Ensuring a Safe Climate

A National Imperative for Research in Climate Intervention and Earth System Prediction

SilverLining

Ensuring a Safe Climate

A National Imperative for Research in Climate Intervention and Earth System Prediction

A SILVERLINING REPORT
WWW.SILVERLINING.NGO

COVER PHOTOGRAPH BY CHRISTOPHER MICHEL

SilverLining

Table of Contents

Executive Summary

This report discusses the near-term risks of climate change; possible techniques that can be used to directly reduce warming in the climate; possible risks, benefits, and costs of these techniques; an overview of governance considerations and mechanisms; the nature of research for these techniques; the current state of play; and recommendations for policymakers for exploring these approaches to expand options for ensuring safety.

Rising heat energy in the Earth's atmosphere is changing the world's climate and is likely to lead to catastrophic changes in natural systems with devastating effects on people and society. Interventions in the climate system to reduce warming by increasing the reflection of sunlight from the atmosphere (also known as atmospheric climate intervention, solar radiation management, or solar geoengineering) may provide options for protecting the safety of the world's people and stability of its natural systems. Such interventions could provide much-needed time to allow deployment of next-generation technologies for energy generation, transportation, agriculture, and industrial processes as well as emerging options for carbon capture and removal. But today, there are no formal sources of funding for this research in the United States in either the private or public sector, and funding is less than $5 million annually throughout the world.

While there are many questions that still need to be explored by the scientific and policy community regarding research related to climate interventions and atmospheric sunlight reflection, the following is currently known:

- Warming climate poses enormous risks to people and ecosystems within the next 10 to 30 years, and the world does not have sufficient options available to ensure human safety and protection of critical infrastructure.
- Of the many factors that influence warming and cooling in the atmosphere, the effect of sunlight reflection by clouds and aerosols is one of the largest but least understood. Current actions, such as improving emissions standards, may produce unintended negative consequences, such as rapid warming from the loss of cooling particles. Basic research is lacking and is urgently needed.
- Atmospheric climate intervention techniques might rapidly reduce warming, but their potential efficacy, risks, and costs are currently unknown, and there are currently no Federal programs or formal sources of funding for research.

> "Warming climate poses enormous risks to people and ecosystems within the next 10 to 30 years, and the world does not have sufficient options available to ensure human safety and protection of critical infrastructure."

- Existing laws and institutions have some jurisdiction over these interventions and could be adapted for governance, but more may be needed. Information required to govern these capabilities or respond to actions taken by others is currently lacking.
- Cross-cutting programmatic, infrastructural, and organizational investments are needed to assess climate interventions, including a decade of modeling, observations, technology development, and well-controlled, small-scale experiments.
- To assess or use climate interventions, significant improvements in Earth system prediction capabilities (e.g., observations/monitoring, forecasting, and attribution of drivers of warming) are required—none of which are advancing at the required rate. These could be accelerated by increased adoption of technology (e.g., artificial intelligence, cloud computing, and remote sensing) from other sectors.
- Internationally, China, India, and some developing countries have begun to explore these possibilities and the first proposal was raised in the United Nations (UN) before the Montreal Protocol/UN Environment Ozone Secretariat to assess potential impacts.
- The United States is uniquely positioned to support research and development in climate intervention and Earth system prediction. Open international collaboration will promote the strongest scientific and policy outcomes.

RECOMMENDATIONS FOR POLICYMAKERS

Charting a course to ensuring safety in the face of the extreme near-term risks of a warming climate requires swift action. Over the next decade, policymakers will have increased options for protecting the United States and the global community if immediate investments are made in Earth system research and climate intervention assessment. The scale of these investments is relatively modest and can be phased in as research matures, but to understand the options for directly reducing climate warming requires starting work now.

While the world needs to act as a whole, the United States has the highest concentration of assets and resources for understanding climate and is the focus for recommendations in this report. In the United States, a coordinated, multi-agency, multi-sector effort would represent the best approach to reducing uncertainty in predicting Earth system changes and assess climate intervention options. Specifically, to ensure the security of the nation, the safety of the world's people, and the stability of the environment in the face of climate change the United States should commit to delivering the knowledge and capabilities required to assess options for constraining climate warming **within 10 years**. This includes scientific and technical research, public engagement, and policy development that would:

- Provide scientific and technical information for policymakers that includes feasibility, risks, impacts, uncertainties, costs, and controls for climate interventions.

> "Existing laws and institutions have some jurisdiction over these interventions and could be adapted for governance, but more may be needed. Information required to govern these capabilities or respond to actions taken by others is currently lacking."

- Reduce uncertainty in Earth system prediction and improve attribution of the drivers of climate change.
- Provide early warning indicators of precipitous changes in natural systems.
- Establish requirements and designs for capabilities to monitor and manage climate across natural, anthropogenic, and interventional drivers.
- Develop needed advances in observations, models, and computing to achieve these ends, with engagement from the technology sector to accelerate innovation and adoption of these capabilities.
- Establish methods for ensuring safety, transparency, and rigor in research.
- Develop governance models for deployment at local, regional, and global scales.
- Mobilize U.S. resources in support of a wide global research community.
- Engage the public to establish understanding and support for exploring climate intervention.

To support these 10-year objectives, **in the next 2 years**, the U.S. Federal Government should seek to perform the following:

- Build research capabilities for atmospheric climate intervention within science agencies with near-term grant funding for modeling, data analysis, technology development, and small-scale field studies. A key target should be to inform the Intergovernmental Panel on Climate Change's 6th Assessment in 2022.
- Support National Academy of Sciences' assessments to provide a coherent agenda for research, approaches to oversight and governance and advances in Earth system prediction.
- Direct climate research budgets to provide dedicated funding for climate intervention without detracting from the broader portfolio of climate research, mitigation, and adaptation.
- Maintain critical atmospheric observations for continuity and encourage rapid expansion of capabilities to provide atmospheric baselines of key metrics.
- Increase adoption of commercial cloud computing, remote sensing, and other advanced capabilities to accelerate knowledge and expand access to climate models and data.
- Review existing national and international regulations and governing bodies related to atmospheric research and assess requirements for any new or expanded mechanisms, with emphasis on facilitating rather than restricting the generation of information.

Support, through the Montreal Protocol/UN Environment Ozone Secretariat, the scientific assessment of potential risks to the ozone layer posed by stratospheric climate intervention.

Update the *Weather Modification Reporting Act of 1972*[1] to clarify requirements for climate intervention research and provide clearer thresholds for application.

Outside of the U.S. Government, other countries can undertake similar lines of research and promote the generation and sharing of information. For example, the technology sector can accelerate progress by engaging with research programs, sponsoring seed programs, and investing in related innovation. Philanthropic funders can help promote government action and compliment public sector research programs. Media can assist by avoiding sensationalism and helping the public evaluate possibilities in a way that balances the assessment of risks. Finally, individuals can demand that policymakers commit to ensuring safety and invest in exploring viable measures for climate protection. They can insist that failure is not an option.

“Individuals can demand that policymakers commit to ensuring safety and invest in exploring viable measures for climate protection. They can insist that failure is not an option.”

Introduction

In 2018 alone, the United States and Europe experienced their hottest May through July in recorded history, ice losses in Antarctica caused sea levels to rise faster than at any time in the past 25 years[2], and extreme weather events around the world shattered records, ravaging communities and claiming lives.

While the world is aggressively working to reduce greenhouse gases that are trapping heat in the atmosphere in order to restore the health of the Earth system, even the most concerted measures to reduce emissions and remove greenhouse gases from the atmosphere require many decades to take effect. The latest assessment from the United Nations (UN) Intergovernmental Panel on Climate Change (IPCC) describes a high risk of devastating impacts if global temperature increases exceeds 1.5 °C[3], with risk of crossing this threshold in the next 10 to 30 years[4]—faster than currently proposed solutions can deter them.

While efforts to reduce greenhouse gases are being developed and undertaken, direct means of reducing heat energy in the climate system (i.e., climate intervention) may be needed as a means to extend the time available for action.

In 2015, a U.S. National Academy of Sciences review identified the most promising approaches for directly reducing climate warming, recommending that a "… research program be developed and implemented that emphasizes multiple-benefit research that also furthers basic understanding of the climate system and its human dimensions."[5] They named a set of approaches for dispersing particles to increase the reflection of sunlight from the atmosphere (e.g., atmospheric climate intervention, solar radiation management, or solar geoengineering) as priorities for research. With the potential to offset 2 °C or more of warming, if the research produces a positive outcome, then these techniques could prevent severe and irreversible changes to natural systems and protect the lives, communities, and well-being of people around the world.

The scientific and technical research required to assess these approaches takes time. According to prominent experts, it will require a decade of modeling, data studies, and small scale experiments[6] to determine whether they are feasible and whether experts can constrain their risks. Concerns about intentionally altering climate have prevented research on these approaches such that today, there are no formal sources of funding for this research in the United States in either the private or public sector, and funding is less than $5 million annually throughout the world.

In addition to dedicated research, assessing these approaches requires substantially improving scientists' abilities to understand the Earth system and predict climate impacts. For example, scientists currently lack measurement instruments sensitive enough to detect interventions, analyses that are precise enough to attribute them to effects, and predictions that are strong enough to manage risks. The Earth system is one of the most complex systems humans endeavor to understand, representing an enormous challenge to prediction, but one to which all of the latest technologies (e.g., artificial intelligence, remote sensing, and cloud computing, among others) have not been fully applied. Concerted research and innovation to improve prediction of the Earth system are urgently needed.

> "Concerns about intentionally altering climate have prevented research on these approaches such that today, there are no formal sources of funding for this research in the United States in either the private or public sector, and funding is less than $5 million annually throughout the world."

Today, there is insufficient information about the feasibility and risks of climate interventions to develop governance mechanisms for any potential capabilities or to respond to any efforts undertaken by others. Yet, as climate impacts worsen, it is increasingly likely that someone might attempt to rapidly reduce warming through interventions in the atmosphere. As it stands, there is little information upon which these actors might base their decisions about what might be effective and what harm might come as a result. Robust research might prevent dangerous actions and/or inform the international community of potential impacts of these activities.

Recently, policymakers have begun to consider atmospheric climate interventions more seriously. On November 8, 2017, the U.S. House Committee on Science, Space, and Technology held a hearing in which members of both parties recommended research to explore options.[7] In October 2018, the U.S. National Academy of Sciences launched a study to develop an agenda for research and governance of atmospheric sunlight reflection interventions.[8] In December 2018, the UN Environment Ozone Secretariat received a proposal from member States for an assessment of the potential impacts of proposed atmospheric climate interventions on ozone in the stratosphere.[9] Also, in the past 2 years, scientific efforts to explore and assess these interventions have emerged in China[10], India, and a number of developing countries.[11]

While there are many questions for research and assessment, this report seeks to provide guidance on the state of play and possible steps forward. It identifies areas where opportunities and needs exist for expanding the U.S. Government's investment in research and innovation, possibilities for international collaboration, and roles for the technology sector and philanthropy. It also provides a discussion of requirements for governance and its relationship to research. While this report is by no means comprehensive, it is intended to serve as a guidepost to promote a broader portfolio of options for ensuring a safe and sustainable future.

> "While there are many questions for research and assessment, this report seeks to provide guidance on the state of play and possible steps forward."

Near-Term Risks of a Warming Climate

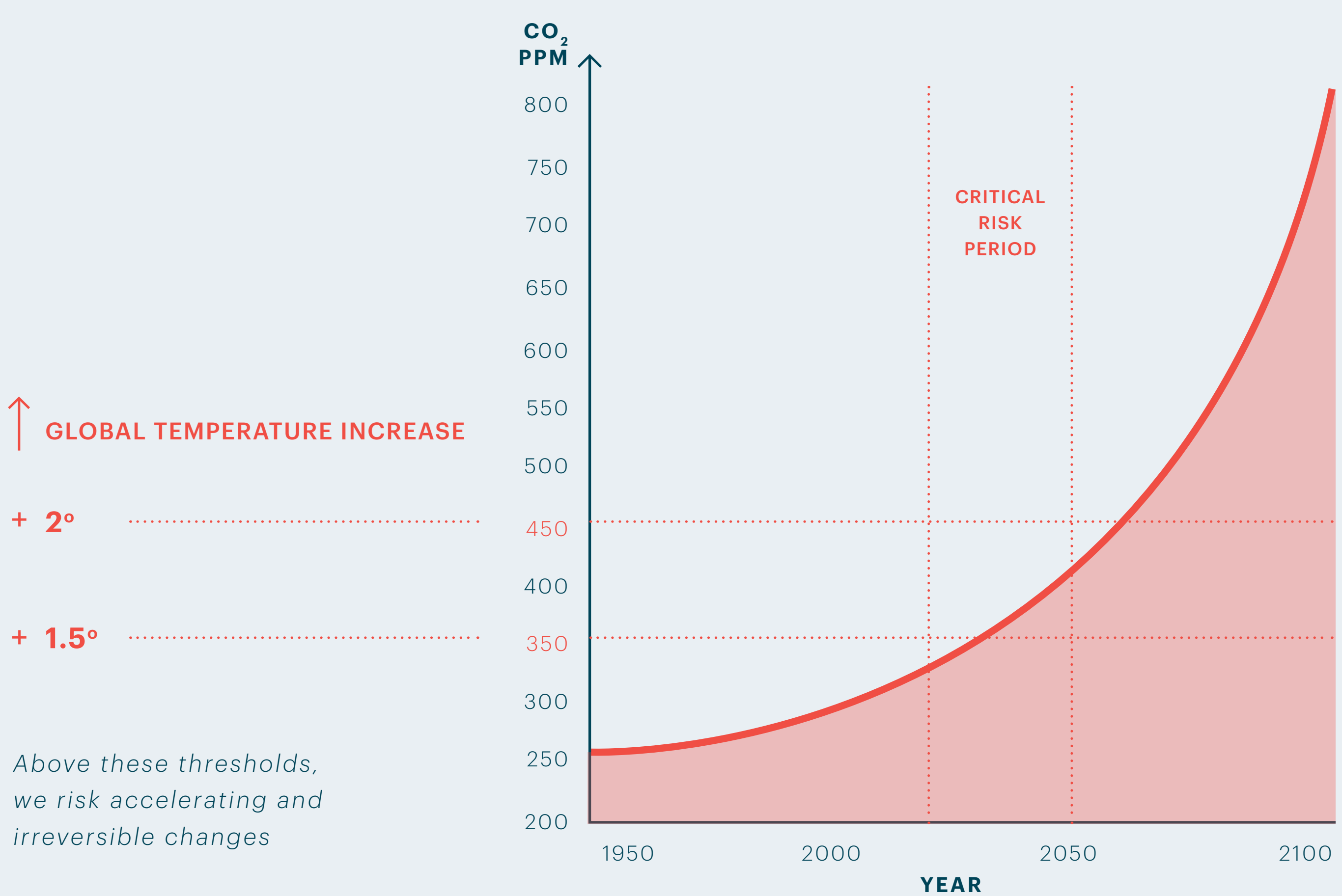
For much of their existence, and more rapidly since the beginning of the Industrial Revolution, humans have moved large quantities of carbon from under the ground to the atmosphere, changing the conditions that natural and human systems are attuned to at a far faster rate than they can adapt. This excess heat energy trapped in the climate system stresses these systems, and, like the human body running a fever, different parts can adjust to some increased heat. But, as temperatures rise, many will sustain damage that is severe and eventually irreversible.

This chapter discusses the near-term risks of warming climate, the uncertainty in forecasts and prediction of impacts, the limitation of current options with respect to reducing warming rapidly and current exposure to high near-term risk.

Escalating Environmental, Economic, and Societal Risks

Unabated heat stress is already causing changes, with damaging effects on communities, infrastructure, and the natural systems that sustain life. Even with success in reaching targeted reduction in emissions under the Paris Agreement, warming is predicted to reach 2.5 to 3 °C by the end of this century, with a high risk of devastating effects on natural systems and human populations in the next 10 to 30 years.[12]

FIGURE 1.
PROJECTED WARMING OVER THE 21ST CENTURY.



IMPACTS ON NATURAL SYSTEMS

Warming climates have negative impacts on natural systems, including land, oceans, and Arctic ice, as detailed in the following subsections.

“Warming climates have negative impacts on natural systems, including land, oceans, and Arctic ice.”

Land

There are numerous risks to land-based systems with warming of 1.5 °C above pre-industrial levels. Increases in extreme weather could lead to severe negative impacts on a number of ecosystems through the increased severity and intensity of drought, wildfires[13], and extreme heat and precipitation, leading to habitat losses and the extinction of keystone species.

For example, food production is impacted as global yields of wheat, barley, and corn decrease with increasing global average temperature.[14] The cumulative impacts of variable weather, changing conditions, diseases, pests, drought, flood, and soil erosion are already damaging some sectors and may cause a sharp drop in agricultural output.[15]

Oceans

More than 90 percent of the anthropogenic heat in the climate system between 1971 and 2010[16] and 30 percent of the anthropogenic carbon emissions[17] have accumulated in the ocean. This additional heat is impacting ocean dynamics and ecosystems.[18] Thermal expansion of water along with continental ice melting is causing sea levels to rise, impacting coastal communities, infrastructure, and island nations.

This rise in ocean temperatures, coupled with ocean acidification and raised sea levels, impacts ocean life, from coral bleaching, to mangrove loss, to increased harmful algae blooms.[19,20] In the next 20 years, studies forecast a loss of nearly all of the world's coral and thus the habitats that support 25 percent of life in the ocean. Warming oceans are also changing the distribution of species, which may either decline in certain areas, while some regions may experience an increase in fish and invertebrates. By 2050, it is possible that the combination of heat and other stressors will lead to substantial losses of saltwater fish.[21]

Arctic Ice

Sea ice covers about 11 percent of the world's oceans depending on the season. The amount of ice regulates the climate and affects the reflection of sunlight (albedo), salinity, and ocean–atmosphere thermal exchange. The Earth's polar regions are warming twice as fast as the rest of the world[22], and the *Special Report on Global Warming of 1.5 ºC* by the Intergovernmental IPCC indicates that under 2 °C of warming, ice-free summers will become 10 times more likely that they would have been without any warming.

A warming Arctic has consequences felt around the rest of the world. While still a subject of debate, warm Arctic summers have been linked with extreme weather elsewhere in the globe.[23] Significant loss of ice and snow would substantially decrease the proportion of sunlight that is naturally reflected from the Earth's surface, absorbing this heat and accelerating warming.

IMPACTS ON PEOPLE

In addition, warming climates also impact people, including health and productivity, migration and security, and infrastructure.

Health and Productivity

The impact of warming climates on human life is profound. Multi-sector risk is one where the risk goes beyond tolerable in at least two of three sectors—water, energy and food, and environment. A recent study found that at 1.5 °C of warming, 16 percent of the world's population in 2050 (i.e., 1.5 billion people) will have moderate to high levels of multi-sector risk. At 2 °C of warming, this almost doubles to 29 percent of the global population (i.e., 2.7 billion people). At 3 °C of warming, that figure almost doubles again to 50 percent of the population, or 4.6 billion people.[24] Severe heat has detrimental impacts on the productivity of workers, reducing mental and physical capacity and increasing the rate of accidents, heat exhaustion, and heat stroke such that by 2030, extreme heat could lead to a $2 trillion loss in labor productivity.[25] The temperature in cities like Calcutta, India, are predicted to be above safe thresholds for working outdoors every day of the year.[26] In some regions of the world, extreme heat is likely to increase the risk of infectious diseases (e.g., dengue fever in Taiwan) and related deaths.[27]

Migration and Security

There is a growing body of research that suggests that increases in temperature and the resulting impacts correspond with increased political instability and other concerning social trends. Increased migration due to drought and conflict could magnify these trends. In a worst case scenario, more than 800 million people will live in these conditions by 2050, with India accounting for almost three-quarters of them.[28] With more areas uninhabitable, increased drought, crop failure, flooding, storms, and mass migration are projected, with effects on social and political stability as well as a high risk of armed conflict.[29]

Infrastructure

The effects of climate change on infrastructure and transportation systems are profound. Extreme temperatures can affect thermal expansion joints, accelerate material degradation, and increase stresses in buildings, bridges, and other structures.[30] Dams, large building projects, and underground infrastructure are at risk as land and surface changes move beyond the conditions they were engineered to withstand.[31] Flooding and storm surges threaten major infrastructure, such as coastal nuclear reactors, military installations, and city centers. Most U.S. sewer systems, for example, are only built to withstand 100-year floods, but 500-year floods, like those experienced with Hurricane Harvey, are likely to become common.[32] Transportation disruption will grow increasingly severe over the next two decades[33], with flights disrupted by heat[34] and storms, shipping impaired by storms, and storms and flooding impacting ground transportation of goods and people.

> "Severe heat has detrimental impacts on the productivity of workers, reducing mental and physical capacity and increasing the rate of accidents, heat exhaustion, and heat stroke such that by 2030, extreme heat could lead to a $2 trillion loss in labor productivity."

ACCELERATED WARMING FROM EARTH SYSTEM CHANGES

Even in an optimistic scenario where greenhouse gases meet or even exceed the targets of the Paris Agreement, excess heat in the Earth system may trigger changes that drive further warming.[35]

Natural systems that capture and store carbon dioxide (CO_2) could change such that they begin releasing CO_2 and other greenhouse gases, substantially accelerating warming.[36] Thawing permafrost, loss of methane hydrates from ocean floors, weakening land and ocean carbon sinks, increasing bacterial respiration in the oceans, changes to ocean circulation, and forest dieback can all release greenhouse gases in quantities that outpace any human ability to address them. Similarly, changes that reduce the amount of sunlight reflected away from Earth, such as reduction of northern hemisphere snow cover, loss of Arctic and Antarctic sea ice, and loss of phytoplankton, which produces natural emissions that help reflective cloud formation, could increase warming to a devastating and unaddressable effect, dramatically altering natural systems and threatening the welfare of people around the world.

> "Even in an optimistic scenario where greenhouse gases meet or even exceed the targets of the Paris Agreement, excess heat in the Earth system may trigger changes that drive further warming."

Uncertainty in Forecasts

Scientists know these impacts are likely to happen, but it is currently difficult to predict when and where (which is critical information for policy) because of the limitations in a primary tool—Earth system models. The Earth is a vast complex system, with dynamics such as feedbacks and abrupt changes in state that make its behavior very difficult to predict. Earth system (i.e., climate) models simulate complex physical, chemical, and biological systems to forecast how the Earth's climate will change under future scenarios. Since the early 1970s, climate models have become ever more skillful in projecting future warming, but there remains a fairly large variation among them[37], mostly due to the differences in how these models simulate clouds in a warming world. When including in projections only those models that best replicate historical observations, there is a 93 percent chance that global warming will exceed 4 °C by 2100; this compares to a 62 percent chance when including all complex models.[38] This uncertainty has significant implications for scientists' current abilities to estimate risk. It is possible that all models share structural challenges that cause them to under-represent abrupt changes and feedbacks, confounding predictions further. Techniques to better understand cloud dynamics, observational data, and other types of analysis (e.g., machine learning) are improving models and predictions, but much more work is needed.

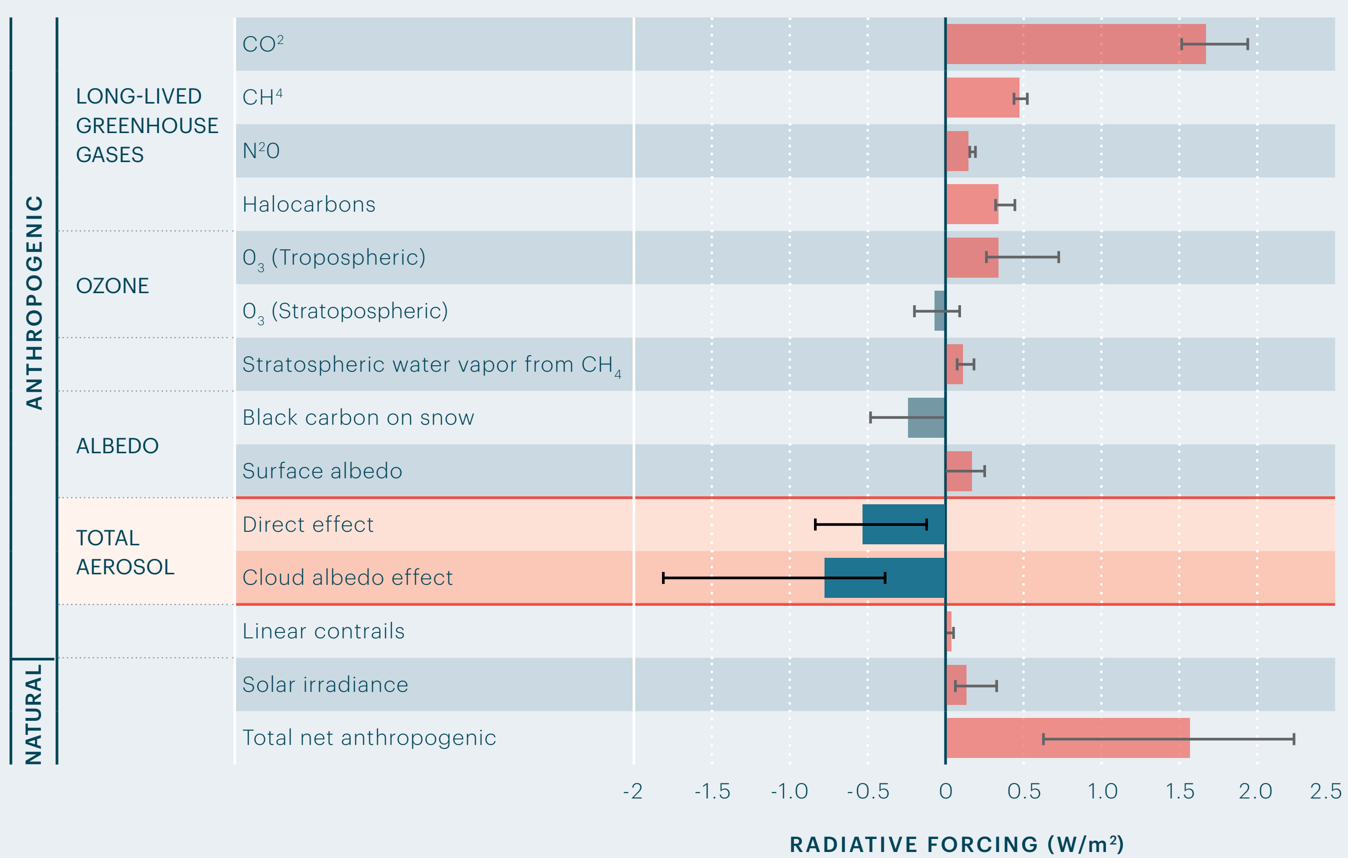
Uncertainty in forecasting climate impairs the world's ability to act. It is known that the magnitude of risk warrants high levels of investment and urgent response, but limitations in scientists' abilities to predict the nature and severity of impacts and the effectiveness of proposed solutions promotes delay. Reducing uncertainty in Earth system prediction is critically important to scientists' abilities to address the challenges ahead.

SPECIAL PROBLEM: COOLING FROM EMISSIONS

Particles (i.e., aerosols) in the atmosphere and their effects on clouds generally increase the total amount of sunlight reflected to space (i.e., through radiative forcing). This is one of the major cooling forces in the Earth system. Most anthropogenic emissions contain both greenhouse gases and other particulate matter and gases, such as sulfur dioxide (SO_2), that later forms particles, which have a reflective cooling effect. This cooling effect comes from the particles both directly scattering and absorbing sunlight (i.e., the aerosol direct effect) and indirectly as the particles mix with clouds (i.e., cloud–aerosol effect) and increase their brightness and/or their duration. The potential global cooling effect of all anthropogenic aerosols is, at the high estimate, equivalent to all of the anthropogenic climate warming to date. These effects are a great source of uncertainty in near-term climate forecasting and among the highest priorities for climate research.[39]

If the world was to eliminate all anthropogenic aerosols, the loss of this cooling "shield" could lead to substantial warming.[40] In 2020, scientists may have an accidental experiment in modifying these effects when new regulations substantially reduce SO_2 emission from ships, though they may not be in a position to measure this effect due to lack of a sufficient observational network.[41,42]

FIGURE 2.
ANTHROPOGENIC SOURCES OF WARMING AND COOLING IN CLIMATE.



SOURCE: Figure 8.15 in IPCC AR5.
NOTE: Estimates of radiative forcing and effective radiative forcing for each anthropogenic and natural agent.

Limitations of Current Options

The challenge faced now is a short and decreasing window for constraining heat in the climate system, with significant risk of devastating changes within 10 to 30 years and a current portfolio of solutions that is unlikely, even in the most optimistic scenarios, to sufficiently reduce warming within that timescale.

RAPID EMISSIONS REDUCTION

Greenhouse gases must be reduced to pre-industrial levels to ensure sustainable natural systems for the future. There is global commitment toward meeting this goal, but these transitions take time, and the most prevalent greenhouse gas—CO_2—leaves the atmosphere slowly.[43] There is also uncertainty about the political will of the world's countries to meet emissions targets under the Paris Agreement and acknowledgment that the goals themselves are insufficient to produce required reductions in warming. This challenge increases as energy and other demands rise as populous and developing countries continue to industrialize.

Transitioning to a zero-emissions society will require astute policy, rapid innovation, and substantial investment toward wholesale transformation of energy, agriculture, transportation, manufacturing, construction, and other sectors.[44] In general, transformations requiring infrastructure replacement take 50 years or longer[45] and face uncertain costs, risks, new technology, unstable public policy dynamics, and other barriers.[46] Transitions might be accelerated by or require societal advances in external costs allocation[47], education, and family planning[48], but these are also highly uncertain.

Over the course of the next century, innovation is likely to lead to wide adoption of zero-emissions and sustainable capabilities. But within the next 30 years, the period when dramatic reductions are required to reduce enough heat energy in climate to ensure safety, this appears highly unlikely.

GREENHOUSE GAS REMOVAL

The IPCC special report on 1.5 °C indicates that under most scenarios, emissions would not only need to be reduced to zero, but, also, greenhouse gases would have to be actively removed from the atmosphere to keep temperature increases between 1.5 and 2 °C by the end of the century.[49] With the risk of precipitous changes in 10 to 30 years, this may be too slow.

There are a number of possible methods for removing greenhouse gases from the atmosphere (i.e., negative emissions technologies or carbon dioxide removal).[50] These are generally still in the early stages of scientific assessment, research, and development. Some examples include the following:

- Biological methods for growing or optimizing plants or organic material to absorb greenhouse gases;
- Physical approaches to absorbing CO_2 in materials ("enhanced weathering") or filtering it from air ("air capture") and reusing it for energy or in materials or storing it in the ground; or
- Hybrid approaches that combine elements of both, such as biocarbon energy with carbon capture and storage, in which trees are grown to absorb CO_2 and burned for energy with emissions captured and stored or reused.

While promising, there are challenges and limitations to these methods. Most require substantial additional research and development and rely on economic incentives (e.g., carbon taxes or fees) that are not sufficient or have not been implemented. They each also have environmental impacts, and even climate effects, at scale[51] and must be assessed carefully. Industrial approaches to filtering and capturing CO_2 or other gases are currently prohibitively expensive[52], while many biological approaches require substantial additional analysis to understand their side effects. There are clear opportunities in restoring and optimizing the greenhouse gas capture of natural ecosystems, but even in optimistic scenarios, most approaches scale to reduce a modest fraction of the greenhouse gases currently emitted each year.[53] These approaches alone are unlikely to achieve targets and minimize risks.

These capabilities must be aggressively pursued. They are likely to be critical to any path to a safe climate. However, because scaled carbon capture capabilities would require substantial research and development, new economic incentives, and global deployment, they are likely to take decades to produce sufficient greenhouse gas reduction to substantially reduce warming. A broader portfolio is needed to reduce risks on a shorter timescale.

ADAPTATION

Presenting even greater challenges than removing and reducing greenhouse gases, adapting to climate change requires enormous, long-term investments across infrastructure, commerce, agriculture, health, and other sectors simultaneously in the context of increasingly stressed resources and growing demands for disaster response. In the United States, for example, much of the infrastructure essential for commerce for coastal cities such as New York, Boston, Miami, Manhattan, New Orleans, Los Angeles, and San Francisco will require protective dikes or other adaptive measures.[54,55,56] The same holds true for coastal military installations, ports, and power plants. Some infrastructure, such as coastal nuclear reactors, may pose particular risks[57], while abandoned infrastructure at the scale of entire cities could create separate environmental disasters. While reinforcing infrastructure is possible with sufficient planning, the scale, cost, and concurrency of required activities are likely to make them feasible for only a small subset of communities and stakeholders. Heat and drought conditions may not be adaptable, causing many areas to become uninhabitable, leading to large-scale displacement. For example, by 2050, worsening impacts of climate change in three densely populated regions of the world (sub-Saharan Africa, South Asia, and Latin America) could see more than 140 million people move within their countries' borders.[58]

> “Presenting even greater challenges than removing and reducing greenhouse gases, adapting to climate change requires enormous, long-term investments across infrastructure, commerce, agriculture, health, and other sectors simultaneously in the context of increasingly stressed resources and growing demands for disaster response.”

While there are numerous adaptation strategies that are available to cope with various climate changes, most require major effort and investment, and there are some losses, such as loss in diversity of species and ecosystems, that lack countermeasures.

Recent advances in genomic tools and technologies may help with identifying plants and organisms that better adapt to new conditions[59] or engineering new ones.[60] However, high costs are associated with replacing species, and there is extensive uncertainty as to the impact on ecosystems. For example, researchers have begun to study engineered replacements to coral to withstand higher levels of heat. But coral systems are communities comprised of large numbers of species[61], and the complexities are immense, as is the scale of the task, such that repopulating coral is akin to replanting a portion of the world's rainforests underwater.[62]

HORIZON FOR INNOVATION

Emerging technologies and promising basic science suggest that over time, with reasonable incentives, innovation could produce sustainable approaches to energy, food production, and other human activities to support a strong quality of life for all the world's people alongside vast, healthy natural systems.

By the end of this century, the world might anticipate widespread renewable energy accompanied by advanced battery and grid technology, safe and cost-effective nuclear energy, fossil energy with capture and storage, and other innovations delivering zero-emissions energy for all of the world's needs. New materials, organisms, and means of production will reduce waste and improve land and ocean use, sustaining the natural system. The challenge now is how to ensure the world's safety and protect the systems that support it to reach this future.

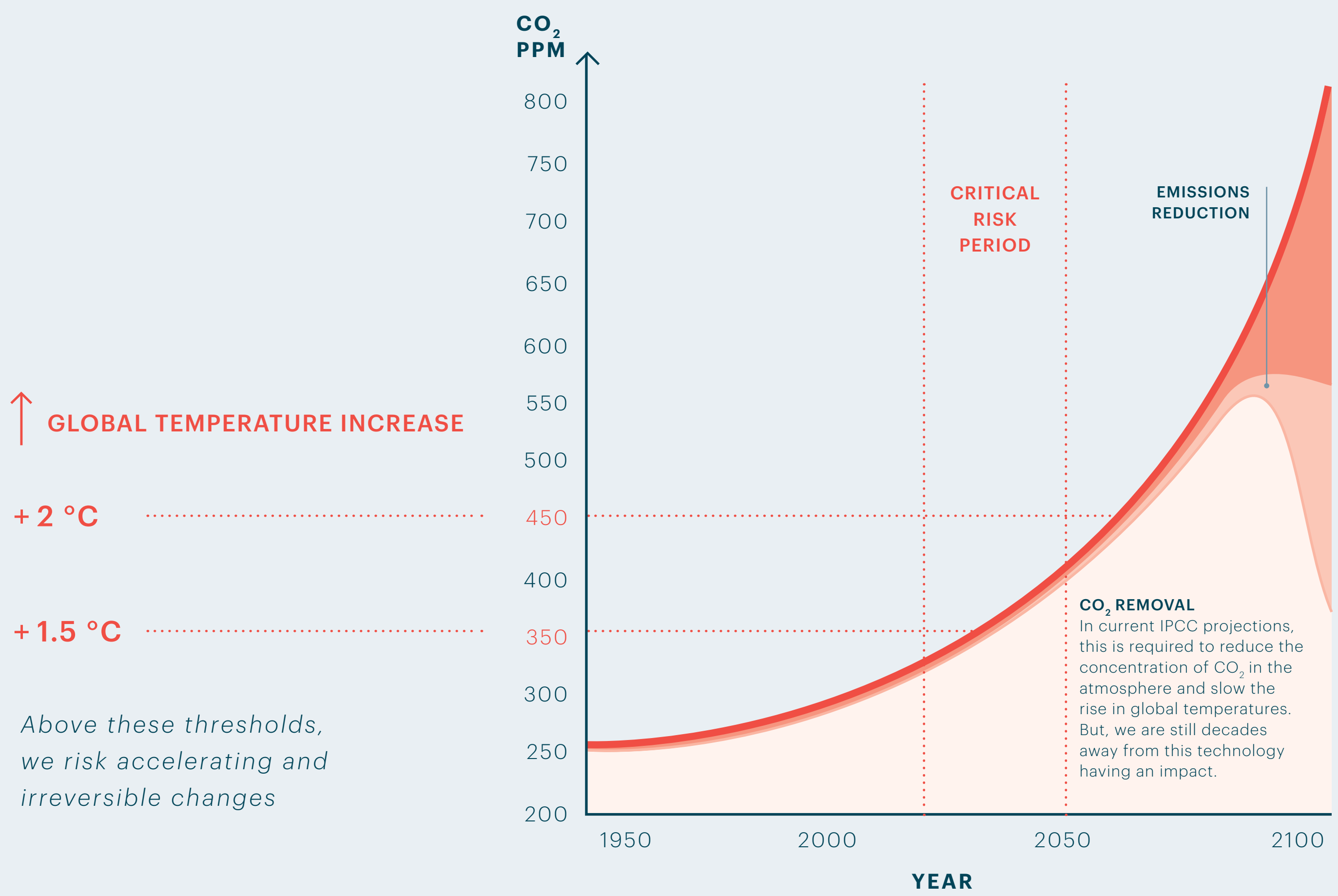
Exposure to Near-Term Risk

Even with aggressive emissions reduction and successful deployment of carbon removal technologies, society is many decades away from reducing accumulated heat energy in the climate system, exposing communities and natural systems to extreme risks in the next 10 to 30 years. These risks encompass human health and safety, infrastructure, economic output, ecosystem services, and global security. Currently available countermeasures (e.g., emissions reduction and greenhouse gas removal) operate over longer time horizons, leaving these high near-term risks unaddressed.

> “Emerging technologies and promising basic science suggest that over time, with reasonable incentives, innovation could produce sustainable approaches to energy, food production, and other human activities to support a strong quality of life for all the world's people alongside vast, healthy natural systems.”

There is a pressing need to expand the portfolio of available options to include approaches with the potential to rapidly reduce warming to provide insurance against the worst threats to safety and stability. Ultimately, it is important to maintain a comprehensive portfolio that includes greenhouse gas removal, emissions reduction, land and ocean management, efficiency measures, and other activities to sustain the Earth system. Additionally, it is imperative to understand and develop options that address near-term risks to safety and stability, and these are not part of the current portfolio. Such approaches have been proposed, with the most promising recommended by scientists for research. It is now time to pursue such research in earnest.

FIGURE 3.
PROJECTED WARMING WITH AVAILABLE COUNTERMEASURES.



Reflecting Sunlight to Cool Climate

It may be possible to slightly increase the reflection of sunlight from the planet to reduce the climate's heat energy (i.e., solar geoengineering, solar radiation management, or albedo modification). This could provide a cooling effect to counteract the warming influence of greenhouse gases.

In 2015, the National Academy of Science, Engineering, and Mathematics released *Climate Intervention: Reflecting Sunlight to Cool Earth*[63], which reviewed the state of the science and provided high-level findings and recommendations about the potential of various proposed methods for reflecting sunlight from Earth. It concluded that the most viable approaches involve increasing the reflection of sunlight from the atmosphere by dispersing particles either into the upper atmosphere (i.e., stratospheric aerosol injection (SAI)) or into low-lying clouds over the ocean (i.e., marine cloud brightening, or MCB).

This chapter describes these approaches, their potential risks, considerations for their deployment, and potential benefits and relative costs.

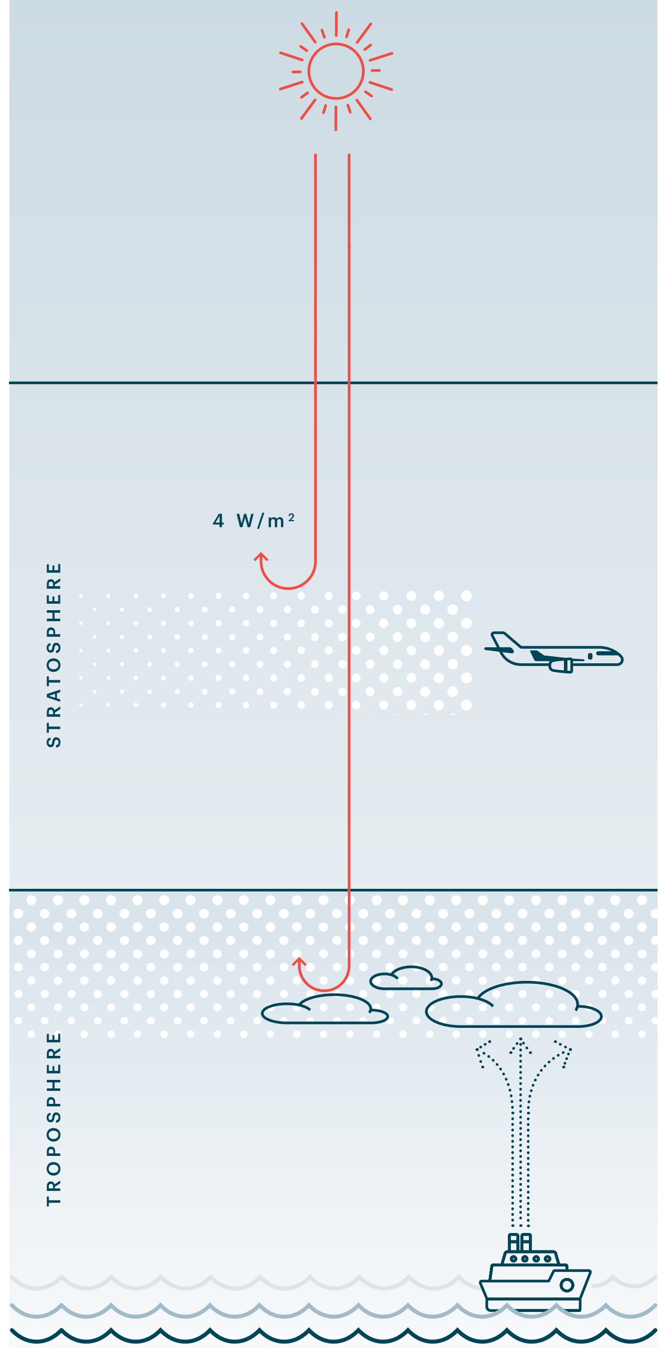
Proposed Approaches

STRATOSPHERIC AEROSOL INJECTION

Sufficiently powerful volcanic eruptions have been observed to reduce global temperature by releasing tons of SO_2 forcefully enough to reach the stratosphere, where they formed aerosol particles. These particles remained in circulation for 1 year or more, reflecting sunlight back into space.[64,65] Most recently, the eruption of Mount Pinatubo in 1991 resulted in observed cooling of over 0.5 °C and a marked increase in Arctic ice cover in the subsequent year.[66]

SAI emulates this effect by dispersing particles into the stratosphere in a managed way that seeks to optimize the reflection of sunlight while minimizing risks, such as adverse impacts on precipitation, stratospheric temperature, and ozone. Optimized tiny particles of SO_2, calcium carbonate, or another substance, preferably identified through extensive risk and efficacy studies, are delivered into the stratosphere in a controlled way, most likely via aircraft with specialized aerosol generation

FIGURE 4.
APPROACHES TO INCREASING THE REFLECTION OF SUNLIGHT FROM THE ATMOSPHERE.

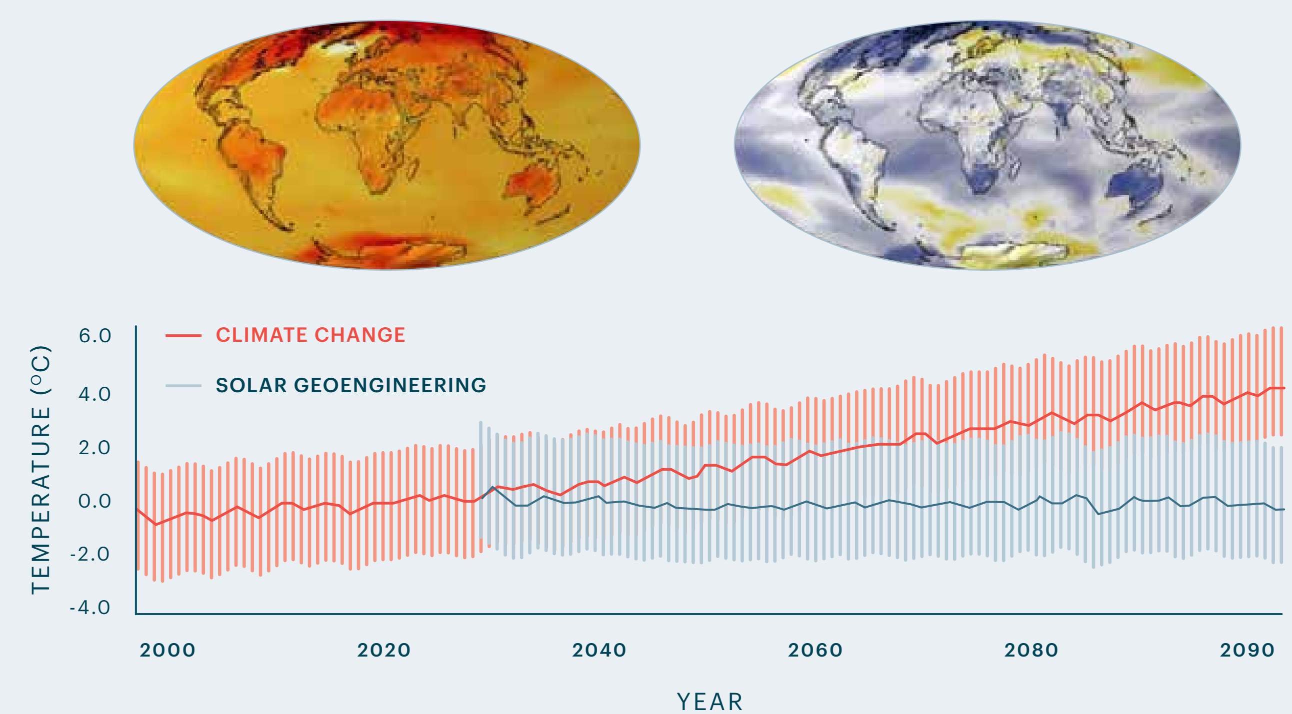


capabilities. This SO_2 oxidizes into particles that reflect sunlight, with characteristic sizes of several tenths of a micron. They disperse rapidly in the stratosphere around a hemisphere, or the whole Earth, and remain for approximately 1 year.

It is estimated that increasing the reflection of sunlight in the stratosphere by 1 percent could offset a doubling of CO_2, or 2 °C or more, of warming. Recent modeling studies simulating a managed regime of gradual introduction of aerosols indicated substantially fewer side effects than previous studies in a regime that held temperature constant through the end of the century.[67]

Of any approach to cool climate directly, SAI has the most substantial evidence for effectiveness in cooling. With relatively simple dynamics for modelers to develop simulations, it also has the largest body of literature. For these reasons, it is often favored as the primary focus of research. But, its global scope and persistence limit controls, maximize the impact of any unforeseen risks, and introduce enormous jurisdictional challenges. Notably, the 2018 World Meteorological Association Scientific Assessment of Ozone Depletion[68] found "an increase of the stratospheric sulfate aerosol burden in amounts sufficient to substantially reduce global radiative forcing would delay the recovery of the Antarctic ozone hole."[69] Due to its controversial nature and the lack of applicability of research to general climate questions, it is considered a difficult topic to introduce into climate and atmospheric research programs.

FIGURE 5.
SURFACE TEMPERATURE CHANGE.



SOURCE: Tilmes et al., National Center for Atmospheric Research (NCAR).[70]

MARINE CLOUD BRIGHTENING

Particles in the atmosphere, from both natural and anthropogenic sources, are catalysts for the formation of clouds and affect their properties in ways that drive weather and climate. Some mix with clouds in ways that increase the amount of sunlight they reflect back to space, producing a cooling effect.

It is generally agreed among atmospheric scientists that particles from anthropogenic emissions (industrial, energy, and shipping), such as SO_2, currently generate cooling, possible as much as all of the greenhouse gas warming to date (about 1.1 °C), and a wide range of uncertainty.[71] This cooling effect is likely to decrease as emissions reduce, contributing to near-term warming. The effect of aerosols on clouds may be particularly strong when emissions are introduced into unpolluted clouds over the ocean, a phenomenon first postulated by Twoomey in the 1960s[72] and subsequently observed in satellite images of the bright trails of ship emissions in clouds resulting in increases in cloud brightness ("ship tracks").

FIGURE 6.
SHIP TRACKS IN THE U.S. PACIFIC WEST COAST.[73]

Observation of this effect led British researchers John Latham and Stephen Salter to introduce a proposal to use an analogue of nature (i.e., particles of salt from sea water) to brighten unpolluted clouds over parts of the ocean (i.e., marine cloud brightening).[74] In this approach, optimized particles of sea salt would be dispersed from ships drawing in sea water, which is then converted to an aerosol spray. The particles would persist for a period of a few days to a week with their reach limited to localized areas so dispersal would be continuous and targeted to the most susceptible areas of clouds.

Early climate modeling studies suggest that using ships to deliver optimized sea salt particles into 5 to 10 percent of the Earth's marine clouds could provide enough cooling to offset a doubling of CO_2, extending the timeline for greenhouse gas reductions prior to the emergence of catastrophic or irreversible impacts.[75] Further research indicates that there might be applications for mitigating local or regional impacts of warming, such as reducing heat stress on coral reefs[76] or coastal redwood forests or reducing the force of hurricanes.[77]

With temporary, localized effects, direct analogues in shipping emissions, cloud seeding for rain, snow making, and similar forms of atmospheric research into aerosol–cloud interactions already occurring, marine cloud brightening has less complex safety and jurisdictional issues for field research and possibilities for incremental deployment. Some believe that it is the climate intervention approach most likely to be deployed first through local or regional efforts to reduce impacts, such as protecting corals or reducing hurricane severity.

Clouds are highly complex systems, and the way that particles interact with clouds to change their properties has large uncertainties. Thus, the efficacy of marine cloud brightening is difficult to determine and very difficult to model, leading to far fewer studies and lower prominence as a means of cooling climate. Research in marine cloud brightening centers on focused understanding cloud–aerosol interactions, which is currently the greatest near-term uncertainty in the quantification of how humans are influencing climate and thus already of high priorities for climate research.[78] Thus, marine cloud brightening research is considered to be "dual-purpose" and, for that reason, is of greater interest to atmospheric scientists and less controversial than studies targeting SAIs. Therefore, of the approaches to directly cool climate, it is a stronger candidate for climate and atmospheric research programs. Yet, the controversial nature of intervention in general has largely prevented its inclusion in research programs to date.

CIRRUS THINNING

Cirrus clouds in the upper troposphere reflect more sunlight back to Earth than they reflect out to space. One proposed approach to increasing the net reflection of sunlight from Earth is to inject particles into cirrus clouds that catalyze the formation of ice crystals in the clouds, causing them to precipitate. This phenomenon, termed cirrus cloud modification or cirrus thinning, 'thins' the clouds, causing more light to be released from below out to space. It is not an approach with a natural or anthropogenic analog, and thus would require experimentation to determine if the behavior predicted by the theory occurs in the physical world. For example, it is possible that material could settle at lower layers of the atmosphere in a way that counters the desired effect.

Impacts of cirrus thinning on atmospheric circulation are highly uncertain, requiring extensive research to understand. Such research would necessarily include research into potential materials (e.g., bismuth tri-iodide) for catalyzing ice formation and the technologies for their delivery. Due to extensive unknowns, cirrus thinning is often positioned below stratospheric aerosols and marine cloud brightening in terms of research priorities, though it may have a comparatively favorable risk profile. Targeted feasibility studies may be valuable in determining the suitability of investment in cirrus thinning research.

SURFACE-BASED APPROACHES

Proposed methods for increasing the reflection of sunlight from the Earth's surface to cool the climate include painting human settlements or planting reflective crops, covering deserts with a reflective polyethylene aluminum to reduce heat absorption, scattering reflective material over polar ice, and churning ocean surface water to generate reflective foam. While these methods might play a role in reducing heat, their contribution is likely to be minor.[79] Additionally, many surface-based approaches affect exchanges of gas and particles with biological life at the surface (biogeochemical processes), leading to severe ecosystem impacts and possible detrimental climate effects.

SPACE-BASED APPROACHES

Proposals for reducing climate heat include reducing the sunlight reaching Earth from space through the deployment of space-based mirrors or filters. These could be highly effective in cooling climate with relatively low ecological impact but could involve enormous engineering challenges and uncertain controls. Thus, they have not been considered candidates for research relevant to near- or medium-term climate intervention.

Atmospheric sunlight reflection approaches (i.e., marine cloud brightening and SAI) is studied for the purpose of this report.

> "There are considerable risks associated with intervention in the Earth system that must be better understood in order to assess, govern, or safely deploy any of these capabilities."

Potential Risks

There are considerable risks associated with intervention in the Earth system that must be better understood in order to assess, govern, or safely deploy any of these capabilities. These fall broadly into the categories of environmental risks, moral hazard risks, uncertainty risks and political risks.

ENVIRONMENTAL RISKS

There are three primary risks associated with atmospheric climate interventions: changes in precipitation, changes in the nature of sunlight that reaches the surface, and changes in atmospheric chemistry.

Changes in precipitation can result from changes in multiple mechanisms, such as changes in wind and circulation patterns, cloud composition and formation, and stratospheric heating. Current research suggests the proposed increases in atmospheric sunlight reflection would likely result in slight reduction in global precipitation relative to today or to pre-industrial conditions.[80,81,82] More significant changes may occur in local areas, which may or may not be readily attributable to sunlight reflection interventions. For example, atmospheric sunlight reflection may be less effective at counteracting hydrological changes (precipitation minus evaporation) from global warming over the Amazon, which can be attributed to the plant physiological response to CO_2 and to a regional dynamical response related to subtle sea surface temperature changes in the Pacific.[83]

With stratospheric aerosols, sunlight intensity would be reduced, but the amount of sunlight arriving from different directions would increase due to scattering by the aerosols.[84] More diffuse sunlight would reach into the plant canopy, increasing photosynthesis, with possible impacts on natural and managed ecosystems.[85] Sunlight reduction could also affect home heating and solar power facilities.[86]

In the stratosphere, an injection of sulfur large enough to compensate for surface warming caused by the doubling of atmospheric CO_2 would strongly increase the extent of Arctic ozone depletion during the present century for cold winters and would cause a considerable delay, between 30 and 70 years, in the expected recovery of the Antarctic ozone hole.[87] Stratospheric aerosols are likely to slightly increase the acidity of the snow and rain reaching the surface.[88] However, this effect is estimated to be a small fraction of the acidity increases associated with industrial pollution.

While some studies have shown that sub-optimum approaches to intervention, like abrupt termination[89] or volcano-like injection, pose high risks, studies have shown that these risks can be addressed during implementation.[90]

MORAL HAZARD

One significant concern is the possibility that intervention options might lessen incentives to reduce greenhouse gases (known as "moral hazard"). It is currently unclear what the influence of this hazard might be, when it is introduced (possibly as early as conceptual discussion), and whether it might increase or decrease in conjunction with research. Reducing heat through reflecting sunlight does not directly address other greenhouse gas impacts, such as ocean acidification, which have risen to dangerous levels, though it may indirectly help by preventing additional greenhouse releases from natural stores.[91] Notably, there are increasing risks and diminishing returns as levels of atmospheric intervention rise[92], creating an upper boundary to the amount of greenhouse gas forcing they can offset. Greenhouse gases must be kept below this boundary for safety and reduced to zero to address other impacts and long-term risks. Any counter-incentives to greenhouse gas reduction must be considered carefully, but, as discussed later in the Governance chapter, it is possible that intervention research could increase rather than decrease them.

UNCERTAINTY AND ATTRIBUTION

Uncertainties in predicting the Earth system behavior pose fundamental challenges to scientists' abilities to make informed decisions and assure safety in climate intervention. This is compounded by challenges in attributing climate effects and impacts, such that it may be difficult or impossible to distinguish a negative natural occurrence from a side effect of intervention.

POLITICAL RISKS

Real or perceived impacts of interventions, or disagreements about their proposed use, could lead to political, economic, or military conflict. With the current state of knowledge, climate-impacting activities pose uncertain risks, and may warrant such a response. While substantial knowledge and investment is required to deploy these capabilities responsibly, it is possible that states or other actors may attempt them in a non-transparent or irresponsible way. Even with more advanced knowledge and capabilities, managing tensions around scientifically grounded, coordinated use is likely to require thoughtful governance approaches and a high degree of transparency.

Understanding and minimizing risks is a critical area of focus for research programs and the ultimate design of any operational systems. Estimating the risks of atmospheric climate intervention is similar in nature to forecasting the impacts of greenhouse gases and will require substantial advances in Earth system prediction capabilities.

Deployment Considerations and Costs

Deployment of atmospheric climate intervention involves regional or global capabilities for modifying the atmosphere to influence climate. It encompasses the goals, methods, technologies, information, processes, and resources, including human resources, to that end. In general, considerations center on managing uncertain risks of intervention against the uncertain risks of a warming climate in the context of uncertain technological capabilities. Due to historical funding constraints and taboos, research is nascent, and a great deal more is needed.

To date, deployment studies have focused on regimes and mechanisms for delivering aerosols into the atmosphere to reflect a targeted quantity of solar energy (also known as "radiative forcing" back to space). A recent study of deployment of stratospheric aerosols describes delivering aerosols into the upper stratosphere via a new type of stratospheric cargo aircraft in a gradually escalating program of injection aimed at reducing the rate of warming.[93] The most recent marine cloud brightening proposal describes spraying sea salt mist continuously from thousands of commercially available autonomous marine vessels into regions of susceptible clouds, with tunable levels of radiative forcing. These proposals all contain scientific, technical, and operational uncertainties that must continue to be explored. In general, beyond delivery and reflective effects, there has been little work on broader deployment considerations.

Critically, there are not yet clearly defined goals or requirements for intervention. In their absence, different assumptions lead to differing proposals with variable objectives and costs. For example, a regime with the goal of reducing the rate of warming such as proposed by Sugiyama et al. (2018)[94] may help minimize intervention risks and slow warming, but its scope may be more narrow than one designed to reduce uncertainty and assure safety. With respect to deployment, it will be critical to define goals and requirements and what we need to achieve them

GOAL AND REQUIREMENTS

Given the nature of climate risk, a reasonable goal for atmospheric climate intervention efforts might be to maximize safety and stability for communities and natural systems. One characterization of this might be **to maintain safe levels of heat energy in the Earth system and prevent precipitous changes within an acceptable level of uncertainty and adverse impact in compliance with laws and regulations and operating in the public interest**.

Requirements for a program with this goal might include the following:

- Attribution, monitoring, and forecasting of natural, anthropogenic, and interventional climate drivers with a high degree of accuracy;
- Analysis and prediction capabilities to assess present and future states, including early warning indicators for precipitous changes and forecasts of localized impacts;
- Continuous, high-sensitivity observations of climate drivers, atmospheric chemistry and, critical environmental functions;
- Mission-critical operations capabilities (continuity, security, etc.);
- Compliance systems for regulatory requirements and governance; and
- Program support including management, research and development, legal, and communications.

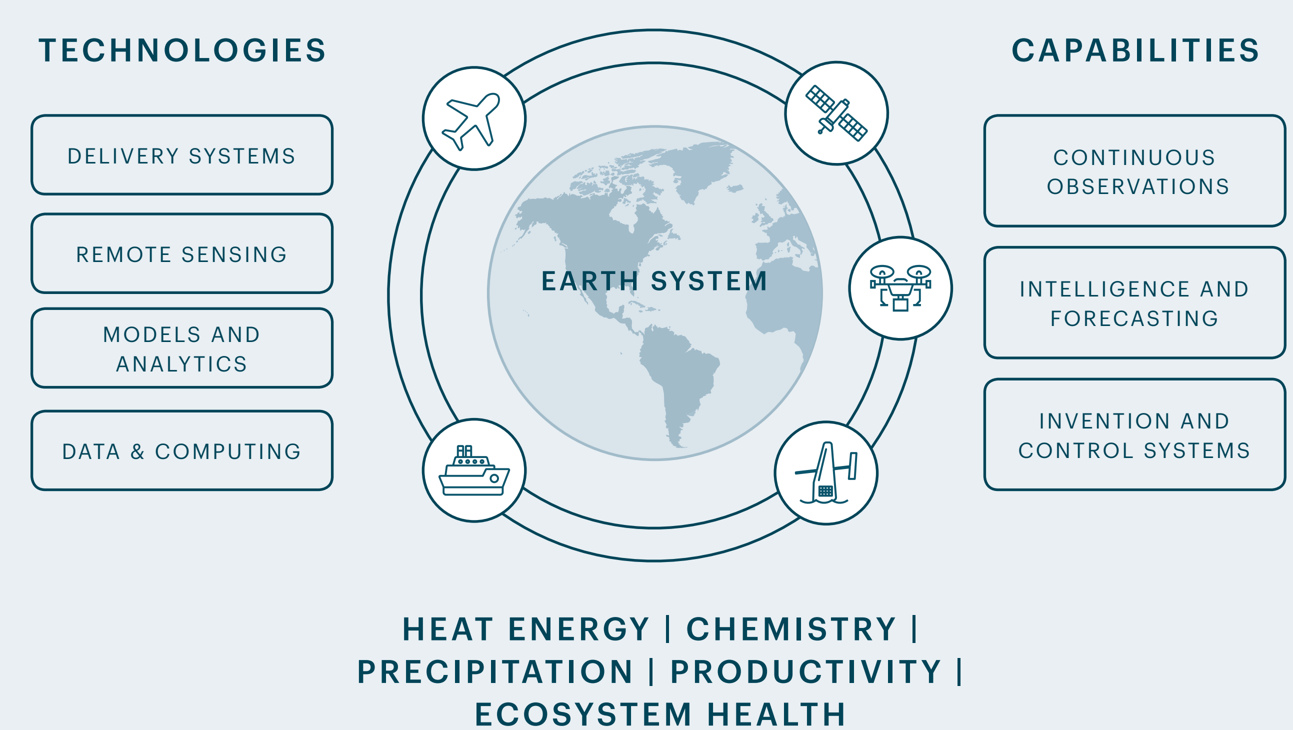
Meeting these types of goals and requirements implies a holistic way of thinking about climate intervention and research, integrating intelligence and action in comprehensive capabilities for sustaining the Earth system.

WHOLE SYSTEMS APPROACH

A critical challenge in climate policy has been a limited ability to tie climate influences to impacts and reduce uncertainty for decision-making and investment. Interventions share these challenges. They require, and are the catalyst for, a holistic approach to understanding and sustaining the Earth system to address both immediate risks and underlying causes of climate change. This approach includes intelligence about the current and future states of the Earth system to support the full range of policies and interventions for influencing them. In this model, atmospheric climate intervention is just one of many influences that should be considered agnostically among short- and long-term measures for restoring and maintaining a healthy climate.

A whole systems approach is particularly important for complex systems, where multiple approaches to understanding the system are required to reduce uncertainty. For the Earth system, it requires advanced capabilities for gathering and synthesizing information and orchestration of elements that engage with the physical world. It will take innovation in technologies such as aerosol generation, delivery platforms, instruments, observational platforms, models, analytics, and computing. It will also require mission programs with strong leadership that can mobilize teams from an array of disciplines to deliver scientific knowledge, innovation, and operational capabilities in a coordinated way. A whole systems approach provides actionable information for policymakers and an integrated view of alternatives on which to act.

FIGURE 7.
WHOLE SYSTEMS APPROACH FOR CLIMATE INTERVENTION.



KEY CONSIDERATIONS

There are important considerations regarding a number of aspects of the development and deployment of atmospheric interventions to reflect sunlight.

Aerosol Dispersion

Atmospheric climate interventions generally employ mobile platforms fitted with technology for delivering aerosolized material continuously in the physical environment, with relevant information and operational support. Lab-scale technology has been developed for sea salt aerosols, which may have applicability for calcium carbonate ($CaCO_3$). No technology exists beyond the lab scale for generating and dispersing aerosols other than sulfur (which is converted to SO_2 in the atmosphere), and no real-world observations are available for materials other than SO_2. SO_2 has some unfavorable properties, and the limitations of aerosol generation technology will determine the feasibility and effectiveness of other materials for this purpose.[95] Without this technology, models and estimates are based on assumptions about primary processes, and risks and costs cannot be adequately assessed. Deployment platforms have also not been developed. SAI may require a new type of high-performance aircraft, which may take a decade or longer to produce.[96] Marine cloud brightening may be possible using commercial autonomous platforms, but systems integration and testing are required. A host of environmental engineering and operations considerations must be explored for the development of any regional or global capability. Additionally, with differing risk and persistence profiles for stratospheric aerosols and marine cloud brightening, there may be potential for use in tandem or as redundant measures. For example, if SO_2-based SAI reduced stratospheric ozone to critical levels, marine cloud brightening could be introduced to augment and reduce SAI use. Conversely, were marine cloud brightening to unacceptably impair rainfall, some of its influence could be replaced by stratospheric aerosols. Given diminishing returns and increased risk as levels of input rise, a regime in which multiple methods are used in tandem might be favorable. In this, as in other areas, very little information is available and a great deal of work is needed.

Intelligence

Reducing uncertainty sufficiently for informed decision-making in climate intervention requires far greater ability to assess and predict the Earth system than we have today. It requires the ability to attribute and forecast various drivers of heat energy, calculate required offsets, predict the impacts of intervention, and measure and assess results. Achieving this requires high-sensitivity observations, advanced models and analytics, and powerful underlying computing systems that marry predictions with the physical world. Interventions are a part of a range of drivers of heat in the Earth system—natural, anthropogenic, and interventional—that are projected to become more variable, and special attention should be given to monitoring and forecasting changes in natural drivers, such as phytoplankton affecting CO_2 absorption and cloud formation and the release of greenhouse gases from ground stores. Similar attention should be given to understanding changes in anthropogenic cooling from reduction in aerosol pollution. Substantial scientific programs are needed to analyze findings and continuously improve models and analytical tools.

Operations

Operations requirements have not yet been developed for systems to intervene in climate, but there may be helpful analogues in global defense, communication, and transportation systems that deliver critical services and operate at scale in the physical world. These systems have requirements, such as continuity, with features like supply chain assurance; over-provisioning and redundancy; security, including multiple redundant measures for both information and physical systems; and compliance, such as automated and human controls, data capture, storage, and retrieval, and various types of external certification that are likely to be important for atmospheric climate intervention capabilities. There may be unique challenges for atmospheric climate intervention, and these requirements will increase the scope and cost estimates for these programs, and significantly more work is required to understand them.

Program Management

Strong program management is essential for the development and ongoing operation of these capabilities. Climate intervention is inherently interdisciplinary, requiring innovation and execution across an array of disciplines, working in parallel to execute against a shared mission. It requires extensive planning, coordination, and decision-making against a balance of objectives and a myriad of requirements. It includes a wide array of stakeholders and holds profound implications for society. Non-scientific and technical aspects, such as legal and communications, play an outsized role. This model is typically challenging for academic institutions, though there are exceptions, and a noteworthy area of success for U.S. mission agencies (e.g., the Department of Energy (DOE) and the Defense Advanced Research Projects Agency (DARPA)).

The goals, requirements, and features of intervention programs and systems inform both the nature of research programs and the costs of research and deployment.

COST ESTIMATES

Cost estimates vary with the scope of programs and assumptions about capabilities and their use. With relatively little research on deployment models and considerations, and yet-to-be-developed technologies, they are difficult to estimate. To date, cost analyses have focused on the delivery of material into the atmosphere, with a recent estimate of annual costs for delivering material into the stratosphere (excluding aerosol technology and instrumentation) of $2.25 billion per year[97] and informal estimates of $3 to $4 billion for marine cloud spraying in the troposphere. With a scope that includes comprehensive capabilities, such as models, analysis, observations, scientific programs, security, governance, and program support, annual costs of $15 to $20 billion may be realistic, and substantially higher costs are possible.

Overall, the nature and cost of deployment is an area that requires extensive further study and assessment and is informed by climate science and climate intervention research, technology development, and input from experts in disciplines such as environmental systems engineering, global field operations, security, risk management, and information technology.

Potential Benefits and Relative Costs

Atmospheric climate intervention techniques could alleviate heat stress on natural and human systems, producing improved outcomes for these systems. At a global level, preliminary studies and natural experiments indicate that reflecting sunlight to cool temperature, though not a substitute for large-scale greenhouse gas reduction, is likely to yield many of the benefits associated with constraining global temperature through reducing greenhouse gases[98], including benefits to specific systems that have not been fully studied. For example, recent studies indicate that heat may play a more dominant role in ocean stress than previously believed[99], with significant benefits for corals, oxygen content, fisheries, and other ocean services.

In the United States, atmospheric climate intervention could prevent outcomes described in the Fourth National Climate Assessment[100], including loss of infrastructure and natural resources, increased energy consumption and loss of life, health, and other impacts on people. It would prevent substantial economic losses and reduce threats to global security and economic and democratic institutions. It would also provide intangible benefits that are harder to quantify, such as reducing anxiety and fear, preserving natural beauty, and providing security and prosperity for future generations.

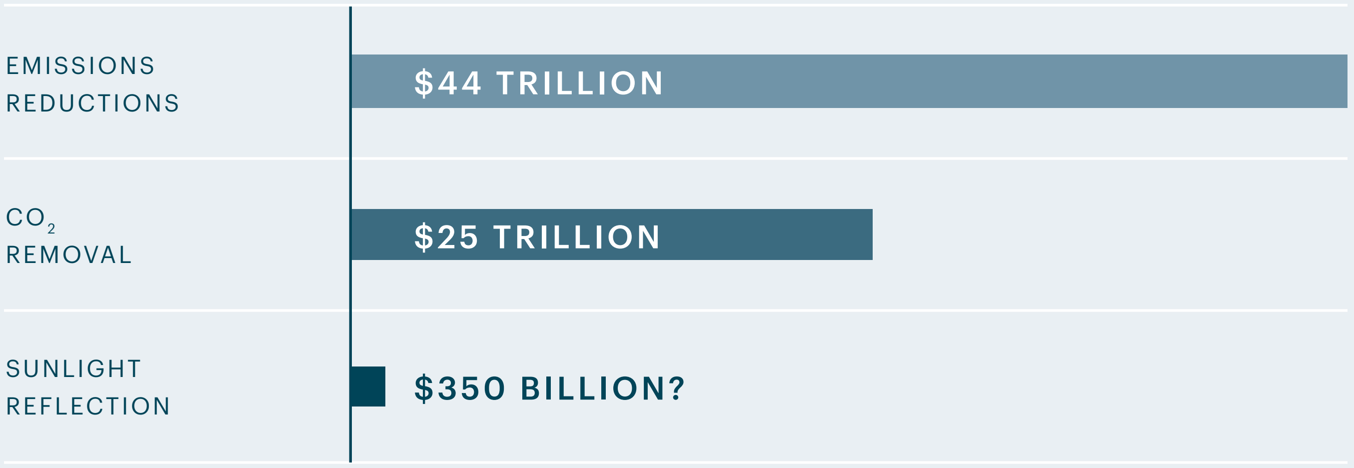
Overall, the benefits of atmospheric climate intervention may be profound in terms of lives, welfare, economic costs, and the sustainability of societal and natural systems. A great deal of work is required to assess the potential benefits against the risks in the context of the increasingly dire risks of warming climate.

RELATIVE COSTS

Even with generous estimates, the cost of atmospheric climate intervention is likely to be orders of magnitude lower than the cost of mitigation or greenhouse gas removal to constrain warming to safe levels, or adaptation to respond to it, in the next 10 to 30 years. According to the most recent National Climate Assessment, the projected cost of unmitigated warming through 2100 could be as high as a 10 percent reduction in the U.S. economy.[101] The International Energy Agency (IAEA) estimates the cost to constrain warming to 2 °C by 2050 through mitigation alone at $44 trillion, though this notably does not include anticipated gains in efficiency.[102] CO_2 removal taken by itself at cost of $40 per ton (far below current estimates) might cost $25 trillion[103] to do the same. By comparison, even with comprehensive programs and conservative assumptions, the cost of atmospheric sunlight reflection to maintain temperatures below safe levels by 2050 is likely to be in the range of several hundred billion dollars.[104]

While there are numerous risks and uncertainties in atmospheric sunlight reflection, in the next 10 to 30 years, it has the potential to constrain warming at a dramatically lower cost than mitigation or greenhouse gas removal while promoting safety and stability. Vital to the health of the climate, greenhouse gas emissions must be reduced aggressively, and concerted efforts must be made to remove them from the atmosphere. It is likely to take all efforts in concert to address risk and restore the health of the climate system, and the world will have to rapidly advance the knowledge base in order to make sound decisions about them.

FIGURE 8.
RELATIVE COST TO STAY BELOW 2 °C BY 2050.



Governance

With respect to climate, governance is often defined broadly in terms of the mechanisms that steer society toward reducing climate risks. Atmospheric climate intervention is among those mechanisms, but it may be appropriate to consider its governance more specifically in terms of oversight and protection of public safety and natural resources. Research is needed to effectively undertake such governance.

To address the complex issues in governing the use of interventions, substantially more information is needed. To date, research has been constrained by concerns related to governance, preventing the generation of scientific information essential to effective policy. For research, well-constructed governance can foster responsible exploration, build public trust, and stimulate a healthy research ecosystem to inform the development of governance mechanisms for any future deployment.

This chapter discusses the drivers for the governances of interventions; provides an overview of existing laws, regulations, and frameworks; describes the current information deficit with respect to governance; and suggests prudent next steps for future action. This discussion is not comprehensive or conclusive but is intended to provide guideposts and ideas for forward exploration.

Drivers for Governance

Atmospheric climate interventions pose potentially enormous physical risks and raise complex societal concerns. Some or all of these drivers for governance could be further explored with additional research to determine their potential impacts on nature and society.

ENVIRONMENTAL AND PHYSICAL RISKS

Climate intervention poses substantial known and unknown risks by making changes to the natural environment that could affect human health and welfare and the natural resources human communities rely on. These changes may not be predictable or equitable. For example, marine cloud brightening could have pronounced effects on precipitation patterns[105], reducing precipitation in particular regions. SAI could damage the ozone layer with severe health consequences for people.[106] Any global-scale change is likely to effect major dynamics of the system, like air and ocean circulation, in ways that are difficult to predict.

It is right to be highly concerned with the possible effects of intervention on communities, ecosystems, and vital resources and how these effects might be distributed. It is also worth noting that scientists and policymakers cannot know how serious these risks are or compare them to the severe risks of increased warming with our current level of information. Without significant investment in atmospheric studies, sensing, satellites, and modeling, policymakers will not be equipped to make meaningful decisions about these capabilities or design systems that minimize the net risks of implementing or not implementing specific interventions. Governance regimes developed without a clear understanding of technical and scientific realities will be at best ineffective at minimizing potential harms and, at worst, could inhibit research before policymakers are able to weigh potentially viable options to increase safety.

> “Climate intervention poses substantial known and unknown risks by making changes to the natural environment that could affect human health and welfare and the natural resources human communities rely on.”

SOCIETAL DYNAMICS

Governance discussions to date have focused heavily on the societal risks and implications of pursuing climate intervention. These include a potential negative impact on political will to reduce greenhouse gas emissions[107], slippery slopes of technological and institutional lock-in[108,109], inequitable decision-making[110], and larger philosophical questions about the role of humans with respect to the environment.[111]

Moral Hazard

A central theme of climate intervention criticism is that investment in these techniques, even in small-scale research, can lead policymakers and the public to believe that there is a silver-bullet solution and that large-scale reductions in greenhouse gas emissions are not immediately necessary. The world is not on track to meet its targets agreed upon in the Paris Agreement[112] and is far from implementing the large-scale industrial and societal changes necessary to limit warming to the 1.5 °C recommended by the IPCC special report released in 2018.[113] In this context, the effect of moral hazard, if real, may be negligible. In fact, it is possible that exploration of emergency measures is consistent with a level of urgency that bolsters the case for immediate mitigation measures.

It is also possible that more consequential moral hazards may arise at the earliest stages of dialogue about a new technology and may be reduced by research. This dynamic was demonstrated in global policy considerations of both adaptation and negative emissions technologies. In these instances, moral hazard concerns delayed research, but proposals began to appear in policy frameworks with highly optimistic estimates of their effectiveness.[114] Climate intervention research will highlight the risks and limitations of interventions and may provide further imperatives for greenhouse gas reduction.

Slippery Slopes and Technology Lock-in

Some have argued that the activities of research and development themselves influence in favor of a technology's eventual use. Proponents of this idea contend that research in climate intervention "may generate its own momentum and create a constituency in favor of large-scale research and even deployment"[115] where stakeholders may suppress unfavorable findings and inhibit real understanding of risks. But climate intervention research has characteristics that reduce the risk of lock-in, including a lack of commercial market for deployment and a close relationship to climate research broadly. A well-designed research agenda, a vibrant ecosystem of research programs, and strong scientific assessment functions can check conflicts and biases in research and policies that prioritize safe and sustainable outcomes and will help promote rational investment.

Rapid Scaling ("Escape Velocity")

Closely related to lock-in is the concern that a new technology will scale rapidly before risks are understood and without adequate controls. Technologies like social media, artificial intelligence, and gene editing are helping to fuel these concerns. This type of risk is related to the speed at which a new technology might grow beyond the ability to control it, that is, its '"escape velocity."
Escape velocity is tied to the drivers of a technology's propagation; for example, the self-replicating nature of biological innovations and relatively low barriers to entry allow for the possibility that large changes to the physical environment could result from even small levels of activity and investment. In the human sphere, technologies with immediate market drivers and low barriers to entry can scale rapidly through independent commercial efforts, which was a major cause for concern regarding early activity in ocean fertilization.[116]

Atmospheric climate intervention, however, lacks these features and largely precludes rapid scaling. The elements in proposed atmospheric climate interventions are not self-replicating: the physical impact of an intervention scales proportionately with the amount of the substance introduced. Tens or hundreds of millions of U.S. dollars of basic and applied research are required to test and deploy these capabilities, posing a high barrier to entry. Interventions are capital intensive in execution and inherently subject to regulation, increasing barriers further. They are generally observable, making misuse difficult and obvious. Even so, effective, legitimate governance and the required investments in climate monitoring and analysis would safeguard against rogue deployment.

Informed Consent

Due in part to concerns about lock-in and escape velocity, there has been increased emphasis on public engagement and consent in the evolution of technologies with the potential for widespread impacts (e.g., artificial intelligence and gene editing). For climate intervention, proposals by organizations like the Forum for Climate Engineering Assessment[117] and the Carnegie Climate Geoengineering Governance Initiative[118] focus heavily on public notification and consent for any activity regardless of the presence of environmental or safety risks. These groups contend that the previously detailed concerns are enough to warrant high levels of public engagement for research. Engaging the public on emerging technologies is a growing area of study in social science research—and a useful one. However, the introduction of non-scientific inputs to scientific research could pose financial and process barriers to research while introducing new risks to scientific objectivity.

OBJECTIVES OF GOVERNANCE

With a paucity of information arising from a lack of research, to date, debates have been insufficiently informed by scientific and technical realities, and societal concerns have played a magnified role. The objectives of governance proposals vary, with some prioritizing process goals at the expense of health, environmental, and economic outcomes. The orienting goals of governance should be safety for the world's people and sustainability for the natural systems that support them.

Existing Laws, Regulations, and Frameworks

Several organizations and mechanisms exist on international and national levels that have some jurisdiction over atmospheric climate intervention or could be extended for governance. The agreements, regulations, and protocols listed in this section are by no means an exhaustive list but include many of those tools likely to be relevant for governing atmospheric climate intervention. They are organized into atmosphere-specific regulations and broader frameworks for the protection of the environment. A full review of international, national, and sub-national laws and regulations is needed, along with evaluation of the most relevant institutions and processes. (The recent book *Climate Engineering and the Law*[119] is an excellent start.)

INTERNATIONAL

There are multiple international multilateral frameworks with overlapping jurisdictions related to climate intervention activities. Three international frameworks are particularly applicable to climate intervention: the Environmental Modification Convention (ENMOD), the Convention on Long-Range Transboundary Air Pollution (CLRTAP), and the Montreal Protocol. Each may have legitimate claims to various aspects of governance but would need significant updates, changes, or expansion in order to meet the requirements these interventions pose. The Montreal Protocol may be particularly relevant, as it holds with jurisdiction over one important subject of risk management in atmospheric climate intervention—the ozone layer—and is a uniquely successful international cooperation to address environmental risk.

> “The orienting goals of governance should be safety for the world's people and sustainability for the natural systems that support them.”

ENMOD[120]

ENMOD, first signed in 1977, specifically prohibits weather modification with hostile intent. While vague and somewhat antiquated, the agreement nominally precludes the weaponization of weather, and some have argued that climate intervention activities could apply laws of war as normative guidelines[121], including minimizing impacts on civilian populations and their environments. However, a military connotation may be undesirable in this context.

CLRTP[122]

CLRTAP, signed in 1979, monitors invasive pollution and could have jurisdiction over atmospheric climate intervention efforts with transboundary effects. While focused on direct impacts to human health and activity arising from air pollution, this convention specifically regulates SO_2 and may have the authority to regulate any field test that used sulfur oxides, including stratospheric activity with climate impacts and marine cloud brightening with transnational implications. This protocol could be extended to other substances and methods used in climate intervention, but it would need additional functions in order to have the capacity to evaluate scientific findings and make judgements about various activities rather than simply regulating and reducing certain pollutants.[123] Further, there are only 51 signatories to the convention, and most are European and industrialized, creating political challenges.

The Montreal Protocol[124]

The Montreal Protocol regulates substances that deplete the ozone layer in the stratosphere and some replacement compounds. The agreement, and its executing body the UN Environment Ozone Secretariat, have reversed the damage to ozone and evolved a successful framework for ongoing management. Since the agreement was first signed in 1987, the ozone layer has substantially recovered and was, until recently, projected to be fully repaired by 2080.[125] The Montreal Protocol is the most successful international effort to address an environmental issue on record and, along with its companion the Vienna Convention, is the only legally binding environmental agreement signed by every nation in the world.[126] The Montreal Protocol is currently addressing an observed violation[127], which may test its capabilities and affect the ozone's trajectory.

This body has a strong and effective review function with technical expertise in three assessment panels, most notably the Scientific Assessment Panel. Every member of the UN is a party to the protocol, and both parties and non-parties alike are welcome to join its deliberations, fostering a robust and inclusive review process. The body's original design to phase out harmful materials and willingness to curb industries with incentives to scuttle evidence has successfully managed the role of private interests in the process.

The Montreal Protocol and the Ozone Secretariat are already responsible for monitoring and protecting the ozone layer damage, one of the most significant risks of SAI. Four parties to the Montreal Protocol recently requested an assessment by the Ozone Secretariat on the implications of SAI proposals for the ozone layer.[128] Under the Kigali Amendment[129] to the Montreal Protocol, there is also historic precedent for the protocol to be used to regulate non-ozone-depleting gases (i.e., hydrofluorocarbons), which were introduced as replacement gases for ozone-depleting substances but have high global warming potential and are now being phased out. As a successful legal framework with some existing jurisdiction, the Montreal Protocol and its related processes should be reviewed closely and given strong consideration for their applicability to assessment and governance of research and governance of climate impacting activities.

Convention on Biological Diversity

The United Nations Council on Biological Diversity (CBD) seeks to govern the influence of human activity on the diversity of species in natural systems. CBD passed a 2010 moratorium on climate engineering activities that could reduce biodiversity until further assessments could be made[130], with small-scale experiments exempted; however, almost no research has commenced to inform assessments. The United States has not ratified the treaty, further inhibiting its effectiveness. Because of its direct subject-matter ties, the Montreal Protocol may be a better reference point than CBD[131], which is similarly situated under the UN Environment Programme and has considered this issue in the past.

United Nations Framework Convention on Climate Change

The United Nations Framework Convention on Climate Change (UNFCCC) focuses on greenhouse gases. It does not specifically discuss the use of climate intervention but may have a claim to regulating it if it is determined to be a "dangerous anthropogenic interference with the climate system,"[132] as noted in its objective. Further, its focus on economically viable ways to protect people and communities may frame climate intervention as a favorable option. However, its engagement in governance of intervention has significant pitfalls in relation to its political context and wide range of interests. The scientific review body that supports UNFCCC—IPCC—has been slow to consider climate intervention and other options perceived to introduce moral hazard, and while likely to gradually increase its consideration of atmospheric climate intervention, it may not be well-equipped for continuous assessment. Overall, substantial expansion would be required for UNFCCC to support governance of climate intervention, with considerable challenges to implementation.

NATIONAL (UNITED STATES)

Most countries have laws governing or pertaining to atmospheric activity within their jurisdictions and beyond. Analysis of applicable laws and governing institutions should be undertaken quickly and before the development of any new laws, regulations, or processes. This report focuses on the U.S. context. Policymakers in the United States should review existing directives to consolidate existing requirements for climate intervention, clarify language, and ensure that research is not impaired.

> "Analysis of applicable laws and governing institutions should be undertaken quickly and before the development of any new laws, regulations, or processes. Policymakers in the United States should review existing directives to consolidate existing requirements for climate intervention, clarify language, and ensure that research is not impaired."

Regulation of Weather and Atmosphere

In the United States, any parties attempting to modify weather, defined as "any activity performed with the intention of producing artificial changes in the composition, behavior, or dynamics of the atmosphere," are required to submit public reports detailing their activities to the Secretary of Commerce and National Oceanic and Atmospheric Administration (NOAA) under the *Weather Modification Reporting Act of 1972*.[133] This is an excellent first reporting step, but it should be clarified to fit the current context and provide clearer thresholds for application.

The *Clean Air Act* and the U.S. Environmental Protection Agency (EPA) have additional jurisdiction over air pollution, intent notwithstanding.[134] EPA's National Ambient Air Quality Standards for Sulfur Oxides, which already monitors emissions from both mobile and stationary pollution sources like fossil fuel combustion, coal power plants and others, would certainly apply to stratospheric injection of a significant scale to impact human or environmental health. However, small-scale field testing would be significantly below the 100 tons per year threshold for permitting and oversight. The air quality standards also apply specifically to emissions that cross state boundaries under the Cross-State Air Pollution Rule.[135] These standards and their underpinning scientific justifications are required to be periodically reviewed and opened for public comment, creating a transparent and scientifically robust process with significant flexibility. EPA's standards are required by law to provide an adequate margin of safety "intended to address uncertainties associated with inconclusive scientific and technical information available at the time of standard setting."[136] This model, in addition to providing vital information about substances that could be tested or used in climate interventions, provides an excellent example for scientific monitoring in the face of both risks to human populations and scientific uncertainty and should be considered as governance discussions progress.

Broader Environmental Protection

Federally, environmental protections are in place under the *National Environmental Policy Act*[137], which would be applied to any Federal research or field experiments of ecologically significant scale. It requires a sometimes costly process and "often generates public scrutiny and creates opportunities for those opposed to a planned project to seek to halt it, either politically or in court."[138] In the United States, 15 States have similar State-level laws and requirements for environmental impact reports.

Other requirements to consult with or report to Federal agencies may arise if a field experiment may endanger the lives or habitats of wildlife. This could include the jurisdiction of endangered species under the *Endangered Species Act*[139], protected birds under the *Migratory Birds Treaty Act*[140], or certain mammals under the *Marine Mammals Protection Act*[141] in addition to requirements by each of their State-level counterparts. It is not likely that research will reach the level of harms required by these statutes in the near term, giving policymakers time to consider these requirements and modify or clarify where necessary.

Federal Grants and Scientific Oversight

U.S. Federal grant-making processes, through which the majority of climate research in the United States is funded, embed their own requirements for scientific review, transparency, and oversight. For experimental research, agency programs have established methods of oversight, including scientific review boards, for particular domains, including atmospheric research. These should also be examined for their sufficiency and for possible improvements.

Non-regulatory developments in climate intervention governance in the United States include a 2015 National Academy of Sciences study[142] and Congressional attention.[143] A National Academies study, sponsored in part by NOAA and DOE and launched in October 2018, seeks to equally address governance concerns and to define a research agenda to guide the development of the field. The National Academy of Sciences have extensive experience running a scientifically focused process, drawing together diverse perspectives and stakeholders to reach conclusions about complex topics. This study will be instrumental to any further decisions about formal governance. Relatedly, Congress has begun to consider this issue with governance prominently featured. In order to play an effective role in coordinated future governance, Congress would likely need to increase its capacity for scientific evaluation and policymaking.

SUB-NATIONAL

Many sub-national government bodies have additional laws and regulations governing the release of material in the atmosphere and protections against adverse environmental impacts. In the United States, several States have developed their own rules intended to establish precedent or influence industry and thereby affect national and international regulations. State-level clean air initiatives and wildlife regulations exist in more and less strict forms than their Federal counterparts. In 2017, California policymakers joined a discussion of atmospheric climate intervention research governance in which they emphasized the presence of related research in the state (e.g., rain making, snow making ,and pollution testing) and decided that a review of relevant state laws was a critical precursor to any other governance initiatives.[144]

ACADEMIC AND CIVIL SOCIETY

Several initiatives exist that bring together governance experts to study and make recommendations about the governance of climate intervention. These academic and civil society groups are currently shaping the conversation and some are highly concerned that the space be extensively governed, even before research can inform the process.[145,146] Other groups have assembled voluntary codes of conduct for research and governance considerations, like the Oxford Principles.[147] These efforts are a healthy sign of public engagement in the topic and the creation of norms for researchers to follow, but if governance efforts are insensitive to the progress of research and the downstream effect on options for safety, this raises real concerns. Without scientific research, the state of the science and the urgency of the climate threat can be drowned out in these conversations.

Existing laws and institutions may meet many of the requirements for governing atmospheric climate intervention research, and their use is likely to reduce friction, avoid duplication, and minimize politicization while addressing the need for oversight, environmental protection and public safety. In this way, early research (e.g., baseline observations, modeling, analysis, and small-scale experiments) can proceed and be used to inform a more robust system of governance for large-scale field testing and possible deployment.

Governance and Climate Impacts

Because it can be difficult to differentiate research experiments from deployment activity for the purposes of regulation[148], it may be useful to frame forward governance efforts not in terms of the intent of activities but in terms of their potential impacts. Research that does not meaningfully impact the environment or rise to a level already recognized by regulations ("de minimis") carries a different set of concerns and a lower risk profile than do climate-impacting activities (large-scale experiments and deployment). Therefore, it is important to govern them differently.

Separating the two categories allows research to progress quickly to inform governance of climate-impacting activities. Under any governance regime, non-climate-impacting research should be protected and

"Research that does not meaningfully impact the environment or rise to a level already recognized by regulations ("de minimis") carries a different set of concerns and a lower risk profile than do climate-impacting activities (large-scale experiments and deployment). Therefore, it is important to govern them differently."

enabled to provide policymakers with the necessary information to evaluate the risks and benefits of scaled research efforts or deployment—still decades in the future. Small-scale field testing restrictions should be limited and considered in the larger context of transnational pollution by industry, agriculture, and other sources of environmental harms. Scientific studies should be undertaken freely but subject to review and periodic assessment by a scientific governing authority that can validate claims and interpret findings for policymakers and the public. Relevant new technologies should be openly available for research, and data and models should be openly available for validation.

Climate-impacting deployment of these technologies can and should be heavily debated and governed by legitimate bodies with relevant expertise and social license for decision-making. These bodies will need the best information available to make wise decisions under extreme pressure in the context of uncertainty and the dynamic risks of climate change. The world must build research capacity to inform the growing needs of national and international bodies to make decisions to ensure the safety of communities and the preservation of natural systems.

Today, there is insufficient information on the feasibility, risks, information capabilities, and controls for proposed climate interventions to develop meaningful governance regimes regarding their use. Particular atmospheric climate intervention techniques may prove to be too ineffective, too harmful, or technologically infeasible to use making the nature and jurisdiction of interventions uncertain. The quality and accuracy of information available about outcomes and risks is uncertain, but it would shape policies that would allocate risk, compensate for loss, or apply controls. The infancy of the field and the lack of adequate data to even nominally assess the viability of interventions or their risks, highlights the need for further exploration.

The risks of climate intervention techniques are closely related to the technologies and capabilities available to minimize them. For example, SO_2, a reflectivity-enhancing substance whose behavior is most well-understood, is an environmental pollutant. The feasibility of using more benign material for stratospheric injection requires both technological innovation and field study. Similarly, possibilities for control and modulation of these capabilities to manage risk requires technical design and operational research along with scientific exploration. Without support for field studies, few options will be understood on the scale required to minimize the risks of intervention in the event that it is deemed necessary to avoid the coming impacts of climate change.

If the generation of information about interventions is impaired by imprecise regulation or lack of adequate assessment, policymakers will be unable to make informed decisions about the use of intervention strategies. The ability to predict the impacts of interventions rests on the ability to forecast climate, which is currently insufficient for governance. Today, scientists lack measurement instruments sensitive enough to detect interventions, analyses that are precise enough to attribute them to effects, and predictions that are strong enough to manage risks, all of which are essential to governance. Reducing uncertainty in the prediction of Earth's systems dynamics and increasing the quality of data available will be essential to support sound climate policy broadly and governance of interventions specifically.

Governance of Research

Given the severity of the climate problem and the imperatives for better information, governance of non-climate-impacting research (e.g., models, observations, and small-scale experiments) should be designed to promote progress, leveraging existing frameworks for oversight and assessment.

Proven models for assessment, in particular, may promote rigor, increase confidence, and lay a strong foundation for governance of climate-impacting activities. New mechanisms that introduce non-scientific procedures should be treated with caution. In an environment where there are no existing formal sources of funding and regulatory risks to research are perceived, there is a serious risk that programs will not develop.

REGULATORY CAUTION

One precedent for this is the suppression of experimental research in growing phytoplankton to capture CO_2 (ocean iron fertilization). In response to early commercial efforts in ocean iron fertilization, The London Convention under the International Maritime Organization adopted an assessment framework that "does not contain a threshold below which experiments would be exempt from its assessment provisions."[149] Experiments of any size, no matter how small, are subject to a lengthy and indeterminate process, including an initial assessment, extensive impact assessment reports, and monitoring, lacking clear criteria for success and making approval highly uncertain. Approaching the process requires other legal resources not commonly available to researchers.

The combined effects of these processes dissuaded researchers and chilled sources of funding, perhaps as intended as "the tone set by Parties to the CBD and the LC/LP discourages all ocean fertilization projects, including those with scientific value."[150] No experimental research has been conducted within the jurisdiction of the London Convention since the framework was adopted in 2010.[151] Today, understanding of the potential for ocean fertilization as an option for CO_2 removal is limited, providing a cautionary tale for governance that lacks due attention to outcomes. Any regulation of climate intervention research should favor structures already in place for similar types of efforts, with new elements carefully vetted for impact on research.

> "Given the severity of the climate problem and the imperatives for better information, governance of non-climate-impacting research (e.g., models, observations, and small-scale experiments) should be designed to promote progress, leveraging existing frameworks for oversight and assessment."

ASSESSMENTS

Scientific assessment functions are critical for the healthy development of a research ecosystem and accurate information for policymakers and the public. Today, individual studies using relatively simple models can lead to broad, sensational conclusions.[152] Assessment entails deliberate expert review of a myriad of studies looking at different aspects of the problem under different scenarios to develop a view of broader implications. This catalyzes a larger body of work, such that researchers, journals, and media are disincentivized from drawing broad conclusions from any one piece of work. The engagement of the Ozone Secretariat, IPCC, scientific academies, and other assessment bodies will promote strong science, informed dialogue, and better policy and should be encouraged.

TRANSPARENCY

Transparency in the scientific study of climate interventions is critical. Peer-reviewed publications are standard, but open data and models should be encouraged, though not mandated without full consideration of their costs and effects on progress. Model inter-comparison efforts should be established and expanded where they exist. Commercial cloud platforms can promote transparency, replicability, and access, and their use should be expanded. It is critical that research in climate intervention both is, and is perceived to be, objective. Commercial affiliations with research subject matter should be explicitly disclosed in every paper, publication, talk, or media interaction to prevent disruption in confidence, as recently took place in cancer research.[153] (Today, researchers with commercial interests in CO_2 removal interventions, for example, do not consistently disclose similar financial entanglements.) Scientific journals should enforce disclosure requirements and assessment bodies and presentation events should disqualify researchers who do not comply.

TECHNOLOGY ACCESS

Atmospheric climate interventions require technologies that are early in development. Licensing for these technologies that provides open access to researchers who comply with governance provisions, while restricting other uses, may provide an additional means of advancing research and supporting governance objectives.

The Way Forward

While public interest is growing, and concerns about safety and societal impacts are evident, emphasis must be placed on enabling research to produce information to inform governance of climate-impacting activities in the future. Where successful models for experimental oversight or research assessment exist, they should be closely reviewed for applicability and use. New mechanisms that require communications, legal, or other resources not commonly available to researchers should be avoided in favor of existing structures and enabling technologies for open science.

> "While public interest is growing, and concerns about safety and societal impacts are evident, emphasis must be placed on enabling research to produce information to inform governance of climate-impacting activities in the future."

A review of existing laws and protocols should be undertaken to provide a clear picture of the regulatory and governance landscape. International cooperation is imperative; the Montreal Protocol in particular, and other international agreements as necessary, should be thoroughly evaluated for their applicability to non-climate-impacting research. In the United States, relevant laws governing weather modification and atmospheric inputs should be closely reviewed, with, in particular, the *Weather Modification Reporting Act*[154], clarified by Congress and modernized to fit current realities.

Decision-makers should use and expand their capacity for scientific assessment for policymaking. Internationally, assessment of ozone impact by the Scientific Assessment Panel of the Montreal Protocol is an important first step, and the possibility for expanding or emulating their assessments for atmospheric interventions more broadly should be closely considered. Investments should be made in research for submission to the IPCC 6th Assessment Report[155], with more expansive coverage of this area encouraged. In the United States, the National Academy of Sciences serves as a critical source of objective scientific advice to the Nation, and its findings in this area are likely to be important foundations for national governance efforts. Congress faces gaps in its ability to evaluate complex scientific and technological developments, such as climate intervention, and may benefit from the reintroduction of an expert assessment function similar to the previous Office of Technology Assessment.[156]

Finally, at all times, and in every way, governance initiatives and civil society organizations should consider atmospheric intervention in the context of climate risks, with the aim to minimize the combined risks of the two. They should promote the rapid generation of information in support of informed dialogue with the public.

Research

Lacking funding and a significant research base, no capabilities for atmospheric climate intervention exist, and much is unknown. Prominent researchers have stated that assessing the feasibility and risk of these approaches will require a decade or more of work.[157]

Scientists' abilities to assess the impacts of interventions rests on their ability to forecast climate, which is currently inadequate. Today, scientists lack measurement instruments sensitive enough to detect interventions, analyses that are precise enough to attribute them to effects, and predictions that are precise enough to manage risks. Improving this requires directed research efforts that span Earth system prediction and intervention. The ability to advance such research has been inhibited by the lack of a defined mission and research agenda to drive requirements and support interdisciplinary research programs. To support a mission to ensure a safe climate, this work must begin in earnest now.

This chapter provides an overview of research to date, the nature of a research mission, considerations for science and technology research in atmospheric climate intervention, the need for uncertainty research, policy and social sciences research, and the nature of mission programs. This discussion is not comprehensive but is intended to provide guideposts and ideas for further exploration.

> "Scientists' abilities to assess the impacts of interventions rests on their ability to forecast climate, which is currently inadequate. Today, scientists lack measurement instruments sensitive enough to detect interventions, analyses that are precise enough to attribute them to effects, and predictions that are precise enough to manage risks."

Research to Date

Since the first paper to propose stratospheric geoengineering by Nobel laureate Paul Crutzen in 2006[158] was published, several hundred others have been published, consisting largely of modeling studies and social science research. Computational modeling work has evolved and expanded, including the establishment in 2015 of the Geoengineering Modeling Intercomparison Project (GeoMIP)[159], establishing model experimental designs for stratospheric sunlight reflection interventions.[160]

In recent years, two major assessments of proposed interventions in climate were undertaken, one by the U.K. Royal Society in 2009[161] and one by the U.S. National Academy of Sciences in 2015.[162] Both identified atmospheric sunlight reflection (i.e., solar geoengineering or solar radiation management) as a priority for research. In 2012, two small experiments were also attempted, the Stratospheric Particle Injection For Climate Engineering (SPICE) experiment to spray water at a 1-km altitude from a hose lofted via tethered balloon, which was canceled over controversy, and Eastern Pacific Emitted Aerosol Cloud Experiment (E-PEACE), a release of smoke and exhaust into marine clouds.[163,164]

In the past decade, two interdisciplinary programs emerged in the United States to attempt to study atmospheric interventions in a more concerted way: (1) the Solar Geoengineering Program at Harvard University[165] and (2) the Marine Cloud Brightening Project, which is a collaboration between the University of Washington, the Pacific Northwest National Laboratory, and a team of retired engineers in Silicon Valley (more recently joined by the Palo Alto Research Center).[166] With support from a benefactor, the Harvard effort raised over $10 million since its inception and is progressing actively. The Marine Cloud Brightening effort has had only formation funding to date, leveraging voluntary resources for engineering[167] and ad hoc resources for modeling and planning.

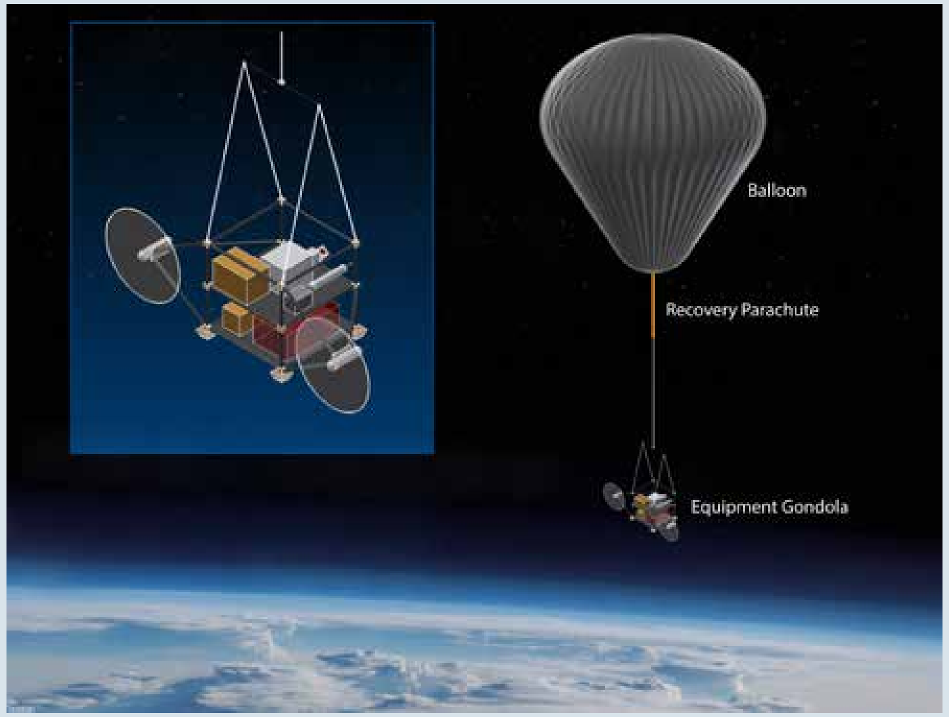
[SPOTLIGHT]

HARVARD SOLAR GEOENGINEERING AND STRATOSPHERIC CONTROLLED PERTURBATION EXPERIMENT (SCOPEX) RESEARCH PROGRAM

The Harvard Solar Geoengineering program is an interdisciplinary effort to study the feasibility, risks, and societal considerations of increasing the reflection of sunlight from the stratosphere. The program consists of chemistry studies, modeling, technical studies, and a proposed field experiment, ScoPex, to study the chemistry and behavior of small quantities of select materials in the stratosphere.[168] Early work has also begun in the requirements and nature of delivery platforms.[169]

The intent of the ScoPex experiment is to release small quantities of material from a navigable balloon in the stratosphere (using novel technology that the team is developing) to study aspects of aerosol microphysics and atmospheric chemistry. The scale and nature of the experiment is such that environmental impact is negligible (the amount of material is orders of magnitude below, for example, a single aircraft that travels in the stratosphere). But, small volumes of material and an unproven platform could impair its ability to measure releases and produce robust findings. There have not yet been published proposals for stratospheric experiments beyond ScoPex.

FIGURE 9.
STRATOSPHERIC CONTROLLED PERTURBATION EXPERIMENT (SCOPEX).



SOURCE: Harvard Keitsch Research Group.

[SPOTLIGHT]

MARINE CLOUD BRIGHTENING RESEARCH PROGRAM

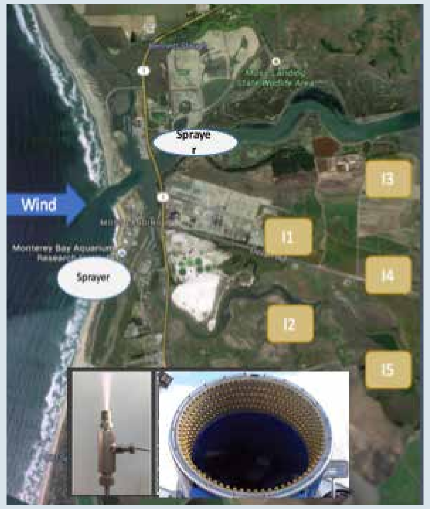
The Marine Cloud Brightening Research Program is a dual-purpose research effort to improve understanding of cloud–aerosol interactions and their effect on climate and the feasibility of controlled modification of this effect for cooling. The experimental approach has the potential to significantly advance understanding of cloud–aerosol interactions[170], the greatest uncertainty in quantifying how human activities have driven climate change, and, regardless of geoengineering interests, a high priority for climate research.[171]

To achieve this, a team of researchers designed a program that includes the development of technology for generating aerosolized salt mist from sea water; the development of models of cloud aerosol dynamics from the scale of an individual plume through to regional and global simulations; a gradually escalating sequence of process studies, tests, and experiments culminating in a study (i.e., the Limited Area Field Experiment (LAFE)) designed to determine the change in cloud reflectivity (albedo) in an area sufficient to detect an effect (100 × 100 km)[172]; and an array of related observational and scientific studies.

The experimental approach closely follows the design of observational studies of cloud–aerosol effects from anthropogenic sources from ship track studies to major observational campaigns. LAFE is similar in scale and design to recent Observations of Aerosols Above Clouds and their Interactions (ORACLES)[173] and VAMOS Ocean-Cloud-Atmosphere-Land Study (VOCALS)[174] observational studies. Thus, requirements, costs, timing, risks, and impacts are well understood. With sea salt aerosols naturally occurring, effects transient and reversible and meaningful results possible at scales below environmental impact, marine cloud brightening experiments do not pose significant environmental risks.

FIGURE 10.
MARINE CLOUD BRIGHTENING EARLY RESEARCH PROGRAM.

1. **BUILD AND TEST A SPRAY SYSTEM**

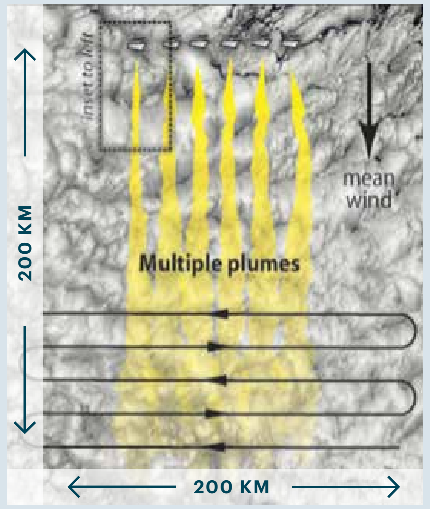


1–2 YEARS; $4–5M

2. **STUDY BASIC PROCESSES**

2–3 YEARS; $10M+

3. **CLOUD BRIGHTENING EXPERIMENTS**



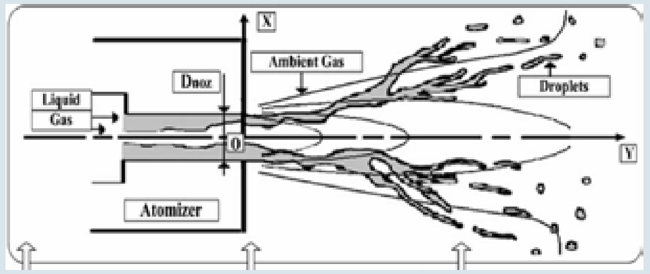
3–5 YEARS; $25M+

SOURCE: University of Washington.

AEROSOL TECHNOLOGY DEVELOPMENT

The Marine Cloud Brightening Program is the only effort to date that has developed technology for aerosol generation at the lab scale, which is a significant technical challenge.[175] Over the course of 6 years and after trial of several approaches, a team of retired, distinguished engineers from Silicon Valley working on a volunteer basis developed a nozzle that generates high volumes (3 trillion particles per second) of tiny particles of salt (<100 nm) from filtered sea water. Scaling from a single nozzle to a spray system for marine cloud brightening requires sequential testing of scaled nozzle configurations and subsequent construction of a spray system incorporating 400–500 nozzles that can generate very large quantities (10^{16} particles per second) and loft them high enough for circulation to lift them into the marine boundary layer (~100 m). In addition to its applications for climate intervention, such a spray system would be a highly valuable research tool for controlled experiments to study cloud–aerosol interactions for climate research. The Marine Cloud Brightening Program has recently established a partnership with Palo Alto Research Center for this work, but progress currently awaits funding. This nozzle technology is also being studied for generation of calcium carbonate aerosol for stratospheric aerosol injection in collaboration with the Harvard Solar Geoengineering program.

FIGURE 11.
EXPLODING ANNULAR FLOW TECHNOLOGY.



SOURCE: https://link.springer.com/article/10.1007/s11433-011-4536-1.

FIGURE 12.
MARINE CLOUD BRIGHTENING SPRAY NOZZLE.

SOURCE: Marine Cloud Brightening Project, Armand Neukermans.

In the past few years, researchers at NCAR, Pacific Northwest National Laboratory, NOAA, Cornell University, California Institute of Technology, and other U.S. institutions have published studies with indications of growing interest among researchers. Internationally, researchers in Europe, China, India, and an array of other countries have held meetings and published research.[176] But to date, research has not been set in the context of consistent goals or a defined agenda, and it has not been framed as a holistic assessment of the relative risks and benefits of unmitigated climate change versus implementation of some degree of atmospheric climate intervention (geoengineering). The result has been a hesitancy to fund scientific research into interventions and to and exacerbate concerns amongst the public and policymakers about these approaches.

Research Considerations

To date, research in atmospheric climate intervention has focused on natural science questions related to specific interventions, and policy debates have centered on governance models for hypothetical deployment scenarios. There has been far less work done to define the research mission—that is, the goals, key questions, requirements, and timescales required for decision-making. From these, research programs can be developed for execution across the full range of relevant disciplines to deliver information for policymakers and society.

MISSION AND QUESTIONS FOR RESEARCH

Atmospheric climate intervention research is not simply theoretical; it is aimed at reducing the risk of un-remediated heat accumulation in climate. The broad mission of such research is to identify and assess possibilities for improving safety for people and stability for natural systems. With this mission in mind, research efforts should orient around fundamental questions, such as the following:

- What is the safest and most effective way of avoiding severe impacts and runaway climate change in the next 10 to 30 years?
- What is the safest and most effective way to restore the climate to an equilibrium state over the course of the century?
- What questions do we need answers to and what capabilities need to be made available to make informed decisions within a decade?

These questions shift emphasis from isolated parts of the problem, such as how efficient a given mechanism might be at reducing incoming sunlight, to thinking about the entirety of knowledge needed with respect to the system. They inform the goal and the definition of high-level requirements that shape a research agenda and the design of research programs.

To support decision-making in a decade, questions might include the following:

- Are there viable atmospheric interventions to reduce heat in climate? If so, what are their environmental effects and risks?
- How and when would we deploy such interventions?
- What level of certainty can we attain in predicting outcomes?
- What are the requirements for a system (or systems) for intervention?
- What information is required to govern these activities?
- What are the costs, benefits, and risks of intervention versus unabated climate change?

Capabilities sought might include the following:

- Multiple viable approaches, with reasonable understanding of their effects and risks;
- Core technology for each approach;
- System design and operating model for interventions;
- Governance and decision models for differing geopolitical scenarios; and
- Actionable information (observational and analytical systems) for monitoring resulting climate changes.

While these are a few of the many possible questions, the definition of what information and capabilities are needed, and in what timescale, is critical to designing climate intervention research programs that are relevant to societal decision-making against a time-bound problem. Having determined these, research programs can be designed to meet them.

SCIENCE AND TECHNOLOGY RESEARCH AGENDA

Assessing the feasibility and risks of climate intervention is dependent on the ability predict the Earth system and attribute the drivers of climate. A research agenda for climate intervention will overlap and propel Earth system (climate) research, with objectives and questions that are cross-cutting through the lens of intervention.

For example, the highest-level questions for research might include the following:

- Are there feasible atmospheric interventions to reduce warming? What is required to assess them?
- Are Earth system predictions developed enough to use them? What is required to establish baselines, detect precipitous changes, predict outcomes, and attribute drivers within an acceptable level of uncertainty?

Exploring these questions will require both lines of research specific to assessing climate intervention and broader efforts to rapidly advance Earth system prediction.

REDUCING UNCERTAINTY IN EARTH SYSTEM PREDICTION

Climate intervention capabilities are only one part of a solution for ensuring safe outcomes in climate. Information is the essential partner to any program for intervening in climate. To assess and deliver climate interventions requires significantly better information, that is, less uncertainty in forecasting and greater ability to attribute drivers, than available today. It requires the ability to monitor and forecast natural and anthropogenic drivers of warming (e.g., greenhouse gases and aerosols emitted from natural stores and pollution sources) in order to compensate for their net effect. It also requires the ability to predict impacts within an acceptable level of uncertainty to minimize risks and sensitive enough measurements to monitor interventions and assess their performance.

A mission to assess and deliver options for atmospheric climate intervention within the next decade requires an equivalent mission to reduce uncertainty in Earth system prediction, with relevant advances in models, analytics, observations, scientific input, and underlying technologies to achieve it. Some related assessments have been proposed or undertaken, notably the *Future of the Weather Enterprise* assessment proposed by the National Academy of Sciences. These should be pursued in earnest in the context of a comprehensive mission to reduce uncertainty in Earth system prediction.

SPECIAL CASE: UNCERTAINTY RESEARCH

Complex systems, such as the Earth system, are inherently hard to predict and therefore force decision-making under uncertainty. A primary objective for research is to reduce uncertainty; better understanding of how best to do this is vital. Climate response involves decision-making with enormous risks and under a high degree of uncertainty. Having as a goal better understanding of the net climate risks and associated uncertainties of intentional and unintentional anthropogenic climate change has implications for the design of scientific research programs, the development of governance mechanisms, and the definition of policy.

ASSESSING INTERVENTIONS

Assessing atmospheric sunlight reflection approaches requires understanding their technological limitations, feasibility, and risks. This encompasses a range of scientific and technical questions in different areas, including aerosol generation and dispersion; microphysical, chemical, and biological interactions; local, regional, and global effects; and side effects and environmental impacts.

METHODS

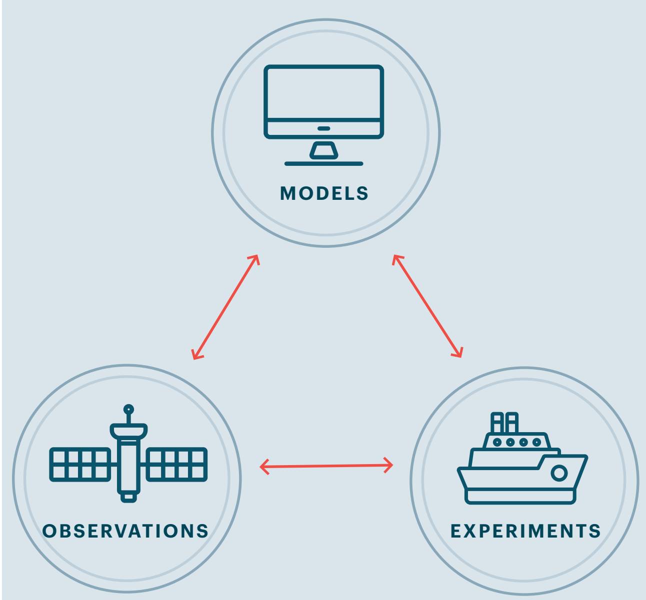
Exploring these questions requires interplay between the knowledge provided by simulations (i.e., models), real-world data (i.e., observations) and controlled tests (i.e., experiments). Some have contended that sufficient understanding can be achieved through models[177] and that, in particular, field experiments are unnecessary, while others assert that real-world data and controlled experiments are essential and imperative.

Models are flexible and efficient tools for advancing understanding but require initialization and testing against real-world data generated through observations. Controlled experiments can address questions that may be unanswerable with other methods[178] and are a gold standard for testing and tuning models. Models help shape requirements for observations and parameters for experiments. Atmospheric sunlight reflection research programs must incorporate all three to the extent possible, with substantial advances in each.

Modeling

Models are an exceptionally valuable and efficient tool for exploration and can be used to simulate intervention actions, from process-level to global scales. They are the primary tool for prediction and for simulation experiments to test various scenarios to better understand relationships and effects. However, models are imperfect; in particular, they do not yet robustly capture the complex physics and chemistry involved with quantifying aerosol–cloud interactions (critical for representing the efficacy of marine cloud brightening), and, in some cases, contain incomplete information due to a lack of observations to use for input (e.g., the current/natural level and composition of stratospheric aerosol). Some important processes, such as the behavior and effects of changes in permafrost, are only beginning to be incorporated into models. Extensive work is required to improve the sophistication of models for assessing atmospheric intervention, both in terms of data used as inputs and their robustness in representing key processes. Efforts to achieve the latter in particular would benefit significantly from rigorous model inter-comparison exercises.

FIGURE 13.
CLIMATE INTERVENTION RESEARCH.



There is exceptionally high return on investment in extending models to simulate realistic approaches to injecting particles in the stratosphere and troposphere and incorporating chemical, ocean, and other processes to predict their impacts. Stratospheric aerosol models are early in their development and have not yet incorporated the full range of chemistry and other dynamics that will influence the effects of aerosol injection. Previously, to simulate these effects, many studies have used volcanic simulations or studies that "turn down the sun," though this is changing. Marine cloud brightening rests on explicit understanding of cloud–aerosol interactions and their effects on climate, currently an area of particular challenge in climate models. Further investment in cloud–aerosol modeling, with tests against real-world data and controlled experiments, is needed both for assessing marine cloud brightening and for all climate research. In particular, improved capabilities for modeling aerosol–cloud interactions, regardless of geoengineering interests, would help reduce uncertainties in climate sensitivity to increasing greenhouse gases and in climate prediction.

Observations

Surface, air, and space-based measurements of the atmosphere and climate (observations) are critical for quantifying the effects of small-scale atmospheric climate intervention experiments, studying natural and anthropogenic analogues, and establishing baselines. In the United States, climate observation data and platforms are provided by NOAA, NASA, DOE, and other agencies, though private sources are growing. These capabilities, while the most extensive in the world, are currently inadequate for the requirements of understanding atmospheric interventions. For example, the anticipated regulatory reduction of pollution from shipping emissions in 2020 is an accidental experiment in large-scale reduction of cloud brightening aerosols. To detect this incremental change in cloud brightness, measurements of Earth radiation budget would need to be far more precise than can be achieved with the 0.5 W/m^2 uncertainty of the current observational system. Similarly, were a powerful volcanic eruption to occur, the United States lacks sufficient response capabilities to study many highly relevant stratospheric chemistry, aerosol dispersion, and brightening effects. Overall, continuous, high-sensitivity measurements improve models and analyses and will be required to detect, assess, and manage any atmospheric intervention. Capabilities recommended by *Thriving on Our Changing Planet: A Decadal Strategy for Earth Observation from Space* (2018)[179], *Sustaining Ocean Observations to Understand Future Changes in Earth's Climate* (2017)[180], and other studies are likely to be essential, along with evaluation of specific needs relevant to climate intervention.

Experiments

Some types of small-scale tests and experiments may be essential to inform models and downstream assessments of feasibility and risks. Many valuable experiments—from lab studies, to dispersion tests, to studies of localized physics and chemistry, to studies of brightening effects (changes in albedo)—can be undertaken without environmental impact. Without them, models and other assessments must use assumptions about fundamental processes that often lead to wide divergence from reality. For example, the only material for reflecting sunlight in the atmosphere available to study through observations is sulfates/SO_2, a pollutant with adverse human health effects in the lower atmosphere and adverse effects on ozone in the stratosphere. More benign materials may be feasible, but their dispersal and basic physical and chemical interactions in the atmosphere are not understood and would need to be studied through experiments. As mentioned previously, the effects of aerosols on clouds, essential both for better understanding of determining the feasibility of marine cloud brightening and more accurately predicting climate, are likely to require controlled experiments to understand.[181] Such experiments take time, both in their execution and their analysis, such that many years are required for the sequence of incremental studies that might produce answers at the process level to inform assessments.

Technology Development

The physical effects of atmospheric climate interventions arise from the properties of the materials used to deploy them. The alternatives available (and their properties) are based on the limitations of the technologies available. Today, the material about which most is known, sulfates/SO_2, is also the readiest for dispersion but its environmental side effects make other materials preferable. Proposed materials, such as sea salt particles for use in the troposphere or calcium carbonate for use in the stratosphere, require new technology for aerosolizing these solids at high volumes. These technologies will inform assumptions about aerosol characteristics from which effects are derived. They are also the tools for research and are thus a barrier to progress in atmospheric climate intervention.

SCALES AND IMPACTS

Assessment of atmospheric climate interventions requires lines of research focused on different scales, from process level though local, regional, and global scales, and with emphasis on different ecosystems. Model and observational studies can be undertaken safely at all scales and pursued in parallel. Experiments and technology development are recommended at process and local scales beneath the threshold for environmental impact, starting at the process level and progressing incrementally while informing downstream modeling assumptions.

> "An important consideration for the value of research in climate intervention is its applicability to understanding climate more generally, thereby reducing overall risks and uncertainties around climate."

RESEARCH PRIORITIES

Until the feasibility and risks of any approach are well understood, parallel study of multiple approaches, that is, a portfolio approach, helps minimize the risk of failure. SAI and marine cloud brightening have very different risk/benefit profiles, which is beneficial to a portfolio. These differences may also make them candidates for a regime that includes multiple interventions, which is a line of questioning that can be explored in a portfolio approach. Portfolio advantages also apply to cirrus thinning and any new ideas that may emerge. A program design might include full program efforts in SAI and marine cloud brightening along with modeling and other evaluation for cirrus thinning and other promising approaches.

Research programs may benefit from prioritizing questions related to risks and limitations and through this establishing exclusion criteria. For example, SAI is likely to be very effective in reflecting significant amounts of sunlight but may damage stratospheric ozone. For SAI, it may be important to focus early research on ozone layer risks and the feasibility of alternatives that reduce them. For marine cloud brightening, the potential for reflective forcing is uncertain, and early research in the magnitude of the effect will help determine the role marine cloud brightening can play in an intervention portfolio. In both cases, it is possible that research could surface risks and limitations that rule out one or both of these options, and it will be helpful to reveal these as rapidly as possible.

An important consideration for the value of research in climate intervention is its applicability to understanding climate more generally, thereby reducing overall risks and uncertainties around climate. For example, the primary questions for marine cloud brightening are aimed at understanding the nature of cloud–aerosol effects on climate—a major source of uncertainty in climate prediction and a high priority of climate research. Experts have proposed that the controlled experiments contemplated for marine cloud brightening research may help reduce this uncertainty, which is a potentially powerful accelerator for improved predictions of climate. The National Academy of Sciences designated this type of research as "dual-purpose" and identified dual-purpose attributes as an important consideration in the design of research programs.[182]

TIMELINES AND COSTS

Work is needed to develop research programs and assess their costs, but early efforts provide some indication. Marine cloud brightening research plans benefit from similar observational programs. The University of Washington team designed a field program with well-founded cost estimates. Figure 14 describes the technology and field experimental components of a marine cloud brightening research program designed to answer primary process-level questions about cloud–aerosol effects and culminating in an experiment to measurably brighten an area of marine clouds. This sequence takes place over 7 to 10 years at a cost of $40 to $50 million, including observational platforms (which are a substantial portion of costs). The work in the first stage is primarily technology development and testing and is therefore ineligible for most climate research funding programs. Once the needed technology is developed (i.e., funded through private sources and/or innovation grants), scientific studies may be eligible for grant-funding from traditional sources, particularly for dual-purpose marine cloud brightening/cloud–aerosol research.

Estimates do not include the entire array of parallel modeling studies, social sciences, communication, legal, and other support. They also reflect only one program and one sequence of experiments without replication. A complete program for assessment for each approach is likely to include ongoing technology research, replication of experiments, and a diverse ecosystem of researchers. Overall, research costs for exploring multiple approaches to atmospheric climate intervention might reasonably run to hundreds of millions of dollars over a decade. The scale of these investment is relatively modest, and can be phased as research matures.

TECHNOLOGY INNOVATION

Assessing and developing options for climate intervention and improving Earth system prediction requires accelerated adoption of advanced and/or agile technologies such as cloud computing and remote sensing, innovation in platforms such as exascale computing and stratospheric aircraft, and the development of new technologies for aerosol generation and delivery. This will require consideration for the design of research programs and adaptation of funding and staffing models to better support adoption of commercially available advanced capabilities (e.g., cloud computing) and better access to specialized expertise (e.g., data scientists and developers).

POLICY AND SOCIAL SCIENCES RESEARCH

While this report focuses on the scientific and technical research required to support decision-making in atmospheric climate intervention, there are parallel lines of research required to support policymaking and the development of governance mechanisms for any use of these capabilities. These include, but are not limited to the following:

- National, international, and subnational laws and regulations;
- Economics, energy, and industrial systems;
- Social welfare, minority rights, and equity;
- International relations and security; and
- Innovation policy and governance of technology.

Such research efforts should be undertaken in a structured way within government institutions as well as independently across a broad ecosystem. Today, these efforts lack the technological and scientific information required to work effectively on these problems, and a key aim of scientific research is to close the gap.

TABLE 1.
MARINE CLOUD BRIGHTENING EXPERIMENTAL RESEARCH PLAN.

	TEST (LOCATION)	DURATION	KEY EQUIPMENT (ANALYSIS TIMESCALE)
STAGE 1: 1–2 YEARS $4–5M	Indoor dispersion test (Ames Hangar)	1–3 months (repeated as needed)	Particle size spectrometers (weeks)
	Outdoor dispersion test (Chico?)	1 month	Scanning lidar (1 month)
	Coastal dispersion test (Moss Landing?)	1–2 months	Aircraft instrumented with particle size spectrometers (2–4 months)
STAGE 2: 2–3 YEARS $10M+	Coastal cloud impacts (California Coastal Site; spring/summer)	1–2 months	Ground sites, aircraft, and tethered balloon (3–6 months)
	Single shiptrack (~100 km offshore; spring/summer)	2–3 months	Ship-ready sprayer, short-range research aircraft (1–3), satellites, and research vessel (3–6 months)
STAGE 3: 3–5 YEARS $30M+	Cloud Albedo responses to merged plume from 5–10 sprayers over 100 x 100 km region (NE Pacific ~500–1,000 km offshore; spring/summer)	1–2 months	Ship-ready sprayers, multiple deployment platforms, long-range research aircraft (3), satellites, and research vessel (1–2 years)

SOURCE: University of Washington.

MISSION PROGRAMS

To deliver against an expansive mission like that of ensuring climate safety, research programs must encompass all of the disciplines required to assess and develop an entire solution, with collaborators working to a shared set of objectives along a shared timeline, which is known as a "whole-systems" approach. For atmospheric climate intervention, this includes engineering, atmospheric and environmental sciences, computer and data sciences, economics and risk analysis, policy, law, and behavioral sciences, with arenas of focus ranging from nanoscale particle interactions to global operations and governance.

The mission requires coordinated lines of research specific to climate interventions, along with broader research in Earth system prediction, and enabling innovations from risk instruments[183] to computing and remote sensing.

Interdisciplinary mission programs require leadership that can receive goals and requirements from policymakers and administrators, translate them into concrete objectives and plans, and devolve them across the array of disciplines and lines of work required to deliver them. They must build teams, organizations, and processes that foster collaboration and promote the welfare of the mission over any particular effort within it. For climate intervention and Earth system prediction, the demands for program management are high[184] and likely to operate at different levels in various agencies and institutions in an interactive way. Recent research suggests that effective program management may be critical to the success of government programs and has been a chief factor in the success of U.S. Federal science programs.[185] Early thought should be given to developing program management capabilities for climate intervention in order to organize research efforts, ensure delivery against objectives, and manage investments.

WHAT'S NEEDED

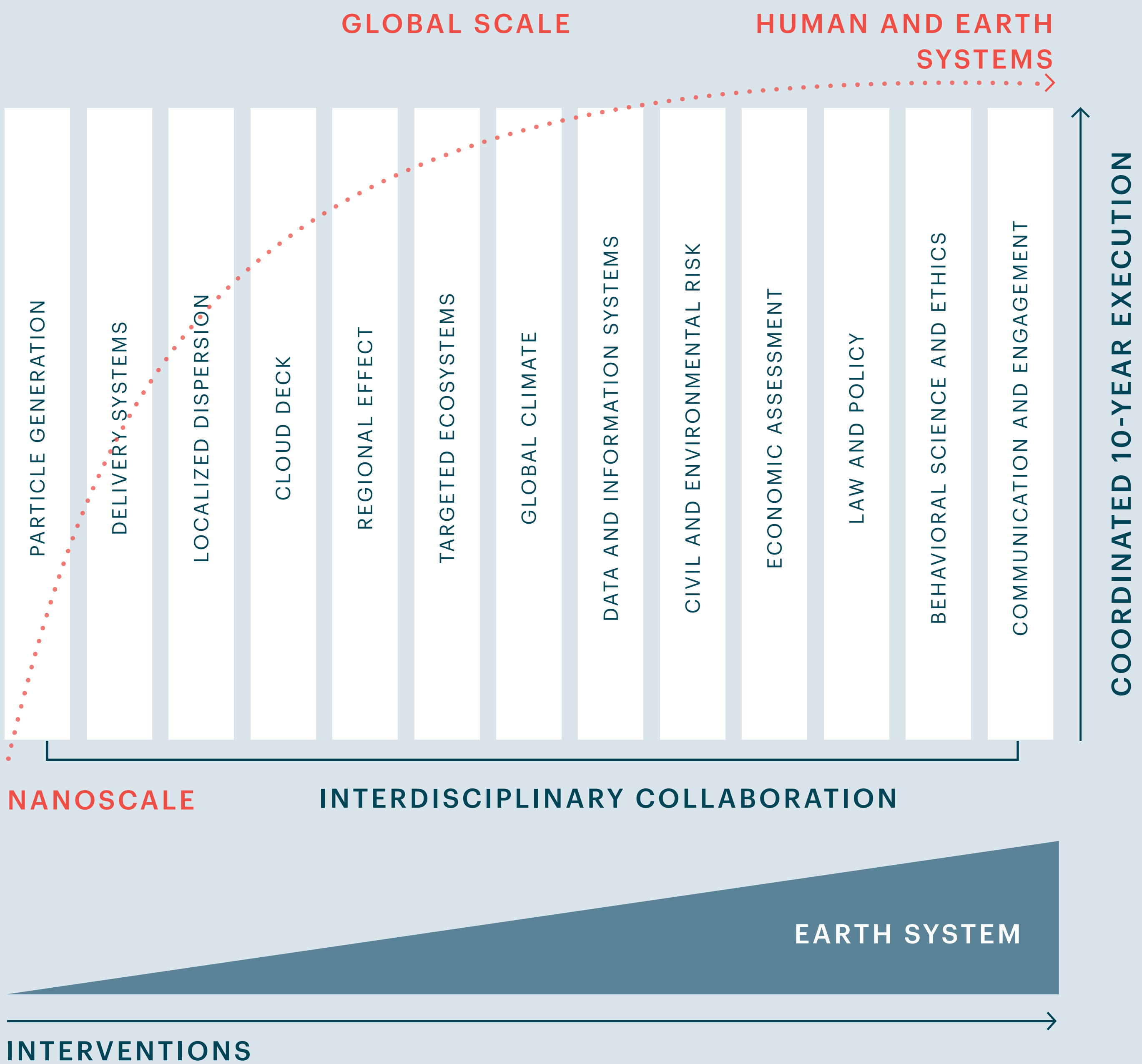
A concerted effort must be made to assess atmospheric climate interventions and reduce uncertainty in Earth system prediction within the next decade.

To date, the field has lacked a well-defined mission, research agenda, and governance for research. The process launched by the National Academy of Sciences to develop a research agenda and governance approach is likely to be a cornerstone to the development of programs that can deliver against such a mission. This, along with and similar assessments to advise on reducing uncertainty in Earth system prediction, should be supported and their recommendations considered deeply.

A vibrant international research ecosystem is required to help rapidly deliver information, promote confidence in scientific findings, and support effective global decision-making. Government funding in the United States and around the world will enable researchers to work within existing well-governed structures. Philanthropic funding for research could help expand the community, fund worthy projects that are frequently rejected by highly competitive grant programs, and support the development of programs within academic institutions. Strong assessment functions such as those in the UN Environment Programme's Ozone Secretariat[186] can help promote discipline and organize research priorities.

The technology sector can help accelerate progress by collaborating with the research sector to develop offerings that facilitate adoption of the most advanced capabilities, supported by highly skilled talent in areas such as artificial intelligence, computing, and remote sensing.

FIGURE 14.
PARALLEL RESEARCH EFFORTS IN A MISSION-DRIVEN ATMOSPHERIC CLIMATE INTERVENTION PROGRAM.



State of Play

Globally, the total funding for scientific research in climate intervention is less than $5 million annually, with limited knowledge and no capability for atmospheric climate intervention in the United States or any other country. Actionable information on the feasibility and risks of these approaches requires a decade of research that includes both intervention programs and improvements in Earth system observation and prediction.

Today, no country or governing body is in a position to evaluate the risks and potential benefits of atmospheric climate intervention, respond to activities commenced by others, or define specific governance protocols for their use. But interest has been rising, and emerging efforts indicate a need for more knowledge and coordination.

This chapter discusses recent developments in atmospheric sunlight reflection and the current state of play. It mentions major weather modification efforts as possible precursors to climate intervention activities.

International

In 2015, the Chinese government commenced a $3 million/year modeling and scientific program consisting of 15 faculty and 40 students across 3 institutions to explore sunlight reflection in the atmosphere (solar geoengineering). It is currently the largest government-sponsored program in atmospheric sunlight reflection in the world.[187] This year, parties in China approached several leading U.S. researchers about participation in a larger research consortium. China has a history of various weather modification efforts. In 2018, media reported a new large-scale weather modification program by the state-owned Aerospace Science and Technology Corporation designed to generate rainfall over the Tibetan Plateau.[188] It would deploy machines at the base of Tibetan mountains to generate silver iodide aerosols in an effort to increase rainfall over an area roughly the size of Alaska.

On July 24, 2018, leading scientists in India held a meeting on the potential for sunlight reflection/solar geoengineering to mitigate climate impacts which produced recommendations for a modeling and scientific research program for the Indian state science agency.[189]

In 2018, the Australian government provided modest grants for efforts to explore the possibility of localized sunlight reflection through brightening clouds over the ocean (i.e., marine cloud brightening) as a means of sustaining coral reefs in the face of an existential threat to the Great Barrier reef due to ocean warming.[190]

In 2015, the United Arab Emirates (UAE) launched the UAE Research Program for Advanced Rainmaking Science, making grants of $5 million per year to researchers from around the world, operating in conjunction with experimental flights and weather stations throughout the UAE.[191]

In 2015, the U.K. Royal Society launched the Solar Radiation Management Governance Initiative (SRMGI)[192,193], an effort to fund natural and social science research in sunlight reflection/solar geoengineering undertaken by researchers in developing countries. It is now housed at the Institute for Advanced Sustainability Studies in Potsdam, Germany.

In the past few years, meetings have been held in the United Kingdom, Germany, Kenya, and elsewhere which featured or included representatives from developing countries and small island states. In general, these meetings have called for research in atmospheric sunlight reflection alongside other measures in response to impacts to their countries, which have already begun to occur. Small island states have expressed specific interest in the exploration of techniques to brighten clouds over ocean regions to reduce the force of hurricanes, while acknowledging they lack the resources to develop these capabilities.

U.S. Context

The United States has the largest infrastructure for climate research in the world, encompassing observational platforms, computing, models, data, and expertise. Atmospheric sunlight reflection research efforts can build from these capabilities but require new programs and resources for technology development, field trials, enhanced observation methods, and improved climate modeling. Current funding for scientific research in the field, encompassing all sources, is less than a few million dollars annually in the United States, largely concentrated in the privately funded Harvard Solar Geoengineering Program. There is potential to drive rapid immediate progress through extending Federal agency grant programs, collaboration with the technology sector, and modest philanthropic activity.

"The United States has the largest infrastructure for climate research in the world, encompassing observational platforms, computing, models, data, and expertise. Atmospheric sunlight reflection research efforts can build from these capabilities but require new programs and resources for technology development, field trials, enhanced observation methods, and improved climate modeling."

U.S. FEDERAL RESEARCH LANDSCAPE

In recent years, there has been increased attention from policymakers and scientific institutions in the United States. In February 2015, the National Academy of Sciences released a technical assessment of climate intervention technologies in a two-part study called *Climate Intervention: Reflecting Sunlight to Cool Earth*.[194] The National Academy of Sciences also recently initiated a follow-on study to establish a research and governance agenda.[195] In April 2016, a Senate Appropriations Committee report for the Energy and Water Development Subcommittee instructed the DOE Office of Science Biological and Environmental Research Program to review the findings of the study "and leverage existing computational and modeling capabilities to explore the potential impacts of albedo modification."[196] On September 21, 2016, the U.S. President released a Presidential Memorandum on climate change and national security. It called for an interagency working group, in collaboration with United States Global Change Research Program and the National Science and Technology Council, to recommend research guidelines concerning the Federal Government's ability to detect climate intervention activities.[197] On December 22, 2016, USGCRP issued a draft climate science special report that included a discussion on albedo modification and declared that it could potentially serve as a means to reduce temperature increases if CO_2 levels are not reduced to safe levels on an appropriately swift timeline. USGCRP also issued a triennial update to its 10-year strategic plan on January 9, 2017, that included a discussion of albedo modification and its theoretical potential to temporarily reduce climate forcing while aggressive emissions reductions are pursued.[198]

For research efforts, in 2017, the U.S. Defense Advanced Research Program Agency provided $500,000 in grants for modeling and data research. This modest body of work substantially advanced understanding of potential side effect risks of intervention in the stratosphere and indicated priorities for observational and modeling research.[199] DOE, largely through the Pacific Northwest National Laboratory, has supported a small body of modeling research. NSF, through climate modeling efforts at NCAR, has funded and undertaken a modest number of modeling studies. In general, however, U.S. Government agencies have not provided funding for study in atmospheric sunlight reflection in any administration.

Of the 13 U.S. Federal agencies with climate-related research programs, those most relevant to atmospheric sunlight reflection research are DOE with a focus on the troposphere and Earth system modeling, NOAA with weather and climate observation and prediction responsibilities for the Nation, NASA with stratospheric platforms and Earth system observations, NSF in fostering community-driven research, and DARPA with expertise in early mission programs. There are near-term opportunities for extending grant 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 climate intervention assessment, these agencies' broader climate research programs are likely to require substantial additional investment.

Climate intervention research has, thus far, been an area of bipartisan cooperation on climate, including recent carbon removal legislation[200] and a constructive hearing on sunlight reflection intervention in the House Committee on Science, Space, and Technology.[201] Related activities included opinion editorials from both Lamar Smith (R-Texas) and Jerry McNerney (D-California) in support of atmospheric climate intervention (solar geoengineering) research[202] and a legislative proposal in support of the National Academies of Science study.[203]

TECHNOLOGY SECTOR

The United States is home to the highest concentration of technology companies relevant to advancing capabilities in climate, including cloud and exascale computing, analytics and artificial intelligence, and remote sensing (e.g., satellite, drone). U.S. technology companies have not been extensively engaged in applying their capabilities to understanding the Earth system. This is beginning to change as climate warming increases volatility in weather, with increasing market demand for weather-related data, prediction, and risk products driving a small but growing commercial market. Federal Earth system research programs lag other sectors in adoption of newer cloud and data service products, and there is opportunity for technology companies to expand this market while helping accelerate progress.

PHILANTHROPY

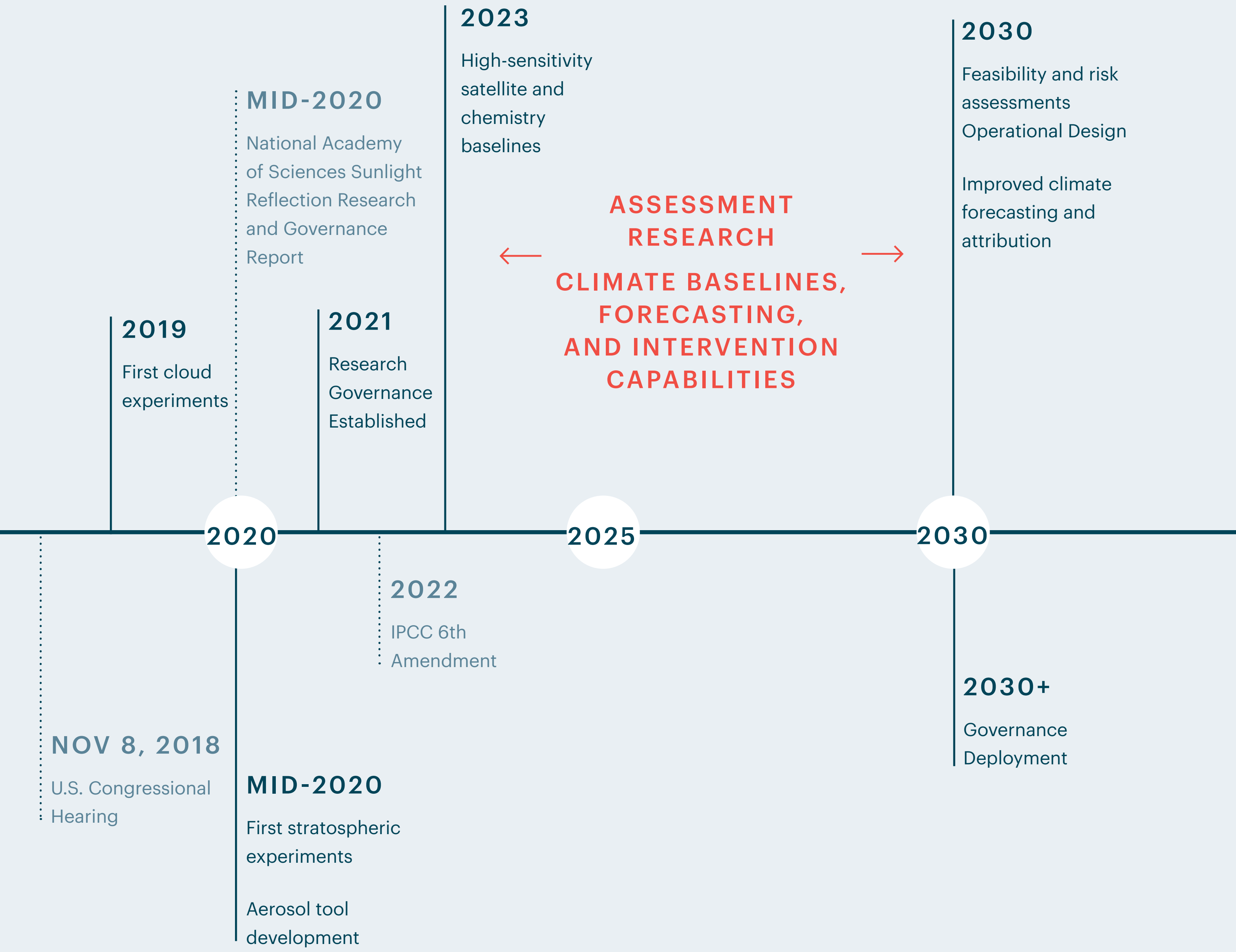
U.S. climate philanthropy is estimated at $6 to $7 billion annually, generally directed to large, traditional foundations and advocacy efforts. Direct funding for scientific research is negligible, and any philanthropic funding for atmospheric climate intervention has been almost exclusively directed to governance and social science research. The notable exception is the Harvard program, though its scientific research funding is largely from one source. No foundations or individuals are funding grants in atmospheric sunlight reflection research or research advocacy at the time of this publication, though there is some indication of interest among technology-oriented philanthropists. Philanthropic research funding may play a pivotal role in seeding efforts and bridging to Federal programs. In particular, funding for enabling technologies (aerosol generation) that is not a native part of Federal science programs may catalyze progress. If they expand efforts to include scientific support, environmental foundations may help foster consideration of interventions in the portfolio of possibilities for achieving preservation and sustainability goals.

Timeline for Decision-Making

Calls for research have now been issued by the National Academy of Sciences, the United States Global Research Program, the American Geophysical Union, and various scientific groups around the world. With respect to climate risk, there is a need for intervention options within the next 10 to 30 years, yet achieving this will require a decade of concerted research to assess these options and additional time to develop them. To achieve this, and to include research for consideration in the IPCC Sixth Assessment Report[204] (i.e., the only such assessment in the next decade), work must begin now.

“With respect to climate risk, there is a need for intervention options within the next 10 to 30 years, yet achieving this will require a decade of concerted research to assess these options and additional time to develop them.”

FIGURE 15.
TIMELINE FOR DECISION-MAKING.



Recommendations

Climate change threatens devastating, irreversible damage to natural systems and to society. It is imperative that greenhouse gas emissions are eliminated, and the United States must champion aggressive efforts to do so. But it is necessary to advance knowledge about options that might reduce warming directly in the face of rapidly escalating change.

With concerted effort, efficiency measures, technology innovation, and well-aligned incentives, the world can evolve to a low-emissions civilization that supports the energy and economic needs of its people by the end of the century. But the enormous risks of climate change must be successfully addressed in the next 10 to 30 years, and sufficient options to achieve this do not exist.

Given the timing and nature of risks, the lack of knowledge and the complexity of the research, a concerted effort must be made to understand climate intervention options and to substantially advance Earth system prediction capabilities. This effort must produce information and options within the next decade for decisions to be made that ensure safety and avoid the worst effects of climate change. The objectives for such an effort cut across scientific research and development and social science research and policy.

Policymakers, civil society, philanthropists, innovators, and citizens will need to work quickly and collaboratively to be successful. U.S. Federal commitment to and investment in climate intervention research and capabilities will play a driving role in this process, and this report focuses heavily on recommendations to that end. Also included here are topline recommendations for other actors with important roles in a healthy scientific ecosystem of this nature, such as the research community, media organizations, the technology industry, and more, with the intention of starting conversations within those industries.

10-Year Objectives

Achieving the following objectives requires mobilizing stakeholders across government, academia, industry, and civil society to make unprecedented progress against a time-bound problem. Scientific and technical-related objectives include the following:

- Assess multiple atmospheric interventions to reduce climate warming, with characterization of effectiveness, risks, and impacts.
- Reduce uncertainty in Earth system prediction and improve attribution of the drivers of climate change.
- Develop needed advances in observations, models, and computing to achieve these ends.
- Build the ability to detect early warning indicators of precipitous changes in natural systems.
- Establish the requirements and designs for capabilities to manage climate across natural, anthropogenic, and interventional drivers.

Societal objectives include the following:

- Provide information for policymakers that includes feasibility, risks, impacts, uncertainties, costs, and controls for climate interventions.
- Establish methods for ensuring safety, transparency, and rigor in research.
- Develop governance models for deployment at local, regional, and global scales.
- Mobilize U.S. resources in support of a wide global research community.
- Engage the technology sector to accelerate innovation and adoption of computing, observation, and other relevant capabilities.
- Engage the public to establish understanding and support for exploring climate intervention.

U.S. Federal Research 10-Year Mission Effort

The United States has the highest concentration of relevant talent, technology, and climate research investments in the world, and mobilizing these resources is the best way to ensure the rapid generation of knowledge, options, and open systems for evaluating them. Leveraging these capabilities for international collaboration is likely to accelerate progress and promote effective global decision-making in the future. These recommendations focus on the U.S. context but should be considered in the context of a vibrant global collaboration.

Atmospheric climate interventions should be researched to deliver an assessment and inform decisions within a decade. A coordinated, multi-agency, multi-sector effort should be conducted to develop expertise and reduce uncertainty in Earth system prediction by tenfold.

> "The United States has the highest concentration of relevant talent, technology, and climate research investments in the world, and mobilizing these resources is the best way to ensure the rapid generation of knowledge, options, and open systems for evaluating them."

In **years 1–2**, the following are recommended:

- Build research capabilities in relevant agencies, with near-term grant funding for modeling, data analysis, technology development, and small-scale field studies. Fund research to inform the 2022 IPCC report.
- Undertake or review assessments by the National Academy of Sciences, including, but not limited to, the following:
  - *Climate Intervention Strategies that Reflect Sunlight to Cool Earth: Developing a Research Agenda and Governance Approaches*.[205]
  - *Decadal Survey of Space-Based Observations*.[206]
  - *Sustaining Ocean Observations*.[207]
  - *Future of the Weather Enterprise* (proposal).[208]
  - *Future of Computing for Climate Research* (in scoping).
  - *Early Warning Indicators of Abrupt Climate Change* (suggested).
- Maintain or increase climate research budgets and add dedicated funding for climate intervention research without detracting from existing research, mitigation, or adaptation funds.
- Maintain critical atmospheric observations for continuity and encourage rapid expansion of capabilities to provide atmospheric baselines.
- Increase adoption of commercial cloud-computing capabilities to add computing capacity and facilitate broad access to climate models and datasets.
- Update research funding structures to facilitate service models for purchasing technology as well as facilitate the participation of international collaborators.
- Explore opportunities for better coordination of research funding across multiple agencies, particularly related to observational programs and campaigns.
- Support scientific assessment of the risks to the ozone layer of SAI through the Montreal Protocol/UN Environment Ozone Secretariat, including relevant funding.
- Review existing national and international governance frameworks related to research and requirements for needed new or expanded mechanisms.
- Update the *Weather Modification Reporting Act*.[209]

In **years 3–8**, the following are recommended:

- Execute against research and governance agendas defined by National Academy of Sciences studies to deliver assessment of interventions and improved Earth system prediction capabilities by 2030.
- Substantially increase climate research budgets with significant dedicated budgets for climate intervention research and development.
- Develop and deploy observational capabilities for measuring changes in atmospheric chemistry and for establishing baselines, focusing on high sensitivity and accuracy for measurements related to drivers of climate change.
- Develop and advance models, analytics, computing, and scientific programs to achieve tenfold reduction in uncertainty in Earth system prediction.
- Study the feasibility and risks of multiple atmospheric climate interventions with extensive review of scenarios and impacts, including the development of core technology and deployment models.
- Support the development of a robust international governance framework for atmospheric climate intervention with broad global support, including close consideration of the Montreal Protocol and other frameworks, as necessary.

In **years 9–10**, the following are recommended:

- Perform a national assessment of marine cloud brightening, SAI, and other atmospheric sunlight reflection techniques that appear to be technically and financially feasible, with diverse expert judgements on their possible incorporation into the broader national and international climate strategy.
- Conduct a strategic review of the state of the climate informed by new high-resolution observations and forecasting. Establish leadership and agency/interagency structure for atmospheric climate intervention and Earth system management.
- Establish global governance framework for atmospheric climate intervention deployment in collaboration with the Montreal Protocol/UN Ozone Secretariat.
- Make policy decisions on the level of investment in intervention capabilities for impact–scale research and/or readiness for remediation or emergency response.

Other Sectors

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:

- Support and participate in assessment functions for climate intervention research.
- 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.
- Rigorously enforce standards for commercial conflict disclosure and review conclusions drawn from research studies in journals.

TECHNOLOGY INDUSTRY

Recommendations for the technology industry are as follows:

- Invest in capabilities to improve Earth system prediction. Participate in assessments of Earth system prediction capabilities and identify opportunities to help accelerate, develop, and drive improvements in models, analysis, data, computing, and remote sensing.
- 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 sensitivity observations of the atmosphere and climate drivers for remote sensing.
- Create and support programs to connect technical experts and developers with research programs (e.g., "Code for Climate") to promote collaboration and accelerate the development of open tools and projects.
- Incorporate Earth system prediction into sustainability programs, marketing campaigns, and employee activism.

CIVIL SOCIETY

Recommendations for the civil society are as follows:

- Support non-climate-impacting scientific research to rapidly generate information for decision-making.
- Examine and support proven models for assessment and governance, such as the Montreal Protocol.
- Continue to support research and engagement by countries experiencing the most severe impacts.
- Focus evaluation on the relative risks of projected warming versus climate intervention. Broaden the portfolio of options for consideration and increase emphasis on outcomes for ecosystems and species.

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

PHILANTHROPY

Philanthropy recommendations are as follows:

- Support research in atmospheric sunlight reflection to provide a bridge and complement to public-sector funding.
- Support innovation in technologies and methods for understanding and predicting the Earth system.
- Support social science and governance research.
- Support communication programs for educating and engaging the public.

MEDIA

Media recommendations are as follows:

- Continue strong explanatory coverage to educate the public about climate risks and proposed interventions.
- Avoid sensationalist coverage that draws broad conclusions from individual studies and/or emphasizes extreme or unlikely scenarios.
- Help the public contextualize climate intervention against the escalating risks of climate change.

INDIVIDUALS

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

- Engage in voting, online activity, and outreach.
- Insist that policymakers provide adequate risk and contingency plans, including emergency measures, for ensuring safety in the face of warming climate.

Authors, Contributors, Acknowledgements, and Resources

Authors

Kelly Wanser and
Manaswita Konar

SilverLining
WWW.SILVERLINING.NGO

Contributors

Sarah Doherty, Senior Research Scientist at the Joint Institute for Atmosphere and Ocean, a joint NOAA/University of Washington institute and Lead Author of *National Climate Assessment Volume I: Climate Science Special Report* (2017); **Michael Dunne**, Professor of Physics, Stanford University and Associate Director of Research, SLAC National Accelerator Laboratory; **David Fahey**, Director of the Earth System Research Laboratory Chemical Sciences Division, NOAA; **Corinne Hartin**, Earth Scientist, Integrated Human-Earth Systems Science, Pacific Northwest National Laboratory, a Department of Energy research laboratory; **Penehuro Lefale**, Director of LeA International and Lead Author for the chapter on Small Islands for Working Group II of the Intergovernmental Panel on Climate Change Fourth Assessment Report awarded the Nobel Peace Prize; and **Robert Wood**, Professor of Atmospheric Sciences and Associate Dean of Research for the College of the Environment, University of Washington.

Acknowledgements

The authors would like to thank their esteemed contributors along with the numerous former and current scientists and public servants who contributed to the material covered by this report and continue to safeguard and advance U.S. climate research.

In particular, we would like to thank pioneers in the field of climate intervention for their courage in advancing the work, including Stewart Brand, Ken Caldeira, Ralph Cicerone, Paul Crutzen, Chris Field, Alan Gadian, David Keith, John Latham, Brian Launder, Jane Long, Michael MacCracken, Marcia McNutt, Armand Neukermans, Rafe Pomerance, Philip Rasch, Steve Rayner, Alan Robock, Stephen Salter, Stephen Schneider, John Shepherd, and Pete Worden. And we would also like to acknowledge the remarkable contribution of the following physicists and engineers who worked on a volunteer basis in their retirement to develop technology that would help answer questions about the possibilities of atmospheric intervention: Armand Neukermans, Gary Cooper, Jack Foster, Lee Galbraith, Sudhanshu Jain, and Robert Ormond.

We would also like to thank the other experts from various fields whose prior interactions helped informed our understanding, including Thomas Ackerman, Richard Bailey, Govindiswamy Bala, Banny Bannerjee, Cecilia Bitz, Olivier Boucher, Richard Branson, Christopher Bretherton, Holly Buck, Elizabeth Burtns, William Cheung, Bruce Darling, John Dykstra, Mark Eiken, Scott Elrod, Graham Feingold, Jane Flegal, Peter Frumhoff, James Gibbons, James Gimlett, Steven Hamburg, Linda Hedges, Joshua Horton, Sean Garner, Peter Irvine, Frank Keutsch, Ben Kravitz, George Leonard, Ulrike Lohmann, Douglas MacMartin, Joseph Majkut, Robert McHenry, Franklin Orr, Andrew Parker, Edward Parson, Janos Paztnor, Anna Possner, Arati Prabhakar, Jadwiga Richter, Kate Ricke, Joyashree Roy, Steven Strongin, Simone Tilmes, Gernot Wagner, Boris Worm, and Lowell Wood.

Additionally, the authors would like to thank the Pritzker Innovation Fund and photographer Christopher Michael for their remarkable contributions. Finally, we would like to thank our talented editor Sari Kimmel and designers at Decent People.

Resources

For more reading, we recommend the following works: *Climate Engineering and the Law: Regulation and Liability for Solar Radiation Management and Carbon Dioxide Removal* edited by Michael B. Gerrard and Tracy Hester (2018), *The Planet Remade: How Geoengineering Could Change the World* by Oliver Morton (2015), *Earth in Human Hands: Shaping Our Planet's Future* by David Grinspoon (2016), *The Unnatural World: The Race to Remake Civilization: The Race to Remake Civilization in Earth's Newest Age* by David Biello (2015), *How to Cool the Planet: Geoengineering and the Audacious Quest to Fix Earth's Climate* by Jeff Goodell (2010), and the forthcoming *After Geoengineering* by Holly Buck.

Endnotes

1 Government Publishing Office. (1971). *Weather Modification Reporting Act of 1972*, Public Law 92–205, §1, 85 Stat. 735 [H. R. 6893], 15 CFR Part 90—Maintaining Records and Submitting Reports on Weather Modification Activities.

2 National Aeronautics and Space Administration. (2018). "Ramp-up in Antarctic Ice Loss Speeds Sea Level Rise," NASA, Washington, DC. Available online: https://climate.nasa.gov/news/2749/ramp-up-in-antarctic-ice-loss-speeds-sea-level-rise/, last accessed December 5, 2018.

3 Intergovernmental Panel on Climate Change. (2018). *Special Report on Global Warming of 1.5 ºC*, IPCC, Incheon, South Korea. Available online: https://www.ipcc.ch/site/assets/uploads/sites/2/2018/07/SR15_SPM_High_Res.pdf, last accessed December 6, 2018.

4 Phys Org. (2016). "Global warming set to pass 2C threshold in 2050: report," Phys Org. Available online: https://phys.org/news/2016-09-global-2c-threshold.html, last accessed December 6, 2018.

5 National Research Council. (2015). *Climate Intervention: Reflecting Sunlight to Cool Earth*, The National Academies Press, Washington, DC. Available online: https://doi.org/10.17226/18988, last accessed December 6, 2018.

6 115th Congress, Subcommittee on Environment and Subcommittee on Energy Hearing—Geoengineering: Innovation, Research, and Technology, Testimony by Philip Rasch and Douglas MacMartin, Nov 8, 2017.

7 Johnson, S.K. (2017). "US House Science Committee just had a rational hearing about climate," *Ars Technica*. Available online: https://arstechnica.com/science/2017/11/us-house-science-committee-just-had-a-rational-hearing-about-climate/, last accessed December 6, 2018.

8 The National Academies of Sciences, Engineering, and Medicine. (2018). *National Academies Launching New Study on Sunlight-Reflection Research*, Press Release, Washington, DC. Available online: http://www8.nationalacademies.org/onpinews/newsitem.aspx?RecordID=10162018, last accessed December 6, 2018.

9 UNEP/OzL.Pro.30/CRP.7 7. (2018). *The need to study the relationship between stratospheric ozone and proposed solar radiation management strategies*, United Nations Environment Programme. Available online: http://conf.montreal-protocol.org/meeting/mop/mop30/crps/English/MOP30-CRP7.e.docx, last accessed December 5, 2018.

10 Temple, J. (2017). "China Builds One of the World's Largest Geoengineering Research Programs," *MIT Technology Review*. Available online: https://www.technologyreview.com/s/608401/china-builds-one-of-the-worlds-largest-geoengineering-research-programs/, last accessed December 5, 2018.

11 Rahman, A.A., Artaxo, P., Asrat, A., and Parker, A. (2018). "Developing countries must lead on solar geoengineering research," *Nature*. Available online: https://www.nature.com/articles/d41586-018-03917-8, last accessed December 5, 2018.

12 Intergovernmental Panel on Climate Change. (2018). *Special Report on Global Warming of 1.5 ºC*, IPCC, Incheon, South Korea. Available online: https://www.ipcc.ch/site/assets/uploads/sites/2/2018/07/SR15_SPM_High_Res.pdf, last accessed December 6, 2018.

13 Abatzoglou, J.T. and Williams, A.P. (2016). "Impact of anthropogenic climate change on wildfire across western U.S. forests," *Proceedings of the National Academy of Sciences*. Available online: http://www.pnas.org/content/113/42/11770, last accessed December 5, 2018.

14 Tigchelaar, M., Battisti, D.S., Naylor, R.L., and Ray, D.K. (2018). "Future warming increases probability of globally synchronized maize production shocks," *Proceedings of the National Academy of Sciences*. Available online: https://doi.org/10.1073/pnas.1718031115, last accessed December 6, 2018.

15 National Climate Assessment. (2014). "Chapter 6. Agriculture," in *Climate Change Impacts in the United States*, U.S. Global Change Research Program, Washington, DC. Available online: https://nca2014.globalchange.gov/report/sectors/agriculture, last accessed December 5, 2018.

16 Levitus, S. et al. (2012)."World ocean heat content and thermosteric sea level change (0–2000 m) 1955–2010," *Geophysical Research Letters*, *39*(10), Wiley Online Library. Available online: https://onlinelibrary.wiley.com/doi/abs/10.1029/2012GL051106, last accessed November 6, 2018.

17 Le Quéré, C. et al. (2016). "Global Carbon Budget 2016," *Earth System Science Data*, *8*, pp. 605–649. Available online: https://www.earth-syst-sci-data.net/8/605/2016/essd-8-605-2016.pdf, last accessed November 6, 2018.

18 Bassett, L., Costa, K., Richards, R., and Krishnamoorthi, D. (2018). *Understanding Our Future: Frontiers of Climate and Energy Data and Research*, Center for American Progress, Washington, DC. Available online: https://www.americanprogress.org/issues/green/reports/2018/09/12/457762/understanding-our-future/, last accessed November 6, 2018.

19 It is important to note that degradation of coral is not only attributed to warming of the ocean but also other factors such as destructive fishing, mining of corals, pollution, acidification of oceans, and sedimentation caused by erosion from construction, mining, and farming.

20 Paerl, H.W. and Paul, V.J. (2012). "Climate change: links to global expansion of harmful cyanobacteria," *Water Research*, *46*(5), pp. 1349–1363. Available online: https://www.ncbi.nlm.nih.gov/pubmed/21893330, last accessed November 7, 2018.

21 Brittena, G.L., Dowd, M., and Worm, B. (2015). "Changing recruitment capacity in global fish stocks," *Proceedings of the National Academy of Sciences*. Available online: https://www.pnas.org/content/early/2015/12/09/1504709112, last accessed December 7, 2018.

22 Bassett, L., Costa, K., Richards, R., and Krishnamoorthi, D. (2018). *Understanding Our Future: Frontiers of Climate and Energy Data and Research*, Center for American Progress, Washington, DC. Available online: https://www.americanprogress.org/issues/green/reports/2018/09/12/457762/understanding-our-future/, last accessed November 6, 2018.

23 Cohen, J., Pfeiffer, K., and Francis, J.A. (2018). "Warm Arctic episodes linked with increased frequency of extreme winter weather in the United States," *Nature Communications*, *9*. Available online: https://www.nature.com/articles/s41467-018-02992-9, last accessed November 7, 2018.

24 International Institute for Applied Systems Analysis. (2018). "Global 2 degrees C rise doubles population exposed to multiple climate risks compared to 1.5 degrees C," *ScienceDaily*. Available online: https://www.sciencedaily.com/releases/2018/05/180516101420.htm, last accessed December 5, 2018.

25 Kjellstrom, T. et al. (2016). *Climate Change and Labour: Impacts of Heat in the Workplace*, International Labour Organization. Available online: http://www.ilo.org/global/topics/green-jobs/publications/WCMS_476194/lang--en/index.htm, last accessed December 5, 2018.

26 Im, E-S., Pal, J.S., Eltahir, E.A.B. (2017). "Deadly heat waves projected in the densely populated agricultural regions of South Asia," *Science Advances*, *3*(8). Available online: http://advances.sciencemag.org/content/3/8/e1603322, last accessed December 7, 2018.

27 Beheshti, M. et al. (2015). "Performance loss among workers due to heat stress in high-temperature workplaces," *JOHE*, *4*(2). Available online: http://johe.rums.ac.ir/article-1-159-en.pdf, last accessed November 7, 2018.

28 Rigaud, K.K. et al. (2018). *Groundswell: Preparing for Internal Climate Migration*, World Bank, Washington, DC. Available online: https://openknowledge.worldbank.org/handle/10986/29461, last accessed November 7, 2018.

29 U.S. Department of Defense. (2014). *Department of Defense Quadrennial Defense Review 2014*, p. 30, Washington, DC. Available online: http://archive.defense.gov/pubs/2014_quadrennial_defense_review.pdf, last accessed December 7, 2018.

30 Hagedorn, R. (2016). *Impact of Extreme Summer Temperatures on Bridge Structures*, Master's Thesis, University of Arkansas, Fayetteville, AR. Available online: https://core.ac.uk/download/pdf/80559443.pdf, last accessed December 5, 2018.

31 National Climate Assessment. (2018). "Chapter 11: Urban Systems, Infrastructure, and Vulnerability," in *Climate Change Impacts in the United States*, U.S. Global Change Research Program, Washington, DC. Available online: https://nca2014.globalchange.gov/system/files_force/downloads/high/NCA3_Full_Report_11_Urban_Systems_and_Infrastructure_HighRes.pdf?download=1, last accessed December 7, 2018.

32 Bakemore, E. (2015). "Climate Change Is Turning 500-Year Floods Into 24-Year Ones," *Smithsonian.com*. Available online: https://www.smithsonianmag.com/smart-news/climate-change-turning-500-year-floods-24-year-ones-180956781/, last accessed December 7, 2018.

33 U.S. Environmental Protection Agency. (n.d.). "Climate Impacts on Transportation," (website) USEPA, Washington, DC. Available online: https://19january2017snapshot.epa.gov/climate-impacts/climate-impacts-transportation_.html, last accessed December 7, 2018.

34 Cappucci, M. (2018). "Sometimes, like right now in the Western U.S., it's too hot for airplanes to fly. Here's why," *Washington Post*. Available online: https://www.washingtonpost.com/news/capital-weather-gang/wp/2018/07/27/sometimes-its-too-hot-for-airplanes-to-fly-heres-why/, last accessed November 7, 2018.

35 Steffen, W. et al. (2018). "Trajectories of the Earth System in the Anthropocene," *Proceedings of the National Academy of Sciences*. Available online: http://www.pnas.org/content/115/33/8252, last accessed November 8, 2018.

36 Steffen, W. (2018). "Planet at risk of heading towards "Hothouse Earth" state," (website) Stockholm Resilience Centre. Available online: https://www.stockholmresilience.org/research/research-news/2018-08-06-planet-at-risk-of-heading-towards-hothouse-earth-state.html, last accessed November 7, 2018.

37 Hausfather, Z. (2017). "Analysis: How well have climate models projected global warming," *CarbonBrief*. Available online: https://www.carbonbrief.org/analysis-how-well-have-climate-models-projected-global-warming, last accessed November 28, 2018.

38 Brown, P.T. and Caldeira, K. (2017). "Greater future global warming inferred from Earth's recent energy budget," *Nature*, *552*, pp. 45–50. Available online: https://www.nature.com/articles/nature24672, last accessed November 28, 2018.

39 Intergovernmental Panel on Climate Change. (2013). *Climate Change 2013: The Physical Science Basis*, Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Available online: https://www.ipcc.ch/report/ar5/wg1/, last accessed December 7, 2018.

40 Schiffman, R. (2018). “Interview: How Air Pollution has Put a Brake on Global Warming,” *YaleEnvironment360*. Available online: https://e360.yale.edu/features/air-pollutions-upside-a-brake-on-global-warming, last accessed December 7, 2018.

41 Temple, J. (2018). “We’re about to kill a massive, accidental experiment in reducing global warming,” *MIT Technology Review*. Available online: https://www.technologyreview.com/s/610007/were-about-to-kill-a-massive-accidental-experiment-in-halting-global-warming/, last accessed November 7, 2018.

42 Eyring, V. et al. (2009). “Transport impacts on atmosphere and climate: Shipping,” *Atmospheric Environment*, pp. 1–37. Available online: https://www.geos.ed.ac.uk/~dstevens/publications/eyring_ae09.pdf, last accessed November 8, 2018.

43 Archer, D. et al. (2009). “Atmospheric Lifetime of Fossil Fuel Carbon Dioxide,” *Annu. Rev. Earth Planet. Sci.*, *37*, pp. 117–134. Available online: http://climatemodels.uchicago.edu/geocarb/archer.2009.ann_rev_tail.pdf, last accessed December 7, 2018.

44 The World Bank. (2014). “Transforming the Economy to Achieve Zero Net Emissions,” *The World Bank*. Available online: http://www.worldbank.org/en/news/feature/2014/12/08/transforming-economy-achieve-zero-net-emissions, last accessed December 7, 2018.

45 Lane, J.L. et al. (2015). “Understanding constraints to the transformation rate of global energy infrastructure,” *Wiley Interdisciplinary Reviews: Energy and Environment*, *5*(1). Available online: https://onlinelibrary.wiley.com/doi/pdf/10.1002/wene.177, last accessed December 7, 2018.

46 The National Academies of Sciences, Engineering, and Medicine. (2015). “Chapter 1: Introduction,” in *Climate Intervention: Reflecting Sunlight to Cool Earth*. Available online: https://www.nap.edu/read/18988/chapter/3, last accessed November 7, 2018.

47 United States Congressional Budget Office. (2008). *Policy Options for Reducing CO_2 Emissions*, Washington, DC. Available online: https://www.cbo.gov/sites/default/files/110th-congress-2007-2008/reports/02-12-carbon.pdf, last accessed December 7, 2018.

48 Drawdown. (n.d). “Women and Girls: Family Planning,” (website), Drawdown. Available online: https://www.drawdown.org/solutions/women-and-girls/family-planning, last accessed December 7, 2018.

49 Katsumasa, T. and O’Neill, B.C. (2018). “The Paris Agreement zero-emissions goal is not always consistent with the 1.5 ºC and 2 ºC temperature targets,” *Nature Climate Change*, *8*(4), pp. 319–324. Available online: http://adsabs.harvard.edu/abs/2018NatCC...8..319T, last accessed November 7, 2018.

50 These carbon dioxide removal approaches include greenhouse gas removal technologies, such as afforestation, bioenergy with carbon capture and storage, direct air capture and storage, and marine fertilization.

51 Minx, J.C. and Nemet, G. (2018). “The inconvenient truth about carbon capture,” *Washington Post*. Available online: https://www.washingtonpost.com/news/theworldpost/wp/2018/05/31/carbon-capture/?utm_term=.d6d05976ec22, last accessed December 7, 2018.

52 National Academy of Sciences, Engineering, and Medicine. (2018). “Executive Summary,” in *Negative Emissions Technologies and Reliable Sequestration: A Research Agenda*. Available online: https://nas-sites.org/dels/studies/cdr/, last accessed December 7, 2018.

53 National Academy of Sciences, Engineering, and Medicine. (2018). “Executive Summary,” in *Negative Emissions Technologies and Reliable Sequestration: A Research Agenda*. Available online: https://nas-sites.org/dels/studies/cdr/, last accessed December 7, 2018.

54 The National Academies of Sciences, Engineering, and Medicine. (2012). *Sea-Level Rise for the Coasts of California, Oregon, and Washington*. Available online: https://www.nap.edu/catalog/13389/sea-level-rise-for-the-coasts-of-california-oregon-and-washington, last accessed November 8, 2018.

55 Strauss, B.H. et al. (2012). “Tidally adjusted estimates of topographic vulnerability to sea level rise and flooding for the contiguous United States,” *Environmental Research Letters*, *7*(1). Available online: http://iopscience.iop.org/article/10.1088/1748-9326/7/1/014033/meta, last accessed November 8. 2018.

56 Tebaldi, C., Strauss, B.H., and Zervas, C. (2012). “Modelling sea level rise impacts on storm surges along US coasts,” *Environmental Research Letters*, *7*(1). Available online: http://iopscience.iop.org/article/10.1088/1748-9326/7/1/014032/meta, last accessed November 8, 2018.

57 Kopytko, N. (2011). “The climate change threat to nuclear power,” *NewScientist*. Available online: https://www.newscientist.com/article/mg21028138-200-the-climate-change-threat-to-nuclear-power/, last accessed December 7, 2018.

58 Rigaud, K.K. et al. (2018). *Groundswell: Preparing for Internal Climate Migration*, World Bank, Washington, DC. Available online: https://openknowledge.worldbank.org/handle/10986/29461, last accessed November 7, 2018.

59 Varshney, R. (2018). “Can genomics deliver climate-change ready crops?” *Plant Biology*, *45 Part B*, pp. 205–211. Available online: https://www.sciencedirect.com/science/article/pii/S1369526617302376, last accessed December 7, 2018.

60 Joseph, B., Jini, D., and Ajisha, S.U. (2011). “Fight Global Warming with Genetically Altered Trees,” *Asian Journal of Biotechnology*, *3*(4), pp. 337–344. Available online: https://scialert.net/fulltextmobile/?doi=ajbkr.2011.337.344, last accessed December 7, 2018.

61 Seaworld Parks & Entertainment. (n.d.). “Coral & Coral Reefs,” (website). Available online: https://seaworld.org/en/animal-info/animal-infobooks/coral-and-coral-reefs/coral-reefs, last accessed December 7, 2018.

62 National Academies of Sciences, Engineering, and Medicine. (2018). *A Research Review of Interventions to Increase the Persistence and Resilience of Coral Reefs*. Available online: http://dels.nas.edu/Study-In-Progress/Interventions-Increase-Resilience/DELS-OSB-17-01, last accessed December 7, 2018.

63 The National Academies of Sciences, Engineering, and Medicine. (2015). *Climate Intervention: Reflecting Sunlight to Cool Earth*. Available online: https://www.nap.edu/catalog/18988/climate-intervention-reflecting-sunlight-to-cool-earth, last accessed November 30, 2018.

64 The second largest volcanic eruption of the last century occurred in the afternoon on June 15, 1991, when the summit of Mount Pinatubo collapsed. The stratovolcano, on an island in the Philippines, released 20 million tons of SO_2 into the atmosphere. By reflecting solar radiation, it was estimated that the resulting particles ultimately lowered global temperatures by nearly 1 ºF.

65 The analogy is not perfect because the volcanic aerosols flushed within a few years, and the climate system does not respond in the same way as it would if the particles were continually replenished, as they would be in a geoengineering effort. Perturbations to the climate system that might become evident with constant forcing disappear as the forcing disappears.

66 Stenchikov, G. et al. (2002). “Arctic Oscillation response to the 1991 Mount Pinatubo eruption: Effects of volcanic aerosols and ozone depletion,” *Journal of Geophysical Research*, *107*(D24), pp. 28-1–28-16. Available online: http://climate.envsci.rutgers.edu/pdf/StenchikovEtAl2002JD002090.pdf, last accessed December 7, 2018.

67 Tilmes, S. et al. (2018). “CESM1 (WACCM) Stratospheric Aerosol Geoengineering Large Ensemble (GLENS) Project,” *Early Online Release*, American Meteorological Society. Available online: https://journals.ametsoc.org/doi/10.1175/BAMS-D-17-0267.1, last accessed December 7, 2018.

68 World Meteorological Organization, United Nations Environmental Programme, National Oceanic and Atmospheric Administration, National Aeronautics and Space Administration, and European Commission. (2018). *Scientific Assessment of Ozone Depletion: 2018—Executive Summary*, p. 33. Available online: https://www.esrl.noaa.gov/csd/assessments/ozone/2018/executivesummary.pdf, last accessed December 5, 2018.

69 World Meteorological Organization, United Nations Environmental Programme, National Oceanic and Atmospheric Administration, National Aeronautics and Space Administration, and European Commission. (2018). *Scientific Assessment of Ozone Depletion: 2018—Executive Summary*, p. 33. Available online: https://www.esrl.noaa.gov/csd/assessments/ozone/2018/executivesummary.pdf, last accessed December 5, 2018.

70 Tilmes, S. et al. (2018). “CESM1 (WACCM) Stratospheric Aerosol Geoengineering Large Ensemble (GLENS) Project,” *Early Online Release*, American Meteorological Society. Available online: https://journals.ametsoc.org/doi/10.1175/BAMS-D-17-0267.1, last accessed December 7, 2018.

71 Intergovernmental Panel on Climate Change. (2013). “Figure 8.15,” in *Climate Change 2013: The Physical Science Basis*, Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Available online at: https://www.ipcc.ch/report/ar5/wg1/, last accessed December 7, 2018.

72 Twomey, S. (1977). “The Influence of Pollution on the Shortwave Albedo of Clouds,” *J. Atmos. Sci.*, *34*(7), pp. 1149–52, doi:10.1175/1520-0469(1977)034<1149:TIOPOT>2.0.CO;2. doi:10.1175/1520-0469(1977)034<1149:TIOPOT>2.0.CO;2.

73 Public Broadcasting Service. (n.d.). “Discoveries in Global Dimming,” (website), PBS. Available online: https://www.pbs.org/wgbh/nova/sun/dimm-08.html, last accessed December 7, 2018.

74 Latham, J. (1990). “Control of global warming?” *Nature*, *347*, pp. 339–340, doi:10.1038/347339b0.

75 Slingo, A. (1990). “Sensitivity of the Earth’s Radiation Budget to Changes in Low Lying Clouds,” *Nature*, *343*(4), available online: https://www.researchgate.net/publication/230889462_Sensitivity_of_the_Earth%27s_Radiation_Budget_to_Changes_in_Low_Clouds, last accessed December 7, 2018.

76 National Academies of Sciences, Engineering, and Medicine. (2018). *A Research Review of Interventions to Increase the Persistence and Resilience of Coral Reefs*. Available online: http://dels.nas.edu/Study-In-Progress/Interventions-Increase-Resilience/DELS-OSB-17-01, last accessed December 7, 2018.

77 Latham, J. et al. (2014). "Marine cloud brightening: regional applications," *Phil. Trans. R. Soc. A*, *372*. Available online: http://eprints.whiterose.ac.uk/82346/1/20140053.full.pdf, last accessed December 7, 2018.

78 Intergovernmental panel on Climate Change. (2013). *Climate Change 2013: The Physical Science Basis*, pp. 13–14, Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Available online at: https://www.ipcc.ch/report/ar5/wg1/, last accessed December 7, 2018.

79 The National Academies of Sciences, Engineering, and Medicine. (2015). *Climate Intervention: Reflecting Sunlight to Cool Earth*. Available online: https://www.nap.edu/catalog/18988/climate-intervention-reflecting-sunlight-to-cool-earth, last accessed November 30, 2018.

80 English, J.M. et al. (2012). "Microphysical simulations of sulfur burdens from stratospheric sulfur geoengineering," *Atmos. Chem. Phys*, *12*(10), pp. 4775–4793. Available online: https://www.climate-engineering.eu/single/english-j-m-et-al-2012-microphysical-simulations-of-sulfur-burdens-from-stratospheric-sulfur-geoengineering.html, last accessed December 1, 2018.

81 Heckendorn, P. et al. (2009). "The impact of geoengineering aerosols on stratospheric temperature and ozone," *Environmental Research Letters*, *4*(4). Available online: http://iopscience.iop.org/article/10.1088/1748-9326/4/4/045108, last accessed December 1, 2018.

82 Niemeir, U., Schmidt, H., and Timmreck, H. (2010). "The dependency of geoengineered sulfate aerosol on the emission strategy" *Atmospheric Science Letters*, *12*(2). Available online: https://onlinelibrary.wiley.com/doi/full/10.1002/asl.304, last accessed December 1, 2018.

83 Jones, A.C. (2018). "Regional Climate Impacts of Stabilizing Global Warming at 1.5 K Using Solar Geoengineering," *Earth's Future*, *6*(2). Available online: https://agupubs.onlinelibrary.wiley.com/doi/10.1002/2017EF000720, last accessed December 1, 2018.

84 The National Academies of Sciences, Engineering, and Medicine. (2015). *Climate Intervention: Reflecting Sunlight to Cool Earth*. Available online: https://www.nap.edu/catalog/18988/climate-intervention-reflecting-sunlight-to-cool-earth, last accessed November 30, 2018.

85 Parkes, B., Challinor, A., and Nicklin, K. (2015). "Crop failure rates in a geoengineered climate: impact of climate change and marine cloud brightening," *Environmental Research Letters*, *10*(8). Available online: http://iopscience.iop.org/article/10.1088/1748-9326/10/8/084003, last accessed December 1, 2018.

86 Smith, C.J. et al. (2017). "Impacts of Stratospheric Sulfate Geoengineering on Global Solar Photovoltaic and Concentrating Solar Power Resource" *Journal of Applied Meteorology and Climatology*, *56*, pp. 1483–1497. Available online: https://journals.ametsoc.org/doi/10.1175/JAMC-D-16-0298.1, last accessed December 1, 2018.

87 Tilmes, S., Müller, R., and Salawitch, R. (2008). "The Sensitivity of Polar Ozone Depletion to Proposed Geoengineering Schemes," *Science*, *320*(5880), pp. 1201-1204. Available online: http://science.sciencemag.org/content/320/5880/1201, last accessed November 29, 2018.

88 The National Academies of Sciences, Engineering, and Medicine. (2015). *Climate Intervention: Reflecting Sunlight to Cool Earth*. Available online: https://www.nap.edu/catalog/18988/climate-intervention-reflecting-sunlight-to-cool-earth, last accessed November 30, 2018.

89 Trisos, C.H. et al. (2018). "Potentially dangerous consequences for biodiversity of solar geoengineering implementation and termination," *Nature Ecology & Evolution*, *2*, 475–482. Available online: https://www.nature.com/articles/s41559-017-0431-0, last accessed November 7, 2018.

90 MacMartin, D.G., Kravitz, B., and Keith, D. (2014). "Geoengineering: the world's largest control problem," *Proceedings of the 2014 American Control Conference*, pp. 2401–2406, Portland, OR. Available online: https://dash.harvard.edu/handle/1/23936193, last accessed December 7, 2018.

91 Keith, D.W., Wagner, G., and Zabel, C.L. (2017). "Solar geoengineering reduces atmospheric carbon burden," *Nature Climate Change*, *7*, pp. 617–619. Available online: https://geoengineering.environment.harvard.edu/publications/solar-geoengineering-reduces-atmospheric-carbon-burden, last accessed December 7, 2018.

92 The National Academies of Sciences, Engineering, and Medicine. (2015). *Climate Intervention: Reflecting Sunlight to Cool Earth*, p. 121. Available online: https://www.nap.edu/catalog/18988/climate-intervention-reflecting-sunlight-to-cool-earth, last accessed November 30, 2018.

93 Smith, W. and Wagner, G. (2018). "Stratospheric aerosol injection tactics and costs in the first 15 years of deployment," *Environmental Research Letters*, *13*(12). Available online: http://iopscience.iop.org/article/10.1088/1748-9326/aae98d#erlaae98ds5, last accessed December 7, 2018.

94 Smith, W. and Wagner, G. (2018). "Stratospheric aerosol injection tactics and costs in the first 15 years of deployment," *Environmental Research Letters*, *13*(12). Available online: http://iopscience.iop.org/article/10.1088/1748-9326/aae98d#erlaae98ds5, last accessed December 7, 2018.

95 Dykema, J., Keith, D.W., and Keutsch, F.N. (2016). "Assessing risks of solar geoengineering starts with accurate aerosol radiative properties: Accurate aerosol properties for SRM," *Geophysical Research Letters*, *43*(12). Available online: https://www.researchgate.net/publication/305336003_Assessing_risks_of_solar_geoengineering_starts_with_accurate_aerosol_radiative_properties_Accurate_aerosol_properties_for_SRM, last accessed December 5, 2018.

96 Smith, W. and Wagner, G. (2018). "Stratospheric aerosol injection tactics and costs in the first 15 years of deployment," *Environmental Research Letters*, *13*(12). Available online: http://iopscience.iop.org/article/10.1088/1748-9326/aae98d#erlaae98ds5, last accessed December 7, 2018.

97 Smith, W. and Wagner, G. (2018). "Stratospheric aerosol injection tactics and costs in the first 15 years of deployment," *Environmental Research Letters*, *13*(12). Available online: http://iopscience.iop.org/article/10.1088/1748-9326/aae98d#erlaae98ds5, last accessed December 7, 2018.

98 Horton, J. (2014). "Solar Geoengineering: Reassessing Benefits, Costs, and Compensation," *Ethics, Policy & Environment*. Available online: https://keith.seas.harvard.edu/publications/solar-geoengineering-reassessing-benefits-costs-and-compensation, last accessed December 7, 2018.

99 Dahlman, L. and Lindsey, R. (2018). "Climate Change: Ocean Heat Content," (website) NOAA. Available online: https://www.climate.gov/news-features/understanding-climate/climate-change-ocean-heat-content, last accessed December 7, 2018.

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

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

102 International Energy Agency. (n.d.). "Energy Technology Perspectives," (website) IEA. Available online: https://www.iea.org/etp/, last accessed December 7, 2018.

103 Levin, K., Mulligan, J., and Ellison, G. (2018). "Taking Greenhouse Gases from the Sky: 7 Things to Know About Carbon Removal," (website) World Resources Institute. Available online: https://www.wri.org/blog/2018/03/taking-greenhouse-gases-sky-7-things-know-about-carbon-removal, last accessed December 7, 2018.

104 The Royal Society. (2009). *Geoengineering the Climate: Science, Governance and Uncertainty*. Available online: https://royalsociety.org/~/media/Royal_Society_Content/policy/publications/2009/8693.pdf, last accessed December 5, 2018.

105 Bala, G., Duffy, P.B., and Taylor, K.E. (2008). "Impact of geoengineering schemes on the global hydrological cycle," *Proceedings of the National Academy of Sciences*, *105*(22), pp. 7664–7669. Available online: http://www.pnas.org/content/105/22/7664.long, last accessed December 5, 2018.

106 Keith, D.W., Weisenstein, D.K., Dykema, J.A., and Keutsch, F.N. (2016). "Stratospheric solar geoengineering without ozone loss," *Proceedings of the National Academy of Sciences*, *103*(52), pp. 14910–14914. Available online: http://www.pnas.org/content/pnas/113/52/14910.full.pdf, last accessed December 5, 2018.

107 Keith, D.W., Weisenstein, D.K., Dykema, J.A., and Keutsch, F.N. (2016). "Stratospheric solar geoengineering without ozone loss," *Proceedings of the National Academy of Sciences*, *103*(52), pp. 14910–14914. Available online: http://www.pnas.org/content/pnas/113/52/14910.full.pdf, last accessed December 5, 2018.

108 Corner, A. and Pidgeon, N. (2014). "Geoengineering, climate change skepticism and the 'moral hazard' argument: an experimental study of UK public perceptions," *Philosophical Transactions Series A: Mathematical, Physical, and Engineering Sciences*, *372*(2031).

109 Cairns, R.C (2014) "Climate geoengineering: issues of path-dependence and socio-technical lock-in," *Wiley Interdisciplinary Reviews: Climate Change*, *5*(5). pp. 649–661.

110 Symons, J. (2018). "Geoengineering Justice: Who Gets to Decide Whether to Hack the Climate," *The Breakthrough Journal*, 8, Oakland, CA.

111 Preston, C.J. (2013). "Ethics and geoengineering: reviewing the moral issues raised by solar radiation management and carbon dioxide removal," *WIREs Clim Change, 4*, pp. 23–37.

112 Erickson, A. (2018). "Few countries are meeting the Paris climate goals. Here are the ones that are," *Washington Post*. Available online: https://www.washingtonpost.com/world/2018/10/11/few-countries-are-meeting-paris-climate-goals-here-are-ones-that-are/?utm_term=.52b2320e78fe, last accessed October 30, 2018.

113 Hultman, N. (2018). "We're almost out of time: The alarming IPCC climate report and what to do next," *The Brookings Institution*. Available online: https://www.brookings.edu/opinions/were-almost-out-of-time-the-alarming-ipcc-climate-report-and-what-to-do-next/, last accessed October 30, 2018.

114 Stephens, J.C. and Markusson, N. (2018). "Technological Optimism in Climate Mitigation: The Case of Carbon Capture and Storage," *Oxford Handbook of Energy and Society*. Available online: http://www.oxfordhandbooks.com/view/10.1093/oxfordhb/9780190633851.001.0001/oxfordhb-9780190633851-e-29, last accessed December 7, 2018.

115 Gerrard, M.B. and Hester, T. (2018). *Regulation and Liability for Solar Radiation Management and Carbon Dioxide Removal*, p. 276, Cambridge University Press.

116 Tollefson, J. (2008). "UN decision puts brakes on ocean fertilization," *Nature News, 453*. Available online: https://www.nature.com/news/2008/080603/full/453704b.html, last accessed December 7, 2018.

117 Forum for Climate Engineering Assessment. (2018). *Executive Summary: Governing Solar Radiation Management: Academic Working Group on Climate Engineering Governance*. Available online: http://ceassessment.org/wp-content/uploads/2018/10/AWG_FCEA_governing-solar-radiation-management_EXECUTIVE_SUMMARY.pdf, last accessed December 7, 2018.

118 Carnegie Climate Geoengineering Governance Initiative. (2018). *The C2G2 Approach: Summary, 20 August 2018*, Carnegie Council for Ethics in International Affairs. Available online: https://www.c2g2.net/wp-content/uploads/20180826-C2G2-Approach-summary.pdf, last accessed December 7, 2018.

119 Gerrard, M.B. and Hester, T. (2018). *Climate Engineering and the Law: Regulation and Liability for Solar Radiation Management and Carbon Dioxide Removal*, Cambridge University Press.

120 The United Nations Office at Geneva. (n.d.). "Convention on the Prohibition of Military or Any Other Hostile Use of Environmental Modification Techniques (ENMOD)," (website) UNOG. Available online: https://www.unog.ch/enmod, last accessed December 5, 2018.

121 Chalecki, E.L. and Ferrari, L.L. (2018). "A New Security Framework for Geoengineering," *Strategic Studies Quarterly 12, 2*, pp. 82–106.

122 UNECE. (n.d.). "Clean Air," (website) UNECE. Available online: http://www.unece.org/env/lrtap/welcome.html.html, last accessed December 5, 2018.

123 Gerrard, M.B. and Hester, T. (2018). *Climate Engineering and the Law: Regulation and Liability for Solar Radiation Management and Carbon Dioxide Removal*, p. 73, Cambridge University Press.

124 United Nations Environment Programme. (n.d.). "Home page," (website). Available online: https://ozone.unep.org/index.php, last accessed December 7, 2018.

125 National Aeronautics and Space Administration. (2018). "NASA Study: First Direct Proof of Ozone Hole Recovery Due to Chemicals Ban," (website), NASA, Washington, DC. Available online: https://www.nasa.gov/feature/goddard/2018/nasa-study-first-direct-proof-of-ozone-hole-recovery-due-to-chemicals-ban, last accessed December 5, 2018.

126 U.S. Environmental Protection Agency. "International Actions—The Montreal Protocol on Substances that Deplete the Ozone Layer," (website) USEPA, Washington, DC. Available online: https://www.epa.gov/ozone-layer-protection/international-actions-montreal-protocol-substances-deplete-ozone-layer, last accessed December 5, 2018.

127 Mooney, C. (2018). "Someone, somewhere, is making a banned chemical that destroys the ozone layer, scientists suspect," *Washington Post*. Available online: https://www.washingtonpost.com/news/energy-environment/wp/2018/05/16/someone-somewhere-is-making-a-banned-chemical-that-destroys-the-ozone-layer-scientists-suspect/?utm_term=.da63de6466fe, last accessed December 5, 2018.

128 UNEP/OzL.Pro.30/CRP.7 7. (2018). *The need to study the relationship between stratospheric ozone and proposed solar radiation management strategies*, United Nations Environment Programme. Available online: http://conf.montreal-protocol.org/meeting/mop/mop30/crps/English/MOP30-CRP7.e.docx, last accessed December 5, 2018.

129 United Nations Environment Programme. (n.d.). "The Kigali Amendment to the Montreal protocol: another global commitment to stop climate change," (website). Available online: https://www.unenvironment.org/news-and-stories/news/kigali-amendment-montreal-protocol-another-global-commitment-stop-climate, last accessed December 7, 2018.

130 Convention on Biological Diversity. (n.d.). "Climate-related Geoengineering and Biodiversity: Technical and regulatory matters on geoengineering in relation to the CBD," (website) Convention on Biological Diversity. Available online: https://www.cbd.int/climate/geoengineering/, last accessed December 5, 2018.

131 Convention of Biological Diversity. (n.d.). "Home page," (website). Available online: https://www.cbd.int/, last accessed December 7, 2018.

132 Gerrard, M.B. and Hester, T. (2018). *Climate Engineering and the Law: Regulation and Liability for Solar Radiation Management and Carbon Dioxide Removal*, p. 66, Cambridge University Press.

133 Office of the Law Revision Counsel. (n.d.). *15 USC Ch. 9A: Weather Modification Activities or Attempts; Reporting Requirement from Title 15—Commerce and Trade*, United States Code, Washington, DC. Available online: http://uscode.house.gov/view.xhtml?path=/prelim@title15/chapter9A&edition=prelim, last accessed December 5, 2018.

134 Gerrard, M.B. and Hester, T. (2018). *Climate Engineering and the Law: Regulation and Liability for Solar Radiation Management and Carbon Dioxide Removal*, p. 175–176, Cambridge University Press.

135 U.S. Environmental Protection Agency. (n.d.) "Overview of the Cross-State Air Pollution Rule (CSAPR)," (website) USEPA, Washington, DC. Available online: https://www.epa.gov/csapr/overview-cross-state-air-pollution-rule-csapr, last accessed December 7, 2018.

136 U.S. Environmental Protection Agency. (2014). *Integrated Review Plan for the Primary National Ambient Air Quality Standard for Sulfur Dioxide*, pp. 1–2, USEPA, Washington, DC. Available online: https://www3.epa.gov/ttn/naaqs/standards/so2/data/20140318so2reviewplan.pdf, last accessed December 5, 2018.

137 U.S. Department of Energy. (n.d.). "National Environmental Policy Act," (website). Available online: https://ceq.doe.gov/, last accessed December 7, 2018.

138 Gerrard, M.B. and Hester, T. (2018). *Climate Engineering and the Law: Regulation and Liability for Solar Radiation Management and Carbon Dioxide Removal*, p. 155, Cambridge University Press.

139 United States Congress. (1973). *Endangered Species Act of 1973*, Washington, DC. Available online: https://www.fws.gov/laws/lawsdigest/migtrea.html, last accessed December 7, 2018.

140 U.S. Fish & Wildlife Service. (n.d.). "Migratory Bird Treaty Act of 1918," (website). Available online: https://www.fws.gov/laws/lawsdigest/migtrea.html, last accessed December 7, 2018.

141 Cornell University. (n.d.). "16 U.S. Code Chapter 31—Marine Mammal Protection," (website). Available online: https://www.law.cornell.edu/uscode/text/16/chapter-31, last accessed December 7, 2018.

142 The National Academies of Sciences, Engineering, and Medicine. (2015). "Front Matter," in *Climate Intervention: Reflecting Sunlight to Cool Earth*. Available online: https://www.nap.edu/catalog/18988/climate-intervention-reflecting-sunlight-to-cool-earth, last accessed November 30, 2018.

143 Congress.gov. (2017). "H.R.4586—Geoengineering Research Evaluation Act of 2017," (website). Available online: https://www.congress.gov/bill/115th-congress/house-bill/4586, last accessed December 7, 2018.

144 California Air Resources Board. (n.d.). "Laws and Regulations," (website). Available online https://www.arb.ca.gov/html/lawsregs.htm, last accessed December 7, 2018.

145 Woods, E. (2018). "From geoengineering to gene drives: move over, moratoria," *The Royal Society*. Available online: https://blogs.royalsociety.org/in-verba/2018/11/16/from-geoengineering-to-gene-drives-move-over-moratoria/, last accessed December 5, 2018.

146 Chhetri, N. et al. (2018). *Governing Solar Radiation Management*, Forum for Climate Engineering Assessment, American University, Washington, DC. Available online: http://ceassessment.org/wp-content/uploads/2018/10/AWG_FCEA_governing-solar-radiation-management_EXECUTIVE_SUMMARY.pdf, last accessed December 5, 2018.

147 Oxford Martin School. (n.d.). "The Principles," (website), Oxford Geoengineering Programme. Available online: http://www.geoengineering.ox.ac.uk/oxford-principles/principles/, last accessed December 5, 2018.

148 Gerrard, M.B. and Hester, T. (2018). *Climate Engineering and the Law: Regulation and Liability for Solar Radiation Management and Carbon Dioxide Removal*, p. 275, Cambridge University Press.

149 International Maritime Organization. (n.d.). "Assessment Framework," (website) IMO. Available online: http://www.imo.org/en/OurWork/Environment/LCLP/EmergingIssues/geoengineering/OceanFertilizationDocumentRepository/AssessmentFramework/Pages/default.aspx, last accessed December 5, 2018.

150 Branson, M.C. (2014). *A Green Herring: How Current Ocean Fertilization Regulation Distracts from Geoengineering Research*, *54*(1), p. 31. Available online: http://www.homepages.ed.ac.uk/shs/Climatechange/Geo-politics/green%20herring%20ocean%20fertilization.pdf, last accessed December 7, 2018.

151 Antarctic Climate & Ecosystems Cooperative Research Center. (2016). *Position Analysis: Ocean Fertilization*, p. 26. Available online: http://acecrc.org.au/wp-content/uploads/2016/07/ACE106_Position-Analysis_Ocean-Fert_April-2016_WEB.pdf, last accessed December 7, 2018.

152 Simon, M. (2018). "How engineering the climate could mess with our food," *Climate Desk*. Available online: https://grist.org/article/how-engineering-the-climate-could-mess-with-our-food/, last accessed December 7, 2018.

153 Ornstein, C. and Thomas, K. (2018). "Top Cancer Researcher Fails to Disclose Corporate Financial Ties in Major Research Journals," *The New York Times*. Available online: https://www.nytimes.com/2018/09/08/health/jose-baselga-cancer-memorial-sloan-kettering.html, last accessed December 5, 2018.

154 Office of the Law Revision Counsel. (n.d.). *15 USC Ch. 9A: Weather Modification Activities or Attempts; Reporting Requirement from Title 15—Commerce and Trade*, United States Code, Washington, DC. Available online: http://uscode.house.gov/view.xhtml?path=/prelim@title15/chapter9A&edition=prelim, last accessed December 5, 2018.

155 Intergovernmental Panel on Climate Change. (n.d.). "About Preparing Reports," (website). Available online: https://www.ipcc.ch/about/preparingreports/, last accessed December 7, 2018.

156 Bahr, D. (2018). "Bring in the nerds: Reviving the Office of Technology Assessment," *RStreet*. Available online: https://www.rstreet.org/2018/01/24/bring-in-the-nerds-reviving-the-office-of-technology-assessment/, last accessed December 5, 2018.

157 115th Congress, Subcommittee on Environment and Subcommittee on Energy Hearing—Geoengineering: Innovation, Research, and Technology, Testimony by Philip Rasch and Douglas MacMartin, November 8, 2017.

158 Crutzen, P.J. (2006). "Albedo Enhancement by Stratospheric Sulfur Injections: A Contribution to Resolve a Policy Dilemma?" *Climate Change*, *77*, 211–219. Available online: https://link.springer.com/article/10.1007%2Fs10584-006-9101-y, last accessed December 5, 2018.

159 Kravitz, B. (n.d.). "GeoMIP About," (website). Available online: http://climate.envsci.rutgers.edu/GeoMIP/about.html, last accessed February 18, 2019.

160 Tilmes, S., Mills, M.J., Niemeier, U., Schmidt, H., Robock, A., Kravitz, B., Lamarque, J.-F., Pitari, G., and English, J.M. (2015). "A new Geoengineering Model Intercomparison Project (GeoMIP) experiment designed for climate and chemistry models," *Geosci. Model Dev.*, *8*(1), 43–49. Available online: https://www.geosci-model-dev.net/8/43/2015/gmd-8-43-2015.html, last accessed February 18, 2019.

161 The Royal Society. (2009). *Geoengineering the Climate: Science, Governance and Uncertainty*. Available online: https://royalsociety.org/topics-policy/publications/2009/geoengineering-climate/, last accessed December 7, 2018.

162 The National Academies of Sciences, Engineering, and Medicine. (2015). *Climate Intervention: Reflecting Sunlight to Cool Earth*. Available online: https://www.nap.edu/catalog/18988/climate-intervention-reflecting-sunlight-to-cool-earth, last accessed November 30, 2018.

163 The National Academies of Science, Engineering, and Medicine. (2013). Russell, L.M. "Offsetting Climate Change by Engineering Air Pollution to Brighten Clouds," in *Frontiers of Engineering: Reports on Leading-Edge Engineering from the 2012 Symposium*. Available online: https://www.nap.edu/read/18185/chapter/6#20, last accessed December 7, 2018.

164 The Guardian. (2012). "Geoengineering experiment cancelled due to perceived conflict of interest," *The Guardian*. Available online: https://www.theguardian.com/environment/2012/may/16/geoengineering-experiment-cancelled, last accessed December 5, 2018.

165 Harvard University. (n.d). "Harvard's Solar Geoengineering Research Program," (website). Available online: https://geoengineering.environment.harvard.edu/, last accessed December 7, 2018.

166 Marine Cloud Brightening Project. (n.d.). "Home page," (website). Available online: http://mcbproject.org/, last accessed December 7, 2018.

167 Krieger, L.M. (2015). "Cloud brightening experiment tests tool to slow climate change," *The Mercury News*. Available online: https://www.mercurynews.com/2015/07/11/cloud-brightening-experiment-tests-tool-to-slow-climate-change/, last accessed December 7, 2018.

168 Dykema, J.A., Keith, D.W., Anderson, J.G., and Weisenstein, D. (2014). "Stratospheric controlled perturbation experiment: a small-scale experiment to improve understanding of the risks of solar geoengineering," *Phil. Trans. R. Soc. A*, *372*. Available online: https://keith.seas.harvard.edu/files/tkg/files/dykema_et_al._-_2014_-_stratospheric_controlled_perturbation_experiment_.pdf, last accessed December 7, 2018.

169 Smith, W. and Wagner, G. (2018). "Stratospheric aerosol injection tactics and costs in the first 15 years of deployment," *Environmental Research Letters*, *13*(12). Available online: http://iopscience.iop.org/article/10.1088/1748-9326/aae98d#erlaae98ds5, last accessed December 7, 2018.

170 Wood, R., Ackerman, T., Rasch, P., and Wanser, K. (2017). "Could geoengineering research help answer one of the biggest questions in climate science"? *Earth's Future*, *5*(7). Available online: https://agupubs.onlinelibrary.wiley.com/doi/full/10.1002/2017EF000601, last accessed December 7, 2018.

171 Intergovernmental Panel on Climate Change. (2013). *Climate Change 2013: The Physical Science Basis*, Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Available online at: https://www.ipcc.ch/report/ar5/wg1/, last accessed December 7, 2018.

172 Wood, R. and Ackerman, T.P. (2013). "Defining success and limits of field experiments to test geoengineering by marine cloud brightening," *Climate Change*. Available online: https://www.atmos.washington.edu/~robwood/papers/geoengineering/Wood_Ackerman_CLIMATICCHANGE_2013.pdf, last accessed December 7, 2018.

173 National Aeronautics and Space Administration. (n.d.). "Earth Expeditions: ORACLES," (website), NASA. Available online: https://www.nasa.gov/content/earth-expeditions-oracles, last accessed December 7, 2018.

174 University Corporation for Atmospheric Research. (2008). "VOCALS: VAMOS Ocean-Cloud-Atmosphere-Land Study," (website). Available online: https://www.eol.ucar.edu/field_projects/vocals, last accessed December 7, 2018.

175 Cooper, G. et al. (2012). "A Review of Some Experimental Spray Methods for Marine Cloud Brightening," *International Journal of Geosciences*, *4*, 78–97. Available online: https://file.scirp.org/pdf/IJG_2013012316580130.pdf, last accessed December 7, 2018.

176 Bala, G. and Gupta, A. (2018). "Solar Geoengineering Research in India," *Early Online Release, American Meteorological Society*. Available online: https://journals.ametsoc.org/doi/abs/10.1175/BAMS-D-18-0122.1, last accessed December 7, 2018.

177 Boettcher, M. and Schäfer, S.(2017). "Reflection upon 10 years of geoengineering research: Introduction to the Crutzen + 10 special issue," *Earth's Future*, *5*, pp. 266–277. Available online: https://agupubs.onlinelibrary.wiley.com/doi/pdf/10.1002/2016EF000521, last accessed December 7, 2018.

178 Wood, R., Ackerman, T., Rasch, P., and Wanser, K. (2017). "Could geoengineering research help answer one of the biggest questions in climate science?" *Earth's Future*, *5*(7). Available online: https://agupubs.onlinelibrary.wiley.com/doi/full/10.1002/2017EF000601, last accessed December 7, 2018.

179 The National Academies of Science, Engineering, and Medicine. (2018). *Thriving on Our Changing Planet: A Decadal Strategy for Earth Observation from Space, Unedited Prepublication*. Available online: https://www.nap.edu/catalog/24938/thriving-on-our-changing-planet-a-decadal-strategy-for-earth, last accessed December 7, 2018.

180 The National Academies of Science, Engineering, and Medicine. (2017). *Consensus Study Report: Sustaining Ocean Observations to Understand Future Changes in Earth's Climate*. Available online: https://www.nap.edu/catalog/24919/sustaining-ocean-observations-to-understand-future-changes-in-earths-climate, last accessed December 7, 2018.

181 Wood, R., Ackerman, T., Rasch, P., and Wanser, K. (2017). "Could geoengineering research help answer one of the biggest questions in climate science?" *Earth's Future*, *5*(7). Available online: https://agupubs.onlinelibrary.wiley.com/doi/full/10.1002/2017EF000601, last accessed December 7, 2018.

182 National Research Council. (2015). *Climate Intervention: Reflecting Sunlight to Cool Earth*, The National Academies Press, Washington, DC. Available online: https://doi.org/10.17226/18988, last accessed December 6, 2018.

183 Horton, J., Parker, A., and Keith, D. (2015). "Liability for Solar Geoengineering: Historical Precedents, Contemporary Innovations, and Governance Possibilities," *NYU Environmental Law Journal*, *22*, pp. 225–273. Available online: https://keith.seas.harvard.edu/publications/liability-solar-geoengineering-historical-precedents-contemporary-innovations-and, last accessed December 7, 2018.

184 Long, J.C.S. (2017). "Coordinated Action Against Climate Change: A New World Symphony," *Issues in Science and Technology*, *XXXIII*(3). Available online: https://issues.org/coordinated-action-against-climate-change-a-new-world-symphony/, last accessed December 7, 2018.

185 Mazzucato, M. (2015). *The Entrepreneurial State: Debunking Public vs. Private Sector Myths*. Available online: https://www.publicaffairsbooks.com/titles/mariana-mazzucato/the-entrepreneurial-state/9781610396134/, last accessed December 7, 2018.

186 United Nations Environment Programme. (n.d.). "Science: Assessment Panel Overview," (website). Available online: https://ozone.unep.org/science/overview, last accessed December 7, 2018.

187 Temple, J. (2017). "China Builds One of the World's Largest Geoengineering Research Programs," *MIT Technology Review*. Available online: https://www.technologyreview.com/s/608401/china-builds-one-of-the-worlds-largest-geoengineering-research-programs/, last accessed December 5, 2018.

188 Nace, T. (2018). "China Is Launching Weather-Control Machines Across An Area The Size Of Alaska," *Forbes*. Available online: https://www.forbes.com/sites/trevornace/2018/05/10/china-is-launching-a-massive-weather-control-machine-the-size-of-alaska/#19e9b8286315, last accessed December 5, 2018.

189 Bala, G. et al. (2018). "Solar Geoengineering Research in India," *Bulletin of the American Meteorological Society*. Available online: https://www.climate-engineering.eu/single/bala-g-et-al-2018-solar-geoengineering-research-in-india.html, last accessed December 7, 2018.

190 Grossman, D. (2018). "'Cloud Brightening' Might Save the Great Barrier Reef," *Popular Mechanics*. Available online: https://www.popularmechanics.com/technology/infrastructure/a22161312/great-barrier-reef-cloud-brightening/, last accessed December 5, 2018.

191 UAE Research Program for Advanced Rainmaking Science. (n.d.). Website Home page. Available online: http://www.uaerep.ae/, last accessed December 5, 2018.

192 Institute for Advanced Sustainability Studies. (n.d.). "Climate Engineering," (website) IASS POTSDAM. Available online: https://www.iass-potsdam.de/en/output/dossiers/climate-engineering, last accessed December 5, 2018.

193 Rahman, A.A., Artaxo, P., Asrat, A., and Parker, A. (2018). "Developing countries must lead on solar geoengineering research," *Nature*. Available online: https://www.nature.com/articles/d41586-018-03917-8, last accessed December 5, 2018.

194 The National Academies of Sciences, Engineering, and Medicine. (2015). *Climate Intervention Reports*. Available online: https://nas-sites.org/americasclimatechoices/other-reports-on-climate-change/climate-intervention-reports/, last accessed December 5, 2018.

195 The National Academies of Sciences, Engineering, and Medicine. (2018). *National Academies Launching New Study on Sunlight-Reflection Research*, Press Release, Washington, DC. Available online: http://www8.nationalacademies.org/onpinews/newsitem.aspx?RecordID=10162018, last accessed December 6, 2018.

196 114th Congress 2d Session. (2016). E*nergy and Water Development Appropriations Bill, 2017*. Available online: https://www.congress.gov/114/crpt/srpt236/CRPT-114srpt236.pdf, last accessed December 5, 2018.

197 The White House Office of the Press Secretary. (2016). *Presidential Memorandum—Climate Change and National Security*. Available online: https://www.whitehouse.gov/the-press-office/2016/09/21/presidential-memorandum-climate-change-and-national-security, last accessed December 5, 2018.

198 U.S. Global Change Research Program. (2017). *The National Global Change Research Plan 2012–2021: A Triennial Update*. Available online: https://downloads.globalchange.gov/strategic-plan/2016/usgcrp-strategic-plan-2016.pdf, last accessed December 5, 2018.

199 National Center for Atmospheric Research. (2017). "New approach to geoengineering simulations is significant step forward," *Science News*. Available online: https://www.sciencedaily.com/releases/2017/11/171107150706.htm, last accessed December 7, 2018.

200 *Barrasso-Whitehouse USE It Act*. Available online: https://www.congress.gov/115/bills/s2602/BILLS-115s2602rs.xml, last accessed December 5, 2018.

Veasey-McKinley Fossil Energy and Research Development Act. Available online: https://www.congress.gov/115/bills/hr5745/BILLS-115hr5745ih.xml, last accessed December 5, 2018.

Manchin Fossil Energy Utilization, Enhancement, and Leadership Act of 2018. Available online: https://www.congress.gov/115/bills/s2803/BILLS-115s2803is.xml, last accessed December 5, 2018.

201 Committee on Science, Space, & Technology. (2017). *Subcommittee on Environmental and Subcommittee on Energy Hearing—Geoengineering: Innovation, Research, and Technology*, Podcast. Available online: https://science.house.gov/legislation/hearings/subcommittee-environment-and-subcommittee-energy-hearing-geoengineering, last accessed December 7, 2018.

202 McNerney, J. (2017). "New climate research needed, Rep. McNerney says," *San Francisco Chronicle*. Available online: https://www.sfchronicle.com/opinion/article/Congressman-McNerney-New-climate-research-needed-12448871.php, last accessed December 7, 2018.

Smith, L. (2018). "Technology Advances Civilization. Bureaucrats Do Not," *The Daily Caller*. Available online: https://dailycaller.com/2018/01/29/technology-advances-civilization-bureaucrats-do-not/, last accessed December 7, 2018.

203 U.S. House of Representatives. (2017). *Rep. McNerney Introduces Groundbreaking Geoengineering Bill*, Press Release. Available online: https://mcnerney.house.gov/media-center/press-releases/rep-mcnerney-introduces-groundbreaking-geoengineering-bill, last accessed December 7, 2018.

204 United Nations Climate Change. (2017). *IPCC Agrees Outlines of Sixth Assessment Report*, Press Release. Available online: https://unfccc.int/news/ipcc-agrees-outlines-of-sixth-assessment-report, last accessed December 7, 2018.

205 The National Academies of Sciences, Engineering, and Medicine. (2015). *Climate Intervention: Reflecting Sunlight to Cool Earth*. Available online: https://www.nap.edu/catalog/18988/climate-intervention-reflecting-sunlight-to-cool-earth, last accessed November 30, 2018.

206 The National Academies of Science, Engineering, and Medicine. (2018). *Thriving on Our Changing Planet: A Decadal Strategy for Earth Observation from Space*, Unedited Prepublication. Available online: https://www.nap.edu/catalog/24938/thriving-on-our-changing-planet-a-decadal-strategy-for-earth, last accessed December 7, 2018.

207 The National Academies of Science, Engineering, and Medicine. (2017). *Consensus Study Report: Sustaining Ocean Observations to Understand Future Changes in Earth's Climate*. Available online: https://www.nap.edu/catalog/24919/sustaining-ocean-observations-to-understand-future-changes-in-earths-climate, last accessed December 7, 2018.

208 The National Academies of Sciences, Engineering, and Medicine. (n.d.). "Future of the U.S. Weather Enterprise: Call for Support for a New Study," (website). Available online: http://dels.nas.edu/global/basc/weatherenterprise, last accessed December 7, 2018.

209 Office of the Law Revision Counsel. (n.d.). *15 USC Ch. 9A: Weather Modification Activities or Attempts; Reporting Requirement from Title 15—Commerce and Trade*, United States Code, Washington, DC. Available online: http://uscode.house.gov/view.xhtml?path=/prelim@title15/chapter9A&edition=prelim, last accessed December 5, 2018.

SilverLining is a non-profit mission organization driving research to ensure safe pathways for climate within a decade.

To accomplish this goal, the world must improve its ability to forecast climate and understand the risks and feasibility of interventions to reduce climate warming, such as increasing the reflection of sunlight from the atmosphere. SilverLining engages with the research community, policymakers, technologists, civil society and people from all walks of life to help support research, innovation and learning in efforts to address climate.

LEARN MORE AT WWW.SILVERLINING.NGO

SilverLining
ENSURING A SAFE CLIMATE