date, commercial cloud computing has not been widely used in climate research. One important limitation has been the ability to accommodate the nature and scale of climate models on the cloud. This limitation was overcome recently through the implementation of National Center for Atmospheric Research's (NCAR) CESM model and DOE's E3SM model on the cloud as part of SilverLining as well as NCAR and Amazon Web Services' Cloud for Climate initiative. There are significant barriers to cloud adoption, including access to technical expertise and support, relevant tools, and economic models for procurement. But with its global research and flexibility, the cloud has enormous potential to expand capacity, accelerate science, and democratize climate research.

Solar Climate Intervention Research

Globally, specific funding for physical sciences research in solar climate intervention has risen from less than $5 million annually at the time of publication of SilverLining's 2019 report to greater than $40 million per year today. Funding remains concentrated in the United States. In the U.S. public sector, modest grant funding for solar climate intervention proposals is available though programs at NOAA, DOE, and NSF. In philanthropy, to date, individuals and foundations have made a modest number of direct grants to institutions, and SilverLining has made grants of $7 million through its research catalyst program, the *Safe Climate Research Initiative*.

The scientific community is growing rapidly, albeit from a very small base. Researchers now number in the hundreds, including a large proportion of women, international researchers, and early career scientists. In the U.S., there are significant dedicated scientific research programs on solar climate intervention at Colorado State University, Cornell University, Harvard University, Rutgers University, and the University of Washington. Outside the U.S., there are significant efforts or prominent researchers at the University of Cape Town, Exeter University, Cambridge University, the Institute for Advanced Sustainability Studies (Potsdam), the Indian Institute of Science, the French National Center for Atmospheric Research, and the Max Planck Institute for Meteorology. Published research includes authors from Argentina, Bangladesh, Brazil, Canada, China, France, Germany, Jamaica, Pakistan, South Korea, and many other countries.

In this context, climate modeling studies have progressed, with the first “realistic” full-production simulations of stratospheric intervention and MCB undertaken in a coordinated collaboration between researchers at major modeling centers NCAR, the UK Meteorologica Office, and Pacific Northwest National Laboratory. Data from these simulations enables researchers around the world to study different types of projected impacts in various regions. This has resulted in a sizable and growing number of new publications. Modeling and analysis efforts have included the incorporation of machine learning to study both observational and simulation data to explore detection, attribution, and impacts of solar climate intervention.

While scientific reports have indicated that small-scale release experiments are required to understand solar climate interventions, only very limited efforts have been undertaken, including non-scientific spray tests over the Australian barrier reef and a non-scientific launch of small balloons containing gas intended to reach the stratosphere. The University of Washington’s Marine Cloud Brightening Research Program has published plans for small scale field experiments. As part of these efforts, the program is the first to advance the development of research-scale spray technology (see Figure 26).

There is promising movement forward in the research required to understand and assess near-term climate risk and solar climate intervention. But the world faces substantial gaps in the knowledge and capabilities required in the most relevant areas for research. Researchers from vulnerable and developing countries require substantial resources to participate equitably in order to provide information to their stakeholders. To that end, delivering against a goal-oriented research roadmap would facilitate expanded participation and coordination of national, international and intergovernmental efforts.

FIGURE 26

Sea Salt Aerosol Spray Research at Palo Alto Research Center in 2022

Source: Palo Alto Research Center (PARC)

CHAPTER VI

Recommendations

The coming decades include additional climate warming and escalating impacts that require focused attention to ensure safety for people and natural systems in the future.

As the essential foundation for any forward path, the global community must aggressively reduce GHG emissions. Today, this should include heightened focus on reducing emissions of substances with the potential for greatest reduction in warming in the near term (e.g., methane, nitrous oxide). Due to the high levels of GHGs already in the atmosphere, society must also aggressively remove GHGs. To do this effectively requires a portfolio that considers the speed, scalability, duration, and ecological impacts of various approaches.

Interventions in the climate system to reduce warming by increasing the reflection of sunlight from clouds and particles (i.e., aerosols) in the atmosphere may provide options for protecting the safety of the world's people and the stability of its natural systems while society transitions to a sustainable future.

Of the many factors that influence warming and cooling in the atmosphere, the effects of sunlight reflection by clouds and particles is one of the largest but least understood. Efforts to reduce environmental impacts from particulate emissions may lead to rapid warming through the loss of climate-cooling particles, but observations and scientific understanding are not currently sufficient to evaluate this.

There is a growing need for better information and an expanded portfolio of options to promote the safety of communities and the sustainability of natural systems with respect to near-term climate changes. **The magnitude of climate risks and impacts warrants an ambitious effort to better understand and predict near-term climate impacts and risks and to assess solar and other promising climate interventions.**

Research takes time, and there is a need to define and deliver against ambitious but achievable goals within a set time frame—a "roadmap" for research—to protect people and natural systems in the coming decades. A well-structured roadmap spanning the range of required disciplines designed to a shared set of objectives and goals, such as proposed herein, can accelerate progress and foster a truly open and global collaboration and exchange of information on near-term climate risks and interventions.

International Imperatives

While demand for better information on near-term climate risks and interventions is rising globally, research on the Earth's climate system (as opposed to energy and other research related to reducing emissions) has been broadly subject to flat levels of activity and funding for several decades. It must now be made more commensurate with the enormous value of improved information for protecting human and natural systems from the worst effects of climate change.

The global community should consider it a matter of urgency to better understand and respond to catastrophic near-term climate risks. National governments and intergovernmental institutions should make rapid and concerted efforts on research, governance and decision-making for near-term climate risks and intervention. Imperatives for these efforts should be to:

- **Reduce climate disaster risk** for people and ecosystems, with an emphasis on the most vulnerable communities and natural systems, focusing on the risks posed within the 30- to 40-year time-horizon in which the climate is projected to continue to warm.
- **Monitor and avoid tipping points** for catastrophic changes in major natural systems and economic sectors.
- **Undertake concerted research to support scientific assessment of near-term climate risks and interventions in 5 years,** including rapid improvement in climate observation and prediction and specific research, including small-scale experiments and field studies on climate interventions.
- **Support science-based governance and decision-making** on near-term climate risks and solar climate interventions that include mechanisms for robust, independent scientific assessment.

- **Support international scientific cooperation,** including expansion of activities in the World Meteorological Organization, GAW, Montreal Protocol Scientific Assessment Panel, and IPCC.
- **Provide robust support for research capacity and equitable participation** from vulnerable and developing countries in the Global South.

> "The urgent, transformative nature of global change requires a Federal research enterprise equipped to meet the challenge."
>
> USGCRP 2022–2031 Strategic Plan

U.S. Imperatives for Federal Research

U.S. imperatives for climate safety, security, and economic leadership demand better information on, and an expanded portfolio of options for, responding to near-term climate risks. U.S. scientific research also plays a central role in supporting international climate and environmental scientific bodies and governance regimes for the rest of the world.

A coordinated U.S. scientific research effort structured around a 5-year roadmap could deliver a robust scientific assessment of the potential for solar and other promising climate interventions to reduce near-term climate risks. It could also facilitate expanded international participation in research to support more effective and equitable decision-making, including for those most affected by climate change.

Given this, the United States should undertake a national **Climate Safety Initiative** to generate and assess information on the potential for climate interventions to reduce catastrophic near-term climate risks and support international cooperation on science and decision-making on climate intervention. Specific actions should include:

- **Execute an ambitious 5-year roadmap of research** to support scientific assessment of near-term climate risks and rapid climate interventions in order to:
  - Rapidly accelerate improvements in climate prediction and risk analysis.
  - Rapidly expand observations of the atmosphere and critical natural systems.
  - Deliver the research required to assess approaches for increasing the reflection of sunlight from the atmosphere and any other promising methods of climate intervention.
  - Develop an early warning system and the capabilities to identify and prevent breaching tipping points in major natural systems, including a concerted effort on polar systems.
  - Accelerate adoption of advanced technologies (high-performance computing, cloud computing, unmanned aerial vehicles, etc.) and expansion of the technology workforce for climate research.
- **Provide $2.6 billion per year in new funding for U.S. federal climate research** (see the appendix for details on specific research activities and associated projected costs) over the next 5 years to support the research and observations required to assess near-term climate risk and intervention, with investments centered in observation and projection of influences on the atmosphere and their effects on climate.

- **Establish a mandate for monitoring, reporting, modeling, and projecting the composition of the atmosphere,** including GHGs, aerosols, and other climate-impacting substances and from the lower atmosphere to the stratosphere. This includes developing expansive capabilities for high-fidelity observations, such as:
  - Developing and operating global networks of, and data and scientific capabilities for, atmospheric observing instruments installed on commercial aircraft and ships.
  - Developing and operating a sustained capability for observation of the composition of the stratosphere, including long-range, high-payload platforms.
- **Support the expansion of international cooperation on solar climate intervention in intergovernmental bodies,** including the Montreal Protocol Scientific Assessment Panel, the World Meteorological Organization (including GAW and the World Climate Research Programme), the Inter-American Institute of Global Change, and other intergovernmental scientific bodies.
- **Support international scientific cooperation on research in near-term climate risks and climate interventions,** including substantial financial and technical resources for research in vulnerable and developing countries.

Alongside the assessment of the potential for solar climate intervention to reduce near-term climate risks, U.S. investment in the required research will increase the nation's ability to respond to climate threats in general, protect infrastructure and economic investments, promote national security in a changing climate, and develop world-leading climate solutions.

Recommendations for Key Stakeholders

Many sectors have a critical role to play in advancing research and policy for atmospheric climate intervention and increasing understanding of the Earth system.

In particular, the research community is central, and the technology industry has enormous untapped resources for accelerating progress. Philanthropy could play a pivotal role in catalyzing research, while civil society and the media can proceed thoughtfully to foster progress.

RESEARCH COMMUNITY

Recommendations for the research community are as follows:

- Participate in collaborative efforts to identify goals and develop roadmaps for relevant lines of research on near-term climate risks and climate interventions.
- Include international collaborators, early career scientists, and members of other diverse communities in research, assessment, and roadmap development on climate intervention.
- Support and participate in scientific assessments of climate intervention.
- Use strong transparency practices, including open access to models and data where practical, and specific disclosure of related commercial affiliations in every publication and media interaction.
- Take special care in the accurate communication of any implications from findings from modeling and other studies where simulations are not designed to closely represent the physical climate system or where uncertainties are substantial.

TECHNOLOGY SECTOR

Recommendations for the technology industry are as follows:

- Participate in assessments of Earth system prediction capabilities and identify opportunities to help accelerate, develop, and drive improvements in models, analysis, data, computing, sensing instruments, and observing platforms.
- Improve cloud-computing tools and pricing models for use by the geosciences research community and expand programs for data access and research computing grants.
- Identify opportunities to provide continuous, high-quality observations of the composition of the atmosphere and other relevant climate drivers.
- Create and support programs to connect technical experts and developers with research programs to promote collaboration and accelerate the development of open tools and projects.
- Incorporate climate research and observation efforts into corporate sustainability programs, marketing campaigns, and employee activism.

CIVIL SOCIETY

Recommendations for the civil society are as follows:

- Broaden the portfolio of options for consideration and help to center consideration of climate interventions on real-world outcomes for people and natural systems (i.e., disaster risk reduction) as an urgent matter of climate justice.
- Focus on the relative safety of projected warming versus climate intervention.
- Call for scientific research to rapidly generate information for decision-making on climate risk and intervention.
- Examine and support proven models for scientific assessment and science-based governance, such as the Montreal Protocol.
- Support scientific research by, and capacity development for, researchers in developing countries and countries experiencing the most severe impacts of climate change as critical to equity and justice in research and decision-making.

PHILANTHROPY

Philanthropy recommendations are as follows:

- Support physical sciences and technology research on solar climate intervention and related topics to catalyze and complement public sector activity.
- Support efforts to accelerate the adoption of advanced technologies and methods for understanding and predicting the climate and Earth system.
- Support advocacy for international scientific cooperation and science-based governance to promote effective environmental outcomes.
- Support the expansion of global south research capacity to promote more equitable engagement in both science and decision-making.
- Support communication programs for educating and engaging the public.

INDIVIDUALS

Recommendations for individuals who want to get involved are as follows:

- Call on policymakers to provide adequate risk and contingency plans, including emergency measures, for ensuring safety in the face of warming climate.
- Support organizations working on science-based approaches to climate response.

APPENDIX

Recommended U.S. Federal Climate Research Investments

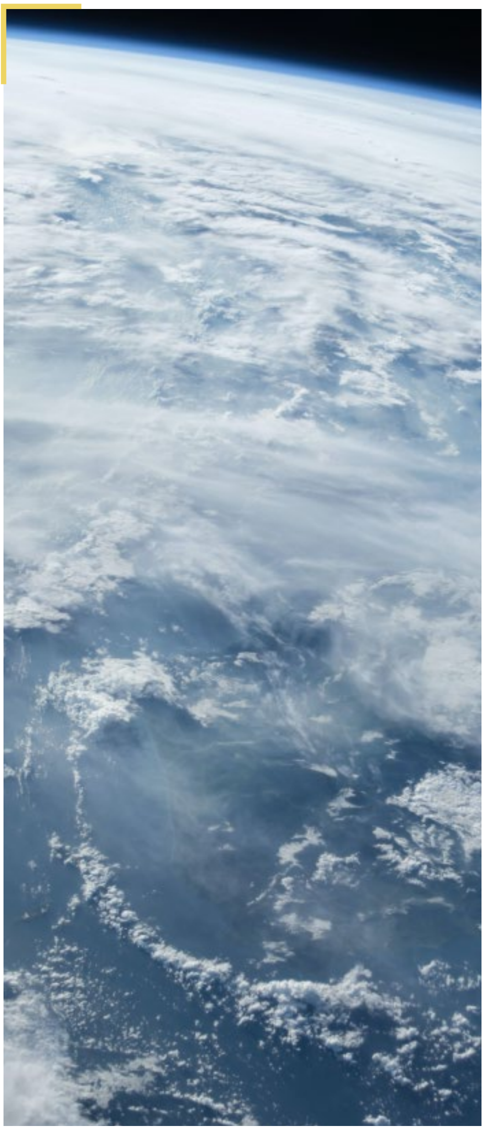
The following tables contain funding recommendations for research activities by research category to deliver against the stated goals in a 5-year time horizon.

For tables A-1 through A-5, the columns on the left describe categories for research, generally by discipline, and a high-level description of research activities. Tables A-1 through A-3 also include a columns containing goals for research within the 5-year time horizon.

For all tables, the columns on the right display recommended U.S. federal investment above FY 2022 levels for FY 2024 through FY 2029.

"Minimum" designates an estimate of the lowest level of increased investment needed to deliver sufficient science to inform assessment and decision-making. "Optimal" designates the estimate for research and research capabilities most likely to narrow uncertainties in projections, reduce failure risks in execution, and support robust forward monitoring and prediction.

Estimates were developed through the application of goals to the expansion of specific programs and capabilities and the analysis of relevant federal agency budgets and programs. Additional information is available from SilverLining at http://www.silverlining.ngo.



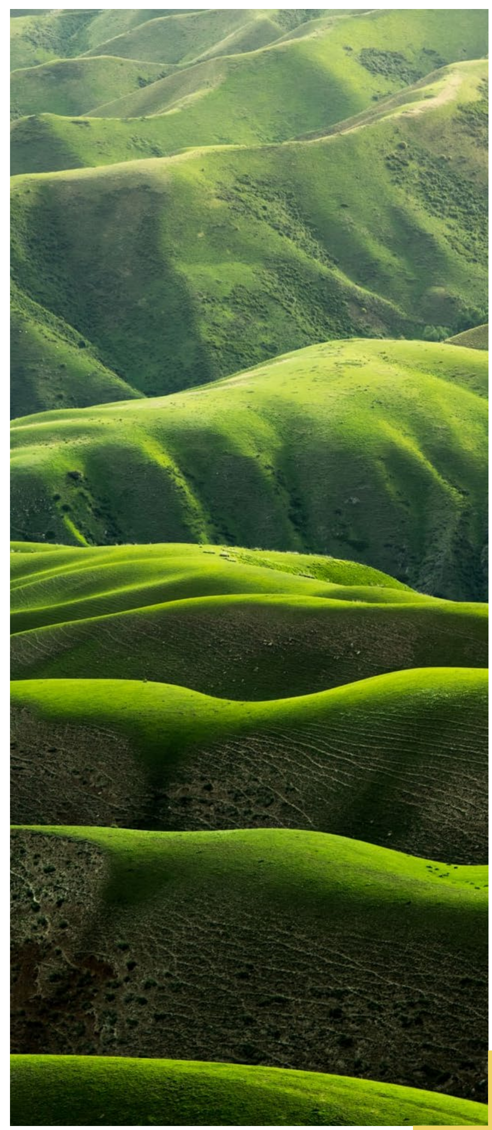


TABLE A-1

Earth System Models and Analyses of Climate and Impacts

Research Category	Research Activities	5-Year Goals	5-Year Investment	
			Minimum	Optimal
Earth system model development	Atmospheric processes associated with interventions	• Improved representation of stratospheric chemistry and transport • Improved representation of cloud–aerosol effects in the boundary layer • Improved representation of aerosol effects on cirrus clouds	$500M	$1,000M
	General	• Accelerated high-resolution modeling efforts and model downscaling at resolutions needed for hydrology, forestry, agriculture, health, and other impacts • Accelerated advances in the sophistication of dynamically coupled ecosystem models and carbon feedbacks • Accelerated improvements to the representation of abrupt changes and feedbacks, including permafrost, wetlands, and forest diebacks	$500M	$1,000M
	Technology	• Improved data assimilation capabilities • Incorporation of machine learning in study design and analyses • Accelerated adoption of cloud computing for expanded capacity and access • Investment in the technology workforce	$500M	$1,000M
Non-model analytical tools and methods	Complex systems science	• Accelerated application of methods from other fields to climate system analysis	$50M	$100M
	Risk analysis and risk management	• Accelerated application of methods from other fields to climate risk management	$50M	$100M
	Artificial intelligence and machine learning	• Accelerated application of methods from other fields to climate processes, impacts, and risks	$50M	$100M
Studies of near-term impacts and risks with and without intervention	Global and regional climate model studies	• Corpus of model simulations of climate impacts with and without intervention for various scenarios for emissions and type of intervention, sufficient to generate data to support analysis of impacts on hydrology, weather, terrestrial ecosystems, and ocean ecosystems with multiple global climate models. • Corpus of integrated assessment model studies of impacts with and without SRM under various scenarios to support analysis of biodiversity, human health, energy systems, infrastructure, economic productivity, and global security	$50M	$300M
	Analog studies	• Corpus of studies of natural and anthropogenic analogs to solar climate interventions (e.g., volcanic eruptions, industrial and natural emissions that influence clouds, and other global emissions impacting events)	$50M	$100M
	Tipping event analyses	• Methodology for analysis to identify precursor signals and potential observational metrics for major tipping points • Systematic evaluation of major near-term (e.g., 10–40 year) tipping risks (e.g., permafrost releases, forest dieback, and ice sheet collapse) • Evaluation of tipping risks most susceptible to reduction by intervention • Suite of studies on various natural system abrupt change pathways against scenarios for intervention	$50M	$300M
Total 5-Year Investment:			MINIMUM: **$1.8 Billion**	OPTIMAL: **$4 Billion**

TABLE A-2

Observations of Natural Systems

Research Category	Research Activities	5-Year Goals	5-Year Investment	
			Minimum	Optimal
Atmospheric observations of high relevance for aerosol-forcing effects/ interventions	Stratosphere	• Baselines of key aerosol processes and populations across seasons and hemispheres and in the lower stratosphere • Sustained observational capabilities adequate to detect and monitor significant influences on solar radiation and stratospheric chemistry • Response capabilities for observations of natural system analog releases of material into the stratosphere (e.g., energetic volcanic eruptions and large wildfires (pyrocumulonimbus) • Observations of anthropogenic analogs (e.g., aircraft and rocket plumes)	$500M	$1B
	Marine boundary layer	• Observations of background aerosol and meteorological conditions in MCB-susceptible regions (e.g., off the west coasts of the Unitedd States,Peru/Chile, Angola/Namibia, and Australia) • Sustained observations of marine aerosols to study anthropogenic analogs • Sustained observational capabilities adequate to detect significant influences on solar radiation	$300M	$1B
	Cirrus clouds	• Observations of background conditions in thinning-susceptible regions • Sustained observation of "clean" low-cloud-condensation nuclei and high contrail-prevalent environments (e.g., Sierra Nevada and the Rockies) • Observations of anthropogenic analogs (e.g., aircraft plumes)	$100M	$500M
	Ocean surface	• Sustained aerosol, GHG, and meteorological observations at the ocean surface in targeted regions		
Global carbon cycle & climate monitoring	GHGs	• Sustained observational capabilities sufficient for flux quantification, attribution of sources, and detection of significant changes in feedbacks from natural systems	$500M	$1B
	General	• Accelerated efforts to eliminate gaps in critical observables • In-situ observations to provide expanded ground-truth sources to support accelerated improvement in satellite information	$500M	$1B
Other natural systems	Polar regions, terrestrial ecosystems, ocean, atlantic meridional overturning circulation, and monsoon	• Sustained observations sufficient for reducing uncertainties in major natural system feedbacks (e.g., forest dieback, permafrost, and methane clathrates) • Sustained observations sufficient for detection of key metrics identified as precursors and risk indicators for major abrupt changes (e.g., major forest collapse, ice sheet collapse, and major GHG release from permafrost)	$500M	$1B
Total 5-Year Investment:			MINIMUM: **$2.4 Billion**	OPTIMAL: **$5.5 Billion**

TABLE A-3

Research on Specific Sunlight Reflection Approaches

Research Category	Research Activities	5-Year Goals	5-Year Investment	
			Minimum	Optimal
Aerosol generation and dispersal studies	Technology development, near-field aerosol dispersal, observations (laboratory) and modeling	• Research-grade aerosol production systems that can deliver required size and distribution of optimum materials	$150M	$300M
Localized processes and outdoor plume studies	Local atmosphere/cloud response to aerosols via field observations, experiments, and modeling and controlled release studies (e.g., single-plume) as needed to test and improve models	• Characterization of conditions and processes that drive the evolution and radiative forcing efficacy of aerosols introduced into the atmosphere • Quantification of uncertainties in response	$300M	$500M
Limited-area processes and environmental studies	Modeling and observational studies of local aerosol evolution and cloud responses to the addition of aerosols and controlled release studies (e.g. multiple plume, without environmental impact) as needed to test and improve models	• Understanding of chemical and dynamical processes and (except for stratospheric intervention) radiative forcing at minimum scale and duration for detecting effects • Development of sub-grid-scale parameterizations of key processes for modeling impacts • Identification of non-radiative effects (e.g., SAI impacts on ozone and MCB impacts on rainfall) • Identification and quantification of related uncertainties in responses	$500M	$1,000M
Analogue and background observational studies	Instrument development and observation of platform integration baselining of atmospheric conditions and studies of natural and anthropogenic perturbation analogues	• Atmospheric baselines established for four seasons across two hemispheres • Adequate observations established for major analogs (e.g., ship-tracks and volcanic eruptions)	*see Tables A-2 and A-3	
Regional and global model inputs	Inputs to regional and global climate model representations of processes underlying interventions; development of tools from simulating interventions in regional and global models; representation in integrated assessment models	• Mechanisms for controlled perturbation in regional and global models • Requirements/priorities for improvement in the representation of key processes related to SRM • Identification of observational data gaps in model instantiation and/or validation of key processes associated with SRM (e.g., chemistry baseline of the stratosphere for SAI) • Proof-of-concept simulations to test and improve the above in multiple major regional and Earth system models	$100M	$500M
Implementation analysis and operational design tools and methods	Comparative assessment of implementation strategies, systems design, delivery platforms	• Development of tools and proof-of-concept simulations for implementation strategies to identify performance boundaries, optimize strategies, quantify model uncertainty, and analyze detection and attribution • Preliminary operational system requirements and designs to inform feasibility studies • Studies of information, compliance, security, and continuity requirements	$100M	$500M
Total 5-Year Investment			MINIMUM: **$1.15 Billion**	OPTIMAL: **$2.8 Billion**

TABLE A-4

Socio-Economic Studies and International Scientific Programs

Research Category	Activity	5-Year Investment	
		Minimum	Optimal
Socio-economic studies	Disaster risk reduction, economic impacts, energy systems/ feedbacks, infrastructure, migration, and human health	$200M	$500M
International scientific cooperation and Global South research support	Expansion of international scientific cooperation programs, open (e.g., cloud-based) access to datasets and models for global researchers, and funding for Global South research	$150M	$300M
Total 5-Year Investment:		MINIMUM: **$350 Million**	OPTIMAL: **$800 Million**

TABLE A-5

Funding Increase Across U.S. Federal Agencies

U.S. Federal Agency Funding	5-Year Investment	
	Minimum	Recommended
5-Year Total	$5.7B	$13.1B
Annualized	$1.14B	$2.62B

TABLE A-6

Estimated 5-year Funding Increases by U.S. Federal Agency

U.S. Federal Agency	5-Year Investment	
	Minimum	Recommended
NOAA	$1.140B	$2.62B
NASA	$1.425B	$3.275B
DOE	$1.14B	$2.62B
NSF	$427.5M	$982.5M
EPA	$427.5M	$982.5M
State Department	$285M	$655M
Other	$855M	$1.965B

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SILVERLINING

SilverLining is a non-profit organization whose mission is to advance research, policy, and dialogue to ensure a safe near-term climate. Like a medical foundation for climate health, SilverLining supports research, policy, technology innovation, and engages with civil society and people from all walks of life in an effort to reduce near-term climate risks, protect vulnerable people, and sustain natural systems for the future.

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