BALANCING ACT

Assessing Risks and Governance of Climate Intervention

National Security Perspective

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Summary

Climate intervention, also known as geoengineering, refers to techniques proposed to alter Earth's climate system to stop or reverse climate change or its adverse effects. Given the expected continued rise in greenhouse gas emissions and accelerated pace of global warming despite mitigation efforts, nations, organizations, and individuals may soon look to climate intervention as a means to avoid the most severe effects of climate change.

The two main climate intervention categories are solar radiation management and carbon dioxide removal. With solar radiation management, the amount of sunlight reflected from Earth is altered to offset global warming. With carbon dioxide removal, carbon dioxide already in the atmosphere is actively captured and used for other purposes or sequestered. Within these two types of intervention are various more specific methods, shown in Figure S-1.

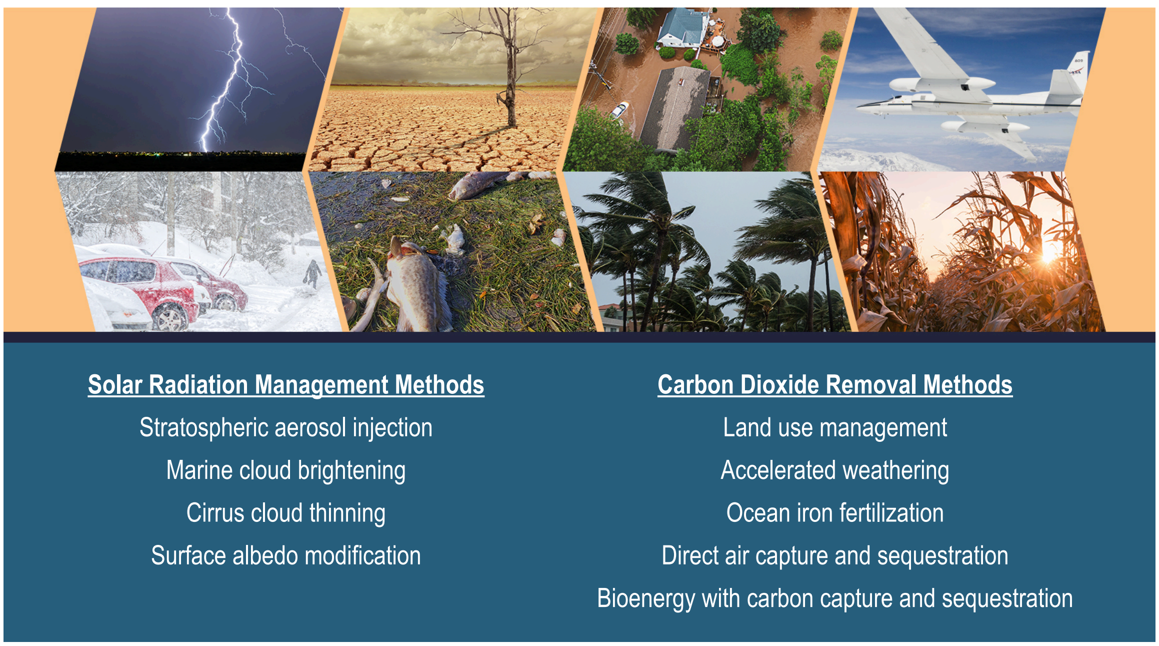


Figure S-1. Climate Intervention Methods

Despite the hope that climate intervention may prevent the increasingly dire climate change projections from becoming reality, the efficacy of many climate intervention methods remains uncertain. Moreover, many methods pose their own risks to the environment, global ecosystems, and critical human systems. Generally, solar radiation management methods would produce effects relatively quickly and could have widespread negative consequences if stopped suddenly. Carbon dioxide removal methods would result in slow changes and are safer to stop if implemented, though some of these methods—accelerated weathering and ocean iron fertilization—could have environmental consequences that are hard to reverse. These uncertainties and risks, when combined with the relatively few barriers to unilateral deployment for many methods, drive the need for national and international regulation of climate intervention research, testing, development, and deployment.

Currently, no formal international or US domestic regime comprehensively governs every type of climate intervention. However, many US and international institutions are investigating questions related to establishing comprehensive governance of climate intervention research and deployment.[1] Moreover, a substantial body of both international and domestic law has significant relevance to narrow aspects of climate intervention activities. That expansive body of law currently serves as the point of departure for many of those seeking to develop proposed governance regimes.[2]

Even with the ongoing governance research,[3] there is a dearth of thinking about climate intervention from a national security perspective, including a lack of research into the possible effects on civilian systems, critical Department of Defense infrastructure and readiness, operational environments, and geopolitical stability. National and global security can be greatly affected by one country's unilateral pursuit of climate intervention, because it may irrevocably alter regional and global environments. Moreover, if climate intervention occurs, national and global security assets may be tasked to play a critical role in governance and monitoring, and possibly even in development and deployment. Security risks posed by climate change need to be weighed against those posed by climate intervention.

In this report, we examine governance principles for climate intervention from a combined national security and technical perspective. This perspective clarifies some aspects of climate intervention relevant to national security decision-makers, science and technology developers, and policy analysts.

First, we summarize climate intervention methods. We then assess the effects of two controversial climate intervention methods—stratospheric aerosol injection and ocean iron fertilization—on national security, considering their abilities to both stop and reverse the effects of climate change and the possible direct, unintended environmental changes. Last, we examine the current state of governance based on national security considerations and make recommendations to integrate these considerations into future governance initiatives.

From these national security considerations and related recommendations, we derive the following principles for addressing climate intervention research, governance, and possible use. These principles share much in common with existing principles but extend their application to the national security realm.

Principles

- Precautionary principle—The benefits of climate intervention methods must be weighed against other options, and risks must be assessed and mitigated.
- Rigorous assessment inclusive of national security equities—Assessments and research conducted to better understand climate intervention methods must include considerations for national security, and the national security community should be a partner in assessments.
- International collaboration—Collaborative research and development, deployment (if warranted), and regulation can lead to geopolitical stability around this issue.

[1] OSTP, *Congressionally Mandated Research Plan*.

[2] Grisé et al., *Climate Control*; and Irving, "Geopolitical Risks."

[3] OSTP, *Congressionally Mandated Research Plan.*

- Observability and transparency—Easily monitored and observed methods and implementations may allay national security concerns and enhance governance.
- Climate intervention as a public good—Any pursuit of climate intervention requires a balance between government regulation and private participation.
- Moral hazard mitigation—Attention and resources must not be drawn away from climate change mitigation and adaptation strategies.
- Dependency hazard mitigation—Potential dependencies on the systems supporting climate intervention must be accounted for and managed.

Recommendations

- Consistent with the characterization of climate intervention as a global good, develop and implement a synergistic framework of public and private-sector roles and responsibilities, along with a robust system of governance. The Office of Science and Technology Policy recommendation that the US Global Change Research Program (USGCRP) coordinate is appropriate, and coordination should include Department of Defense equities, as it does for climate change issues writ large. Engagement with the United Nations will also be important.
- Prioritize and advocate for climate intervention methods that are easy to monitor and explore ways to make otherwise hard-to-detect methods more easily detectable. Organizations such as USGCRP and some of the agencies it coordinates—particularly the National Oceanic and Atmospheric Administration (NOAA) and the National Aeronautics and Space Administration (NASA)—may be in strong positions to advance the need for detectability.
- Focus, organize, and resource the US Intelligence Community to closely and comprehensively monitor climate intervention activities.
- Before deploying any climate intervention, recognize the potential harms of terminating an intervention and develop ways to mitigate the risks. This research and analysis could be led by USGCRP and the agencies it coordinates.
- When developing mitigation measures, explore the vulnerabilities of and required protection for climate intervention–related infrastructure. The Cybersecurity and Infrastructure Security Agency could lead this effort.

The overall effect climate intervention could have on national security remains inconclusive. More research is needed to reduce the uncertainties around how intended and unintended consequences of climate intervention could impact national security and how these consequences compare to those of climate change. Despite these uncertainties, current governance and regulations could mitigate some risks and promote responsible climate intervention research and deployment.

Introduction

> Geoengineering, as a response to human-induced climate change, embodies all of the features of a wicked problem—it is extremely complex and deeply uncertain, entails profound ethical issues and trade-offs, and even raises fundamental disagreements about the nature and framing of the problem itself.
>
> *—Flegal et al., "Solar Geoengineering"*

As the 2021 United Nations Intergovernmental Panel on Climate Change Assessment report[1] documents, the latest climate change projections have raised the level of concern about global warming's pace and destabilizing impacts. Adaptation and mitigation are the two primary approaches countries and organizations have been pursuing to address climate change. Adaptation involves measures that change the human capacity to endure climate change. Mitigation, meanwhile, seeks means to curtail ongoing greenhouse gas emissions through new technologies that obviate the need to produce those gases in the first place.

A third approach has gained attention (and notoriety) in the last several decades. Climate intervention (sometimes also labeled geoengineering or climate engineering)[2] refers to large-scale techniques to directly change Earth's climate system. Proponents claim that these techniques offer effective and comparatively quick solutions to the effects of climate change by broadly attacking the symptoms of climate change, without necessarily addressing the root causes.

Proposed types of climate intervention involve actively removing carbon dioxide from the atmosphere on a large scale (carbon dioxide removal, or CDR) or modifying Earth's radiation balance to reflect more sunlight back into space and lower temperatures without affecting atmospheric carbon dioxide (solar radiation management, or SRM). While some methods could address the effects of climate change, they could also have significant and global negative consequences.

Despite the possible negative consequences, some experts see climate intervention deployment as increasingly likely[3] and are calling for increased research into these methods. A recent US National Intelligence Estimate pointed to an "increasing chance that countries will unilaterally test and deploy large-scale geoengineering."[4] The US National Academies of Science, Engineering, and Medicine called for climate intervention research.[5] Cambridge University set up a Centre for Climate Repair with plans to study certain climate intervention techniques.[6] Recently, the White House announced the start of a five-year research program into climate intervention, following congressional legislation directing research.[7] While there has been some pushback around the feasibility of climate intervention,[8] the calls for studying it have gotten louder.

This push for research has been accompanied by appeals for governance. Some scientists have called for establishing governance structures at the international level before any deployment.[9] At the 2019 United Nations Environment Assembly, Switzerland submitted a draft resolution proposing an assessment of climate intervention methods and current governance frameworks.[10] The member states failed to reach an agreement on the

1 Masson-Delmotte et al., *Climate Change 2021.*

2 NRC, *Reflecting Sunlight.*

3 Simon, "Think Climate Change Is Messy?"

4 US NIC, *International Responses*, i.

5 NASEM, *Reflecting Sunlight*.

6 Pearce, "Geoengineer the Planet?"; and Centre for Climate Repair, "Refreeze the Arctic."

7 USGRP, "Request for Input."

8 Rahman et al. "Developing Countries Must Lead."

9 Rahman et al., "Developing Countries Must Lead."

10 "Geoengineering and Its Governance," Resolution for Consideration.

resolution, however, and it was withdrawn.[11] The White House Office of Science and Technology Policy published a research plan and initial governance framework for SRM.[12] The plan highlights the increasing interest in climate intervention and the need to act responsibly when considering it. It examines SRM issues from a whole-of-government perspective.

While it is clear that climate intervention touches certain aspects of national security, such as geopolitical stability, it may have even wider impacts in this realm. As a global issue, climate intervention may affect international relations and decisions of the future US national security community.

Thus, this report seeks to inform development of national security policy on climate intervention by addressing three primary questions:

(1) What national security implications do emerging climate intervention technologies pose for the United States?

(2) What is the current state of climate intervention governance, both domestically and internationally?

(3) If climate intervention research and deployment were to be pursued by any actor, what guiding principles would help ensure that relevant US national security interests are protected?

Summary of Climate Intervention Methods

Researchers have proposed a variety of climate intervention methods that run the gamut in terms of material use, maturity, and concern. Some methods are straightforward and simply vary current practices, such as changes in land use management. Others, such as stratospheric aerosol injection (SAI), are more complex and novel. In many cases, climate intervention could have both significant positive and negative consequences, and much uncertainty about these methods lingers.

Broadly speaking, climate intervention can be divided into two types: solar radiation management (SRM) and carbon dioxide removal (CDR).[13] This section summarizes the benefits and constraints of various SRM and CDR methods. Appendix A details of the efficacy and risks of, as well as cost estimates for, these methods.

Solar Radiation Management Methods

SRM, also known as sunlight reflection methods or albedo modification, encompasses techniques that cool the earth by increasing the reflectivity of solar radiation incident on the planet. Increasing the reflectivity lowers the amount of solar radiation that is converted to infrared radiation through absorption and emission. Therefore, less infrared radiation gets trapped by greenhouse gases, resulting in an overall cooling effect. Figure 1 depicts this concept and the various methods within it.

Since SRM methods do not decrease atmospheric carbon dioxide concentrations, they would not reduce or reverse some physical consequences of climate change, such as ocean acidification. Moreover, if carbon dioxide concentrations are not simultaneously reduced in other ways, such as CDR methods, and especially if carbon dioxide concentrations continue to grow because of emissions, interruption or termination of SRM methods could cause significant environmental and societal damage. If SRM were to be suddenly terminated, the world would warm, perhaps rapidly, based on the accumulated atmospheric carbon dioxide concentrations.[14] This phenomenon is often referred to as termination risk, termination shock, or

11 UNEP, "Proceedings."

12 OSTP, *Congressionally Mandated Research Plan*.

13 NRC, *Reflecting Sunlight; and* NRC, *Carbon Dioxide Removal*.

14 NRC, *Reflecting Sunlight*.

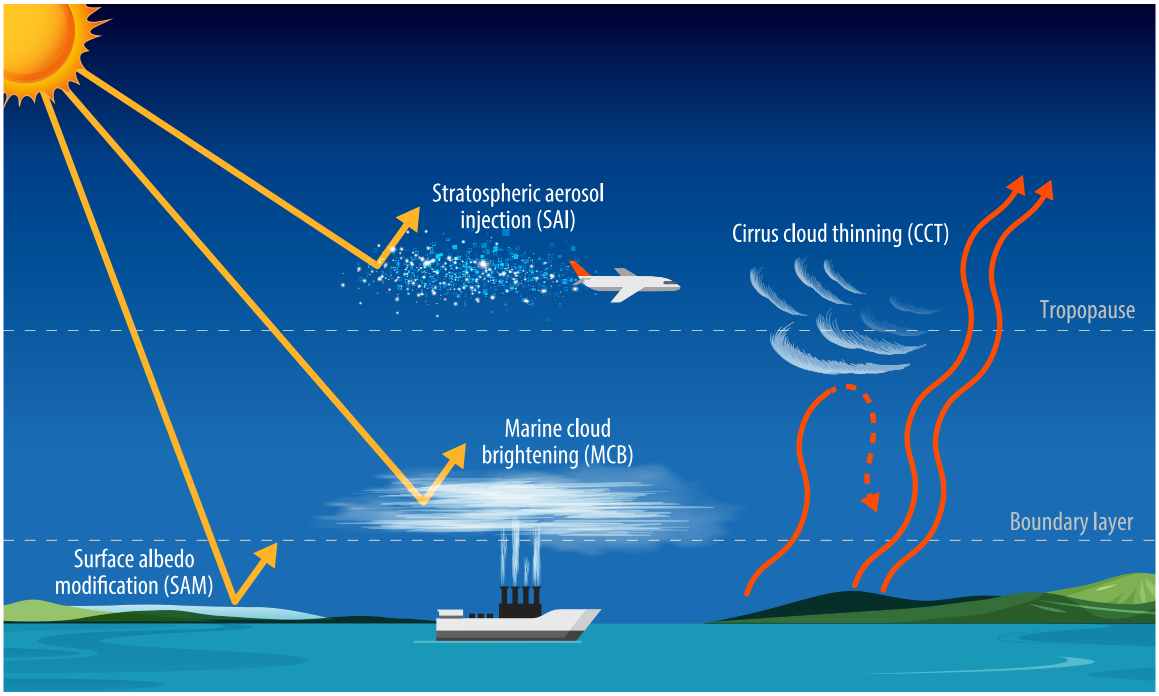


Figure 1. SRM Concept and Methods

millennial dependence.[15] Consequently, if SRM were started for climate intervention, it would need to be perpetually maintained; if the intervention were stopped, climate change could become much worse.

There are four main SRM methods:

(1) Stratospheric aerosol injection (SAI)—Introduction of liquid or solid particles[16] into the atmosphere to reflect a small fraction of incoming sunlight back into space

(2) Marine cloud brightening (MCB)—Deliberate introduction of materials, such as sea salt, into clouds to act as condensation nuclei, thereby increasing the number of droplets that can in turn reflect more sunlight back into space

(3) Cirrus cloud thinning (CCT)—Injection of ice-nucleating agents[17] into regions where cirrus clouds form in order to "thin" the clouds and increase the emission of longwave radiation into space

[15] Termination risk, termination shock, and millennial dependence refer to a hypothetical sudden, catastrophic spike in the global mean temperature if certain climate intervention methods were to be ceased. The phenomenon assumes that the underlying greenhouse gas emissions causing climate change are not curtailed sufficiently, so stopping a climate intervention would shock the climate system, and greenhouse gas concentrations higher than before any intervention would persist. Thus, this shock could potentially lead to a worse situation than if climate intervention were not conducted in the first place. In the absence of CDR, SRM would need to be deployed over the time span it would take natural processes to remove excess carbon dioxide from the atmosphere to avoid any warming. For high carbon dioxide concentrations, this could take millennia (hence "millennial dependence"). NRC, *Reflecting Sunlight*.

[16] A range of reflective aerosol materials have been proposed, including sulfate (sulfuric acid and sulfur dioxide) aerosols, calcite (calcium carbonate), titania (titanium dioxide), alumina (aluminum oxide), and diamond particles, among others.

[17] Example nucleating agents include inorganic compounds such as bismuth iodide and silver iodide. Because of the inorganic agents' toxicity, researchers and companies such as Snomax International have been increasingly examining more benign alternatives, such as ice-nucleation proteins, which are considered nontoxic, nonpathogenic, and biodegradable in the presence of ultraviolet light. Despite these attributes, these agents have increased costs and shorter lifetimes (due to biodegradability) than their inorganic compound counterparts. See https://www.snomax.com/.

(4) Surface albedo modification (SAM)—A variety of methods proposed to increase the albedo, or amount of diffuse reflected light, of Earth's surface

Table 1 summarizes the benefits and constraints of these four main SRM methods. Details and sources are provided in Appendix A.

Table 1. SRM Methods' Benefits and Constraints

Method	Benefits	Constraints
Stratospheric aerosol injection (SAI)	• Evidence of effectiveness from volcanic eruptions • Some international consensus on effectiveness • Easily obtained technology • Decreased land and sea ice melt, including reduced permafrost melt • Decreased sea level rise and coastal erosion	• Currently no experimental data • Current observational capacities lack ability to monitor deployment evolution effects • Major uncertainties about social, environmental, and ecological impacts • Experiments canceled or delayed • Potential health hazards • Ozone loss • Does not directly lower atmospheric carbon dioxide concentration • Potential concerns related to production or procurement of materials • Termination risk • Unknown consequences on extreme weather
Marine cloud brightening (MCB)	• Fast-acting method enabling some form of weather control • Cooling effects can be partially localized (i.e., can target only specific areas) • Uses only natural substances • Climate models consistently indicate that MCB can reduce temperatures as a result of a reduction in solar flux	• Requires continuity; potential for dependence on the technology • Sudden termination could increase threats to biodiversity • Implementation could result in residual regional temperature or precipitation anomalies, such as rainfall reduction • Applicable only over a limited domain of susceptible stratocumulus clouds • Much lower confidence that it would be more effective than SAI • Does not directly lower atmospheric carbon dioxide concentration
Cirrus cloud thinning (CCT)	• Potential for localized deployment • Some form of weather control • Avoids effects such as delayed stratospheric ozone recovery or changes to Earth's hydrological cycle, which can occur in other SRM methods	• Much lower confidence, than with SAI, that a substantial cooling could be achieved • Current understanding of cirrus clouds largely incomplete • Implementation could potentially have the opposite effect than intended • Unpredictable side effects (e.g., significant changes to precipitation) • Localized deployment might not be contained to one geographical area • Termination risk • Does not directly lower atmospheric carbon dioxide concentration
Surface albedo modification (SAM)	• Research into high-albedo crops aligns with efforts to engineer the world's food supply • Clearing forests in heavy-snowfall areas to increase surface albedo could provide (short-term) profits for forestry companies	• Using genetically modified crops or trees has biosafety and land use impacts • Clearing forests to create white deserts would negatively impact biodiversity and climate • Polymer film covering hinders accumulation of desert dust, which is essential for the global climate • Painting mountaintops would negatively affect fragile ecosystems • Eliminating forests would negatively affect the regulation of regional and local climates, and carbon contained in forests would also be lost • Does not directly lower atmospheric carbon dioxide concentration

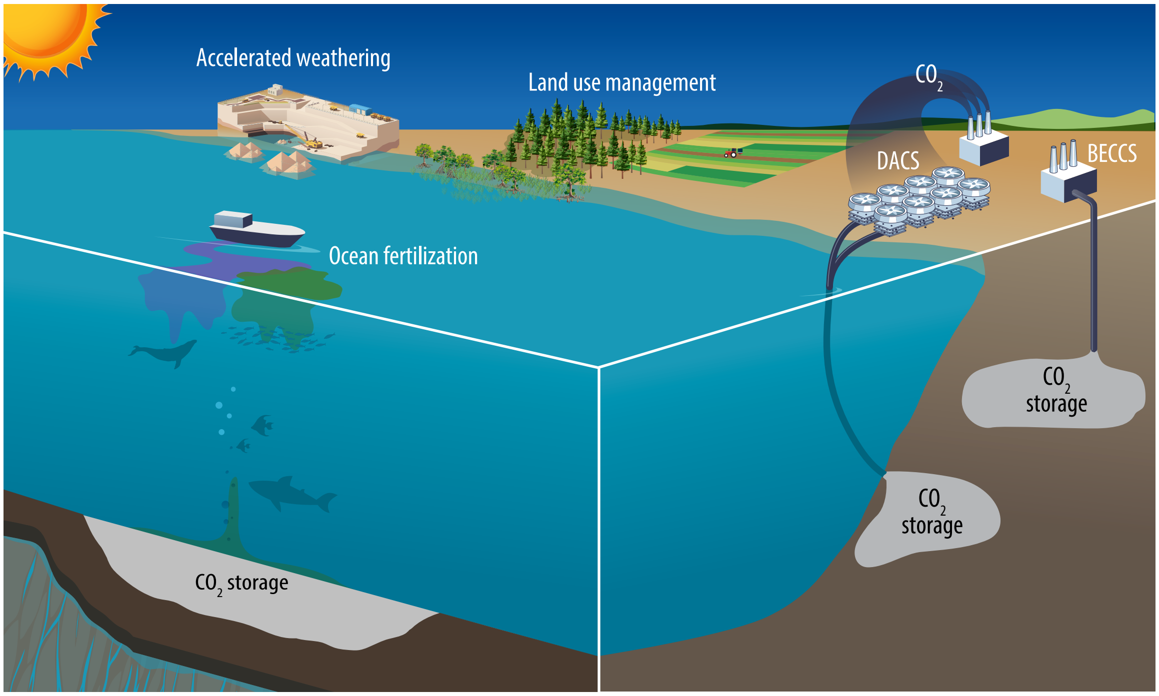


Figure 2. CDR Concept and Methods

Carbon Dioxide Removal Methods

CDR encompasses techniques to actively remove carbon dioxide already present in the atmosphere, decreasing its concentration to increase global radiative cooling. CDR is similar to but, for the purposes of this study, distinct from greenhouse gas mitigation. The latter seeks to decrease or eliminate greenhouse gas emissions by finding alternative energy sources with less or no emission, such as wind and solar energy. CDR alone would not replace greenhouse gas–emitting energy sources; it would, however, remove these sources' emissions from the atmosphere to counteract global temperature increase. Figure 2 depicts this concept and the various methods within it.

Several CDR techniques have been suggested:[18]

(1) Changes in land use management—Proactive changes to landscapes to increase natural carbon uptake from the atmosphere[19]

(2) Accelerated weathering—Chemical reactions to trap carbon dioxide in minerals (such as carbonates and silicates), which are then stored in rock formations on land or dissolved in the ocean[20]

(3) Ocean iron fertilization (OIF)—Strategic introduction of iron compounds into the ocean to seed the growth of phytoplankton in new areas, causing blooms that uptake more carbon dioxide

(4) Direct air capture and sequestration (DACS)—Industrial-scale extraction of carbon dioxide directly from the air, followed by sequestration (i.e., storage, often in geological formations) at an appropriate place

(5) Bioenergy with carbon capture and sequestration (BECCS)—Carbon capture at the point of emission from bioenergy plants

[18] NRC, *Carbon Dioxide Removal.*

[19] NRC, *Carbon Dioxide Removal.*

[20] NRC, *Carbon Dioxide Removal.*

Table 2. CDR Methods' Benefits and Constraints

Method	Benefits	Constraints
Land use management	• Relatively inexpensive and mature • Environmental consequences generally known • Lowers atmospheric carbon dioxide concentration	• Theoretical limits to amount of carbon that can be removed • Must be balanced with agriculture, which may foster debate or conflict
Accelerated weathering	• Low sociopolitical risk for land-based version • Ocean-based version may counter ocean acidification • Cost estimates should be relatively certain because of use of established technology • Lowers atmospheric carbon dioxide concentration	• More research needed to improve scalability • Ocean-based version presents environmental risks due to unknown effects on ocean ecology • Economics may constrain sites to coastal areas • Material needed on a large scale • Legal issues for sequestering carbon dioxide in the ocean
Ocean iron fertilization (OIF)	• May be required in only a few places around the world • Materials easily obtained • Lowers atmospheric carbon dioxide concentration • May increase fish populations	• Overall effectiveness questionable • Ocean acidification decrease expected to be minimal • Difficult to prevent plankton blooms from crossing international boundaries • Legal considerations • Plankton blooms may contain toxic species • Iron addition may reduce nutrients
Direct air capture and sequestration (DACS)	• Capture expected to have relatively minor impacts on the environment • Lowers atmospheric carbon dioxide concentration	• Potential inducement of seismic activity • Subsequent leaking of captured carbon
Bioenergy with carbon capture and sequestration (BECCS)	• Theoretically could account for large portion of world energy supply • To a certain amount of removal, costs may be lower and more certain than those of other methods • Lowers atmospheric carbon dioxide concentration	• Feasible only if a large fraction of world's energy supply comes from bioenergy • Land intensive; requires a lot of land to be set aside for the harvesting of crops just for energy needs • Less land for growing food, but estimates vary • Potential inducement of seismic activity • Subsequent leaking of captured carbon

Table 2 summarizes the main advantages and disadvantages of CDR methods. Details and sources are provided in Appendix A.

SRM and CDR Comparative Assessment

As detailed above, all climate intervention methods involve substantial risks and, therefore, controversy. Some methods could have global reach, affecting many countries beyond the one that initiates the intervention—and not necessarily equally. If something goes wrong or the benefits of use are not equally shared, international or even internal strife and conflict may ensue. There is also concern related to a possible moral hazard—that is, an incentive to abandon complete, comprehensive, and long-term climate change mitigation efforts, such as eliminating the use of fossil fuels, because of the presence of a cheaper, though riskier, alternative. Countries may abandon their efforts to decrease or eliminate greenhouse gas emissions because climate intervention can be used as a quick fix for the symptoms, resulting in further harmful environmental effects and a dangerous dependence on intervention.

Given that climate *change* has implications for national security, it is probable that climate *intervention* will also have significant implications for national security.

In its reports on climate intervention, the National Research Council of the National Academies notes significant contrasts between SRM and CDR.[21] CDR generally involves fewer new risks, poses less grave risks compared to those of SRM and offers methods that can be implemented more gradually to limit undesirable effects. Its climate effects are expected to be relatively modest compared with those of SRM, and they would require a long, sustained effort to maintain. In the long run, CDR is seen as costlier. SRM, on the other hand, holds promise of producing significant effects quickly and could be comparatively lower in cost. However, it is viewed as less understood and more risky, and its effects could span a broader area. While SRM is more controversial of the two climate intervention categories, each category contains a variety of methods that complicate this generalization.

Overall, each specific method poses a different level of risk and controversy. In particular, injecting aerosol into the stratosphere and fertilizing iron in the ocean seem to be the most controversial in their respective categories. The former is only partly understood and uses potentially harmful aerosols but shows some promise for quick effectiveness. The latter seems straightforward to implement, and in fact has already been implemented unilaterally. These methods in particular seem most urgent to analyze from a national security perspective.

[21] NRC, *Reflecting Sunlight*; and NRC, *Carbon Dioxide Removal*.

National Security Perspective

Over the past decade, it has become increasingly clear that climate change will have substantial national and global security implications.[22] Climate change effects on security include threats to homeland security,[23] as well as to current military infrastructure, capabilities, readiness, and sustainment and harmful changes to the operational environment.[24] Other vulnerabilities include demands for military resources for resultant humanitarian assistance and disaster relief missions[25] and decreased geopolitical stability.[26] Given these implications of climate change, it is probable that climate intervention will also have significant implications for national security. By understanding these implications, national security–informed principles for climate intervention governance can be determined.

To date, most research and discussion on the implications of climate intervention have focused on the proposed benefits and potential negative consequences to the physical environment.[27] The claimed benefits include countering negative effects of climate change and even possibly mitigating climate change altogether. Potential negative consequences include effects such as ozone depletion,[28] regional decreases in precipitation,[29] and termination shock. Research has focused on how climate intervention

[22] US GAO, *Risks to National Security*; US NIC, *International Responses*; and US White House, *Findings from Select Federal Reports*.

[23] US DHS, *Climate Action Plan*.

[24] US DOD, *Climate Risk Analysis*.

[25] Vergun, "DOD Preparing."

[26] US NIC, *International Responses*.

[27] Chalecki and Ferrari, "New Security Framework"; Bracmort and Lattanzio, *Geoengineering*; Grisé et al., *Climate Control*; Jayaram, "Foreign Policy"; US NIC, *International Responses*, i–ii; SilverLining, *Ensuring a Safe Climate*; and Robock et al., "Benefits, Risks, and Costs."

[28] Robock et al., "Benefits, Risks, and Costs."

[29] Irvine, Ridgewell, and Lunt, "Assessing the Regional Disparities."

might affect regional ecosystems[30] and systems on which human life relies, such as agriculture.[31] Additionally, research has explored how unilateral deployment, disagreements on proposed benefits and risks, and nonuniform regional effects might decrease geopolitical stability and lead to conflicts.[32]

In this section, we focus on three national security aspects of climate intervention:

(1) How changes in the physical environment due to climate intervention may affect national security

(2) The possibility of other nations or non-state actors deploying climate intervention technology

(3) The available options for shaping and responding to external actors' climate intervention activities that may negatively impact national security

National Security Implications of Changes to the Physical Environment

National security is often broadly defined and encompasses many aspects related to the security of a nation. With an organized description of national security, we can clearly map climate intervention–related changes in the physical environment to specific aspects of national security. To this end, we developed a framework that bins national security implications into four categories: civilian human systems, critical infrastructure and readiness, the operational environment, and geopolitical stability. These may be helpful for policymakers to use as a way to guide understanding and mitigation of risk.

As mentioned, two proposed methods of climate intervention—stratospheric aerosol injection (or SAI) and ocean iron fertilization (or OIF)—framed our primary context for exploring the relevant national security implications. We chose these methods because they are considered plausible and are the riskiest and most controversial within their respective categories and are therefore hypothesized to have more consequential national security implications. The environmental benefits and risks of each are summarized in Tables 1 and 2, respectively. Mapping their possible intended and unintended environmental consequences to the four categories in our framework illuminated both positive and negative implications.

We conducted an extensive literature review and consulted with subject-matter experts from a wide range of relevant disciplines to assess possible alterations of the physical environment and associated secondary impacts. Below is a brief overview of the assessment.

Civilian Systems

As presented in the sixth assessment of the Intergovernmental Panel on Climate Change, climate change is expected to have profound effects on humanity and the systems on which humanity relies.[33] Human systems include physical systems, such as energy, transportation, communications, and sanitation infrastructure; social systems, such as health, education, livelihoods, and cultural heritage; and ecological systems, including air quality, food production, and waterways. The impact climate change will have on each of these systems varies regionally based on the predicted environmental changes and the systems' vulnerabilities and adaptability. Moreover, the complex interactions between climate and human systems are uncertain, partially because of the large uncertainties in high-resolution climate predictions, especially for some climate change variables, such as agricultural drought and changes in local vegetation.[34] Given the substantial impact climate change may have on

[30] Zarnetske et al. "Potential Ecological Impacts."

[31] Yuanchao et al., "Solar Geoengineering"; and Robock et al., "Benefits, Risks, and Costs."

[32] Versen et al., *Preparing the United States*.

[33] Pörtner et al., "Summary for Policymakers."

[34] Bezner Kerr et al., "Ecosystem Products."

human systems, it is probable that climate intervention, including SAI and OIF, would also have large effects on these systems.

SAI, if successful, would mitigate some risks climate change poses to human systems. For example, SAI-driven decreases in mean air temperatures would also decrease energy demands for cooling,[35] heat-related illnesses[36] and disease spread,[37] and heat-related infrastructure material degradation.[38] SAI may also reduce or reverse sea level rise, decreasing the risks to coastal infrastructure and protecting coastal sites of cultural heritage.[39] While these are just a few examples of how SAI could help mitigate the risks climate change poses to human systems, the method's actual impact on these systems, as with climate change, is uncertain and likely regionally dependent. Additionally, SAI would not address climate risks related to carbon dioxide atmospheric concentrations. For example, it would not decrease ocean acidification, which may continue to harm aquaculture and the connected livelihoods.[40]

SAI may also have some direct impacts on human systems beyond its ability to counter global warming. Its impacts on agriculture and food production are uncertain and driven by multiple vectors, including changes to precipitation, soil moisture and evapotranspiration, pest and pollinator habitats, and photosynthesis.[41] Additionally, sulfate aerosols in large quantities have the potential to deplete the ozone layer,[42] resulting in environmental and health problems similar to those the international community has sought to combat since the 1980s. SAI-driven changes in regional precipitation[43] may interrupt critical human systems, such as water availability and quality, hydropower, and transportation via waterways. SAI may also impact human health. If the sulfate particles it uses settle down through the atmosphere to ground level, they may affect asthma sufferers, and much is still unknown about other particles' toxicity and acceptable exposure levels. There is some evidence that SAI may increase the frequency of extreme weather events, such as tropical cyclones.[44] Finally, as detailed in Appendix B, the mere procurement of the raw materials for these methods, not just their direct use to implement the methods, can also cause environmental and health concerns.

By removing carbon dioxide from the environment, OIF has potential to reverse climate change and mitigate most, if not all, climate change effects on human systems. While this is a large benefit over SAI and other SRM methods, it should be noted that OIF may have limited effectiveness in reversing climate change.[45] However, even with limited effectiveness, this method may still reduce risks to human systems by decreasing the rate of climate change and associated extreme weather events and providing additional time for human systems to adapt.

More concerning are OIF's direct impacts on human systems. For example, it could cause toxic algal blooms (Figure 3), which are harmful to health and may wreak havoc on the ocean ecosystem and impact economic activity.[46] Moreover, OIF may have large impacts on marine ecosystems and nutrient distributions, disrupting aquaculture, fishing, and associated livelihoods.[47]

35 Dodman et al., "Key Infrastructure."

36 Cissé et al., "Health, Wellbeing."

37 Cissé et al., "Health, Wellbeing."

38 Reidmiller et al., *Fourth National Climate Assessment*.

39 Birkmann et al., "Sustainable Development."

40 Cooley et al., "Ocean and Coastal Ecosystems."

41 Fan et al., "Crop Yields"; and Pongratz et al, "Crop Yields."

42 Robock et al., "Benefits, Risks, and Costs."

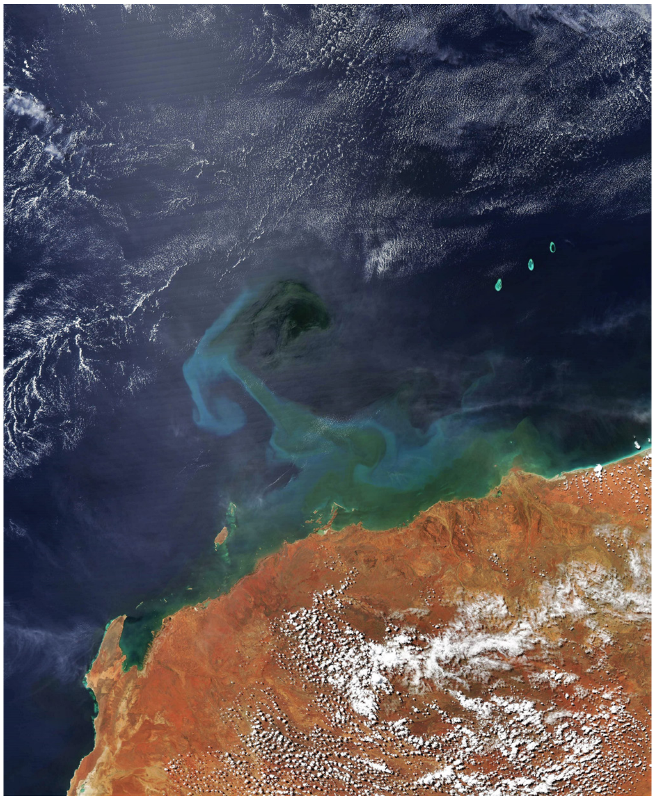
43 Goldstein, Kobos, and Brady, "Unintended Consequences."

44 Jones et al., "Hemispheric Solar Geoengineering."

45 Cao and Caldeira, "Ocean Iron Fertilization."

46 Trick et al., "Iron Enrichment."

47 Behrenfeld et al., "NAAMES"; and Williamson et al., "Ocean Fertilization."



Credit: NASA Aqua satellite, Public domain, via Wikimedia Commons

Figure 3. Algal Bloom off the Pibara Coast of Western Austraia in 2019

Depending on the method, various new systems and infrastructure would need to be established to support any climate intervention techniques.[48] Such systems and infrastructure would conceivably require defense and protection, tasking that would become especially significant when an intervention poses the danger of termination shock if suddenly halted. SAI might also enable termination shock by diverting efforts from combating greenhouse gas emissions; if SAI were ceased, the shock to the climate system could have major security implications for national and human systems.

[48] NRC, *Reflecting Sunlight.*

Critical Department of Defense Infrastructure and Readiness

Department of Defense (DOD) infrastructure includes military installations as well as supporting military and civilian infrastructure, such as energy, transportation, and sanitation. The DOD definition for readiness is abstract: "the ability of the U.S. military forces to fight and meet the demands of assigned missions."[49] This can include equipment and personnel availability and condition as well as training. As with civilian systems, climate change is predicted to have large, but uncertain, effects on critical DOD infrastructure and readiness.

It is uncertain whether SAI or OIF would ultimately benefit or compromise critical DOD infrastructure and readiness. On one hand, it is possible that these methods will reverse or mitigate some or all aspects of climate change risks to these systems. On the other hand, these interventions may introduce new risks and hazards. This section explores those benefits and risks. Because there is a significant overlap in benefits and risks when looking at military and civilian systems, we focus on aspects that are either distinct or are key to DOD infrastructure and readiness.

Injecting aerosols into the atmosphere (SAI) may alleviate or reverse several negative effects of warming on infrastructure and readiness. Increased mean temperatures and increased frequency and severity of extreme heat events caused by climate change are expected to disrupt training and increase instances of heat-related illnesses.[50] It is expected that by midcentury, many US training facilities will have to more frequently curtail or suspend physical training and strenuous exercise because of temperature.[51] Increased temperature will also degrade equipment and infrastructure faster, requiring

[49] US GAO, *Military Readiness.*

[50] US *DOD, Climate Risk Analysis.*

[51] Ryan et al., "Training in a Warmer World."

more frequent repairs.[52] This is especially true for Arctic infrastructure, given the rapidity and magnitude of the increasing Arctic temperatures and the infrastructure damage caused by permafrost melt.[53] SAI may reduce heat-related personnel injury and human performance degradation, as well as heat-related equipment damage.

The DOD has many installations in coastal areas that are at risk from sea level rise and related coastal erosion. Coastal locations are necessary for naval bases but are also ideal for Air Force bases and airfields because they provide close proximity to air training ranges over water. SAI may stop or reverse sea level rise and the associated risks to coastal infrastructure.

SAI will not necessarily reduce all risks posed by climate change, including extreme weather events and pluvial flooding. While some studies show that SAI may decrease instances of extreme weather,[54] other studies find that it could increase the frequency of extreme events, such as tropical cyclones. [55] Moreover, SAI will not reverse or decrease ocean acidification. Acidification can harm natural coastal barriers, such as coral or oyster reefs, increasing risks to coastal bases.[56] SAI may also decrease solar energy production on bases.[57]

Introducing iron compounds into the ocean (OIF), if successful or partially successful, may decrease or reverse the risks extreme weather poses to DOD infrastructure and readiness. It could combat sea level rise and storm surge risks to coastal bases; wildfire, air quality, and drought risks at Western bases; and prolonged and severe heat waves that may seriously disrupt training or even damage equipment.

The effects of OIF also raise questions about the more immediate impact on infrastructure and readiness. For example, OIF might affect maritime training ranges. The presence of a potentially toxic plankton bloom could preclude the use of a maritime range because of human health and safety issues. Additionally, increased phytoplankton growth reduces water clarity and optical detection depth for remote optical systems.[58]

Operational Environment

Emerging research on climate change and DOD operations has revealed that environmental changes can affect the nation's ability to project force and conduct operations.[59] Climate change is predicted to affect the DOD joint warfighting functions, which include command and control, information, intelligence, fires, movement and maneuver, force protection, and sustainment.[60] Given these functions' sensitivities to environmental changes, it is likely that SAI and OIF will affect them—either directly or indirectly by mitigating or reversing some aspects of climate change.

SAI, by decreasing mean temperatures and sea level rise, will decrease risks of heat illness to personnel and heat-related degradation to systems and platforms in the operational environment.[61] These risks are expected to affect information, movement and maneuver, and sustainment. Air operations are particularly affected by heat.[62] Higher surface temperatures create lower surface air density, requiring fixed-wing aircraft to achieve higher speeds to take off. Aircraft will need to be lighter, to include more efficient engines, or to take off from longer runways. This could have large implications for planes

52 Pinson et al., *DoD Installation Exposure*.

53 Hjort et al., "Degrading Permafrost."

54 NRC, *Reflecting Sunlight*.

55 Jones et al., "Hemispheric Solar Geoengineering."

56 Ferrario et al., "Effectiveness of Coral Reefs."

57 Murphy, "Effect of Stratospheric Aerosols."

58 Sinex and Winokus, "Environmental Factors."

59 US DOD, *Climate Risk Analysis*.

60 US JCS, *Joint Operations*; and Bewly et al. "Framework for Climate Security."

61 Pinson et al., *DoD Installation Exposure*.

62 Coffel and Horton, "Climate Change."

taking off from aircraft carriers and airfields with short runways. Moreover, decreased air density in flight can decrease range, loiter time, and payload capacity.[63] SAI may counter some of these issues, but it is unclear how SAI-driven changes to air temperature profiles, turbulence, and air quality intake for engines will affect aviation broadly.

SAI's ability to reverse or stop sea level rise will also decrease climate change–driven risks due to this rise and the ensuing coastal erosion. These changes may limit maneuver and sustainment because of decreased access to international ports. Moreover, rapid climate change–driven changes in coastal areas would require more information- and intelligence-gathering operations for terrain navigation or anomaly detection.

The impact of SAI on extreme events is uncertain, but it is projected to increase tropical cyclones. More cyclones will create additional interruptions to movement and maneuver and sustainment and could decrease information- and intelligence-gathering abilities. Regional changes to precipitation and weather patterns are also possible with SAI, and these changes may impact operational capabilities, such as ground mobility.

The impacts of climate change and SAI on military sensors and signal propagation are still uncertain. Changes to signal propagation and sensing would affect command and control, information, intelligence, and fires (by affecting targeting abilities). Increased global temperatures are expected to increase humidity in maritime environments, attenuating near-surface radio frequency and electro-optical signals. SAI may mitigate those risks, but how it might impact atmospheric sensors or space-based sensing remains unclear. Climate change, through alterations to ocean acidification, salinity, and water temperature, may affect conductivity, temperature, and depth profiles, which impact undersea signal propagation. SAI may reverse or stop ocean temperature increases and salinity changes,[64] but it is not expected to impact ocean acidification.

It is also unclear what, if any, impact SAI may have on DOD mission demand. By reversing or stopping the rapid temperature increases and sea ice reduction in the Arctic, SAI may decrease mission demand poleward. It might also decrease the number of climate change–related humanitarian and disaster relief missions in response to increased temperatures and sea level rise, but changes to the frequency or severity of missions triggered by extreme weather events are uncertain.

By removing carbon dioxide, OIF has the potential to mitigate or reverse climate change–driven risks to operations. At the same time, it may create additional risks to operations. For example, it is unclear whether OIF would change the acoustics or dielectric properties of the ocean because of increased maritime iron content or plankton growth. Additionally, plankton growth would decrease ocean opacity, thereby limiting space-based sensing of ocean bodies.[65] OIF may also change regional biodiversity. Changes to the habitats and migration patterns of marine mammals and the locations of fisheries may impact movement and maneuver, information, and intelligence.

Geopolitical Stability

Finally, OIF and SAI may impact geopolitical stability. Discounting the significant uncertainties related to their risks and efficacy, both methods are technically straightforward and relatively inexpensive. Most nations, various non-state entities, and even individuals could seek to implement crude versions of these methods. Both SAI and

[63] US DOD, *Climate Risk Analysis*.

[64] SAI is likely to decrease sea and land ice melt, and decreases in these large sources of fresh water are expected to change the salinity of the oceans. However, it is uncertain what impact SAI will have on precipitation and runoff, which are also sources of fresh water into the oceans.

[65] Sinex and Winokur, "Environmental Factors."

OIF are unlikely to cause effects confined to only one geographic region. Thus, any associated harms to human health or the environment may extend beyond the target region, if not globally. If the international community by consensus decides to delay or prohibit use of climate intervention technology, unilateral pursuit of these methods by any actor could undermine stability.

In some cases, climate intervention may benefit geopolitical stability by countering the destabilizing aspects of climate change. Additionally, a nation that spearheads a responsible climate intervention research and implementation program may succeed in slowing or minimizing its climate change effects, thereby enhancing its stability and deriving other benefits, such as international clout.

On the other hand, climate intervention may foster conflict. If one nation, or even an organized group of nations, were to decide to alter the planet's climate at the expense of other nations, this would naturally cause international disputes and possibly conflict. Even if countries did not endure a specific harm but were simply excluded from the decision-making process, disputes could still emerge if the excluded parties perceived that the countries deciding to intervene did so paternalistically.

Even if the international community determines that the risk of implementing climate intervention is too great, poor nations that may be most impacted by climate change and cannot afford adaptation or mitigation may be incentivized to pursue climate intervention as their least expensive alternative.[66] This dynamic may breed conflict between developed and developing countries.

Ambiguous or unknown intent could stimulate conflict as well. For example, if one country were to implement OIF and the resulting phytoplankton bloom drifted into the territorial waters or exclusive economic zone of another country, this other country may view the climate intervention as aggression. Similarly, if one country were to implement SAI, another country adversely impacted by the resulting localized precipitation changes may think that the implementing country deliberately caused the changes.

Summary

Weighing the relative national and global security benefits and risks of pursuing SAI, pursuing OIF, or not pursuing either climate intervention is a daunting undertaking—and it does not lead to definitive results, primarily owing to the many unknowns. Future work comparing these benefits and risks will need to account for large uncertainties in (1) climate change and regional variances; (2) climate impacts on national security; (3) the effectiveness of SAI and OIF in countering some or all climate change impacts; and (4) the possibility and consequences of other direct SAI and OIF impacts on national security. All four are active areas of research, with the exception of possible impacts to DOD-specific infrastructure or operations, which is understudied.

Potential Actors in Climate Intervention

National security implications of climate intervention can also be gleaned by considering the various actors likely to play a significant role in plausible future climate intervention scenarios. Careful study of these expected actors may reveal insights on determining possible motivations, strategies, and overall likelihood of a large-scale climate intervention deployment. Exploration of these actors and possible climate intervention scenarios could also illuminate how the United States could or should respond if any of these actors pursues climate intervention.

In this section, we provide profiles of such actors in two broad categories: nation-states and non-states. Although a detailed study of these actors is beyond the scope of this work, the case study in Appendix C

[66] Rabitz, "Going Rogue?"

explores China's strategic interest and research in climate intervention.

Nation-State Profiles

The United States should examine how to respond appropriately when weighing the risks from other countries that pursue climate intervention. This examination entails asking complicated questions, such as whether and how the United States should seek to influence or counter other countries' climate policies that may be in opposition to our own future national security interests or whether and how the US government should articulate principles that can guide, safeguard, and enforce future exploratory research efforts.

Plausible future nation-state profiles include, but are not limited to, the following:

- A great-power country unilaterally pursuing research on or deployment of climate intervention
- One or multiple middle- or small-power countries pursuing research on or deployment of climate intervention
- One or multiple great-power countries attempting to prevent or forestall climate intervention governance or use
- One or multiple non-great-power countries attempting to prevent or forestall climate intervention governance or use
- A nation-state attempting to prevent (or unduly promote) climate intervention by manipulating public opinion (in the form of influence, information, or disinformation campaigns)
- One or multiple great-power countries responding with military action to deployment or potential deployment of climate intervention

Nation-states have the potential to unilaterally, or in concert with others, deploy or forestall climate intervention. While wealthier and more powerful countries generally command the most attention on the world stage, a number of developing countries have both the motivation and means to affect future climate intervention governance, research, and possible use.

Non-State Profiles

A number of plausible non-state actor(s) might become involved in climate intervention activities without the authorization, or even the knowledge, of any nation. These include, but are not limited to, the following:

- Environmentalists, activists, or philanthropists pursuing climate intervention in an effort to stall climate change
- Violent extremist organizations using climate intervention against their adversaries
- Corporations, fishers, or farmers engaging in climate intervention to improve their productivity
- Corporations involving themselves in climate intervention activities or allowing other companies or governments to invest in climate intervention as a tactic to be "carbon neutral"
- Researchers pursuing climate intervention research without government funding or approval
- Environmentalists, activists, philanthropists, or violent extremist organizations who oppose geoengineering and attempt to prevent related activities through the legal system, public opposition, sabotage, or violence

Examples of non-state actors conducting climate intervention activities already exist. In a small-scale atmospheric aerosol deployment in 2022, a US start-up, Make Sunsets, unilaterally released small balloons containing sulfur dioxide in Mexico, leading the country to ban SRM in its jurisdiction.[67] Another example, described in the sidebar, involves the Haida Salmon Restoration Corporation.

[67] Garrison, "Insight."

The 2012 Haida Salmon Restoration Corporation Incident

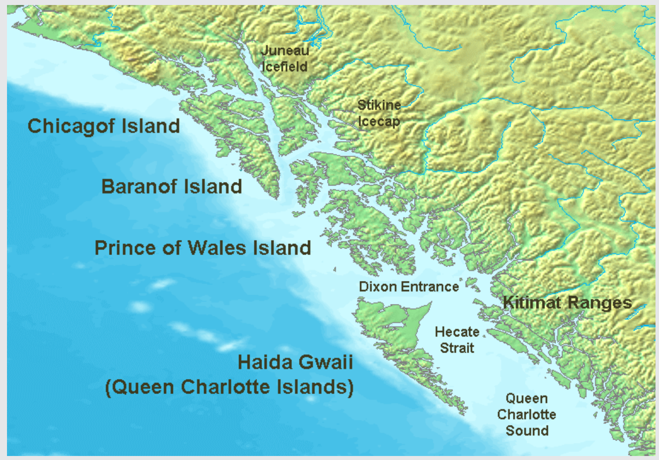
In July 2012, a Haida Salmon Restoration Corporation (HSRC) team chartered a fishing boat, loaded it with iron-containing compounds (iron sulfate and iron oxide),[68] and transited to the Haida Eddies, hundreds of miles west of Haida Gwaii (an archipelago off the coast of British Columbia; Figure 4). There, they mixed the iron compounds with seawater and dumped them into the ocean in a zigzag pattern across a wide patch of water. They returned in August to repeat the fertilization. Their aim was to promote phytoplankton growth and, in turn, increase the population of salmon to support the Haida Nation's fishing industry. HSRC also planned to sell carbon emission offset credits from the sequestration of carbon resulting from the phytoplankton bloom.

Immediately after the dumping, a large phytoplankton bloom covering over 10,000 square miles occurred, as detected by satellite data.[69] A year later, the Alaska Department of Fish and Game reported a record salmon harvest, with high salmon values particularly in southeast Alaska, an area the Haida Eddies would supply.[70]

HSRC pointed to this as proof of the operation's success. However, other scientists were more skeptical and noted difficulties in determining the causal relationship between the phytoplankton bloom and increased fish stocks.[71] Similarly, scientists cautioned that it is hard to calculate the amount the carbon that may have been sequestered permanently by the phytoplankton.[72] Villagers on Haida Gwaii also expressed concerns about potential side effects when observing red tides after the incident.[73]

The legality of this operation is unclear. Many have condemned the operation as a violation of both the London Convention and Protocol and the Convention on Biological Diversity (CBD).[74] However, the London Convention and Protocol is applicable only to dumping waste material, and the CBD is not legally binding and allows for exceptions with regard to experimentation. The operation may have violated Canadian environmental laws, however, as Canada's environmental agency stated that HSRC had not acquired the necessary permits before its expedition.[75]

This incident highlights several key issues with climate intervention: uncertain scientific effectiveness, potential harmful side effects, and a lack of clearly defined legal restrictions.



Credit: en:User:Koba-chan, CC BY-SA 3.0, http://creativecommons.org/licenses/by-sa/3.0/, via Wikimedia Commons

Figure 4. Map Showing Haida Gwaii, the Location of OIF in 2012

[68] Biello, "Hacker Speaks Out,"

[69] Rabitz, "Going Rogue?"; Service, "Legal?"; and Xiu, "Satellite Bio-optical and Altimeter Comparisons."

[70] Alaska Department of Fish and Game, "2013 Salmon Harvest."

[71] Service, "Legal?"

[72] Service, "Legal?"

[73] Falconer, "Can Anyone Stop?"

[74] Service, "Legal?"

[75] Tollefson, "Ocean Fertilization Project."

Means of Influencing or Controlling Climate Intervention Use

Given that a variety of actors could undertake climate intervention activity with national security implications, what are the options for influencing or controlling such actors? While existing law touches on climate intervention (discussed later), there is no comprehensive governance including specific measures. Below is a brief discussion of possible measures.

Sanctions

In addition to potentially being included as part of any global governance system, sanctions can be used to deter or encourage nation-states, individuals, corporations, and other non-state entities with respect to researching, testing, deploying, or misusing climate intervention. Such sanctions could be criminal, civil, or economic, and the United States could seek to impose them unilaterally, together with like-minded countries, or through international treaties or conventions.

Transnational and National Financial Liability

Imposition of financial liability for environmental damage could inhibit corporate, philanthropic, or other actors from pursuing climate interventions. For liability to be an effective deterrent, however, especially for corporations, the financial penalties would typically need to be equivalent to or greater than the gains from climate intervention. This is not the norm; historically, liability standards have seen "haphazard incorporation into public international law," and victims of environmental harm face obstacles to holding polluters liable, even under domestic law.[76] Two significant factors in controlling non-state actors' participation will be "states' receptiveness to entertain lawsuits by foreign plaintiffs and the development of reciprocity standards for the recognition of foreign judgments."[77] Precedent does exist.[78]

Limiting Certain Chemical Availability

A potential option for limiting domestic non-state actors' research and use of climate intervention is constraining or controlling the availability of required chemicals. This approach would likely be ineffective, however, in cases where the chemicals could be procured from other countries, though import bans or other trade measures may address this. Moreover, some of the chemicals occur naturally or are used in everyday products, such as salt from seawater or calcium carbonate (used in antacids, food coloring, and fertilizer).[79]

Sensing

Detecting the implementation of a climate intervention technique through sensing (or other means) would enable the other controlling methods described here. Sensing coupled with attribution of the actor could prove effective in holding actors accountable. Different climate intervention methods may require different sensing schemes.

Summary

The possibility of future climate interventions presents daunting new challenges in many areas, including the national security realm. Certain riskier and controversial methods may impact several

[76] Percival, "Liability for Environmental Harm."

[77] Percival, "Liability for Environmental Harm."

[78] Varvastian and Kalunga, "Transnational Corporate Liability." However, in 2019, "the Supreme Court of the United Kingdom delivered judgment in the case of *Vedanta v. Lungowe*, which concerned the liability of an English company for environmental damage caused by its subsidiary in Zambia. The decision confirms that English parent companies can owe a duty of care to foreign claimants affected by operations of their subsidiaries abroad and that the English courts may have jurisdiction to hear such cases, even when a foreign court is a more appropriate place for the trial."

[79] NCBI, "Calcium Carbonate."

Credit: Lamiot, CC BY-SA 3.0 (https://creativecommons.org/licenses/by-sa/3.0), via Wikimedia Commons

Figure 5. Flags of the Parties to the Convention on Biological Diversity (CBD) in 2015

aspects of national security, from geopolitical stability to the operational environment and critical infrastructure. The US national security policy community will need to consider and address these implications soon to ensure that the nation is fully prepared to respond if and when climate engineering technologies are ever deployed.

Experts and activists who are concerned about the lack of governance of ongoing climate intervention activities differ widely on their recommendations.

Governance and Principles for Climate Intervention National Security

One avenue for addressing the national security implications of climate intervention is through governance and policy actions that decrease risks and promote responsible development, testing, deployment, and monitoring of climate intervention methods. As noted, some international and domestic law is relevant to climate intervention, but comprehensive governance does not exist. However, multiple governance schemes have been proposed. We reviewed relevant domestic and international laws and proposed governance initiatives to identify gaps in governance and formulate principles specific to national security.

Current State of Governance

A substantial body of both international and domestic law has significant relevance to activities similar to those of climate intervention. These laws may serve as the point of departure for developing proposed governance regimes both domestically and internationally.[80]

International Law

Environmental law, human rights law, and the law of war are the primary sources of substantive international law typically cited as applicable to climate intervention. While these sources are useful, they may not touch on all climate interventions and may be difficult to enforce.[81] Two international measures, the London Convention/Protocol and the Convention on Biological Diversity (CBD; Figure 5), directly address climate intervention or particular methods and call for certain actions and norms to be followed. Leading sources of relevant treaty law are highlighted in Table 3.

[80] Grisé et al., *Climate Control*; and Irving, "Geopolitical Risks."

[81] Florin et al., *International Governance Issues*; Grisé et al., *Climate Control*; NRC, *Reflecting Sunlight;* SilverLining, *Ensuring a Safe Climate*; and Versen, *Preparing the United States*.

Table 3. Sources of Applicable International Law

	Law	Relevance to Climate Intervention
Environmental law: Either addresses the atmosphere or ocean specifically or simply provides a broad framework for protecting the environment	Convention on Long-Range Transboundary Air Pollution (CLRTAP)	Monitors air pollution's direct impacts on human health and activity
	Vienna Convention for the Protection of the Ozone Layer	Prohibits activities in the ozone layer that could adversely affect human health and the environment
	United Nations Convention on the Law of the Sea (UNCLOS)	Governs essentially all activities on and below the world's oceans
	Convention on Biological Diversity (CBD)	Posits that potential negative effects of geoengineering would impact biodiversity and ecosystems; requests governments to forgo activity until sufficient scientific knowledge is gained; notes lack of regulatory mechanism[a]
	London Convention and London Protocol	Regulates the deposition of materials in the oceans
	United Nations Framework Convention on Climate Change (UNFCCC)	Works to prevent and recover from anthropogenic damage to the climate through research, conferences, and agreements
	Environmental Modification Convention (ENMOD)	Explicitly prohibits weaponizing the environment
Human rights law: Interprets, recognizes, and assures human rights as a function of complex political processes	Paris Agreement	Advances that when addressing climate change, states should "respect, promote and consider their respective obligations on human rights"[b]
	International Covenant on Civil and Political Rights (ICCPR)	Together these covenants establish certain basic prerequisites for freedom, including a stable global climate and a range of other environmental parameters essential to sustaining human livelihoods
	International Covenant on Economic, Social and Cultural Rights (ICESCR)	

[a] CBD, Decision X/33. [b] Paris Agreement, 2.

Certain international norms and principles within these and other agreements have important applicability to climate intervention:

- No-harm rule—Notes that state actors are responsible for ensuring that activities within their jurisdiction or control do not damage the environment of other states or the "global commons"[82]
- Precautionary principle—Advances that cases involving the possibility of irreversible harm require decision-making that weighs long-term, cumulative, or uncertain outcomes[83]
- Sustainable development norm—Seeks to advance sustainable development by addressing equity across time, sustainable use of natural resources, and the integration of environment and development[84]
- Environmental procedural rights—Includes rights to information, participation, and access to justice[85]

In addition to legal precedent and norms, numerous intergovernmental organizations have current de facto or widely anticipated future roles in climate intervention governance. Leading examples within the United Nations system include not only the Intergovernmental Panel on Climate Change but also the following organizations:

- United Nations Environment Programme

[82] UNFCC.

[83] UN General Assembly, "Report."

[84] Emas, "Concept of Sustainable Development."

[85] UN General Assembly, "Report."

- United Nations High-level Political Forum on Sustainable Development
- World Meteorological Organization
- World Health Organization
- Food and Agriculture Organization of the United Nations
- International Maritime Organization
- International Law Commission

Another key intergovernmental organization is the International Energy Agency established by the Organisation for Economic Co-operation and Development.[86] The US national security community should consider the future roles of such organizations in helping to address climate intervention issues.

Domestic Law

There is currently no formalized US regime that specifically addresses or comprehensively governs contemplated climate interventions. A recent congressional mandate,[87] however, directed a group of agencies to coordinate research into climate intervention. In response, the White House Office of Science and Technology Policy is preparing to conduct a five-year scientific assessment of climate interventions.[88]

The most important sources of relevant domestic law relate primarily to various environmental protections. One of the most directly applicable examples is the Weather Modification Reporting Act of 1972. This law requires reports to the National Oceanic and Atmospheric Administration (NOAA) detailing "any activity performed with the intention of producing artificial changes in the composition, behavior, or dynamics of the atmosphere."[89] NOAA then makes these reports available to the public.[90] Other leading federal statutes include the following[91]:

- National Environmental Policy Act
- Clean Air Act
- Clean Water Act
- Endangered Species Act
- Marine Mammal Protection Act
- Magnuson–Stevens Fishery Conservation and Management Act
- Marine Protection, Research and Sanctuaries Act

Aspects of domestic tort, property, and contract law also apply to certain activities or impacts associated with climate interventions.

Analogous to the international realm is a wide range of federal executive branch agencies with relevant legal and regulatory authorities. Key examples include the following:

- Environmental Protection Agency
- NOAA
- National Aeronautics and Space Administration (NASA)
- Departments of
  - Commerce
  - Defense
  - Energy
  - Health and Human Services

86 Florin et al., *International Governance Issues*.

87 "Division B"; and White House, "Congressionally-Mandated Report."

88 USGRP, "Request for Input."

89 Weather Modification Reporting Act of 1972, 15 U.S.C. § 330 (1976).

90 NOAA, "Weather Modification Project Reports."

91 NRC, *Reflecting Sunlight*.

– Homeland Security
– the Interior
– Justice
– State
– Transportation

Both the federal legislative and judicial branches may also be involved in climate intervention considerations.

Proposed Governance Initiatives

Experts and activists who are concerned about the lack of governance of ongoing climate intervention activities differ widely on their recommendations. Some insist that a robust international governance regime must be in place before any further research is conducted, owing to climate interventions' potential to trigger catastrophic transboundary consequences. Others have drafted governance principles or voluntary codes of conduct with a view to orchestrating their adoption before any large-scale climate intervention deployment is likely.[92] Still others maintain that there is no practical way to design an effective governance regime for any given climate intervention technology until much more is known about that technology's feasibility, risks, and controls. Finally, there are those who assert that existing laws and institutions essentially provide much of the required governance, particularly with respect to atmospheric climate intervention approaches, and that research and development should proceed in the hope that climate intervention options are available in time should they prove essential.[93]

Over the past several decades, virtually all of the various governance initiatives have involved at least some degree of international collaboration. Efforts span governance of basic research and field testing to actual use and deployment of climate intervention technologies. Some proposals champion goals related to the technical means of achieving an intervention, placing much less emphasis on health, environmental, and economic outcomes, while others prioritize human safety and the sustainability of the complex global ecosystem.[94] Several key contributions toward climate intervention governance are highlighted in Table 4. Our understanding is that, so far, none of the proposed governance frameworks has been formally adopted or otherwise implemented to any significant extent.[95]

Armed with understanding of the types of climate intervention methods and governance, we can begin to address the physical and policy implications from a national security perspective.

Adapting Principles

As the governance considerations and possible national security implications show, climate intervention is indeed a complex issue. What guiding principles would help ensure that relevant US national security interests are protected (in the context of overall national interests) in the event of climate intervention being pursued by any actor?

By reviewing and categorizing the national security implications presented above, we derived potential actions or approaches to advance national security interests. We then mapped these actions or approaches to relevant principles from research into governance initiatives, such as the Oxford Principles, and adapted them to the national security realm. Members of the national security community can advocate for and champion this national security–specific subset of principles.

92 Rayner et al., "Oxford Principles"; and Gardiner and Fragnière, "Tollgate Principles."

93 SilverLining, *Ensuring a Safe Climate*; and Versen, *Preparing the United States*.

94 SilverLining, *Ensuring a Safe Climate*.

95 NRC, *Reflecting Sunlight*.

We detailed a set of common climate intervention implications throughout civilian systems, critical DOD infrastructure and readiness, and the operational environment. We noted that climate intervention could decrease some risk to national security activities by decreasing the effects of climate change. The likelihood and degree of any risk reduction, however, is highly uncertain. Conversely, we discussed how climate intervention could increase risks to the national security areas

Table 4. Governance Initiative Highlights

Initiative	Summary
Oxford Principles	First seminal contribution, focused only on geoengineering research, and advances five principles: geoengineering to be regulated as a public good; public participation in decision-making; disclosure of research and open publication of results; independent assessment of impacts; and governance before deployment[a]
Tollgate Principles	Captures many ethical questions the authors believe must be addressed; in contrast to the Oxford Principles, intended to address the full spectrum of climate intervention activities, from research to field testing and development to possible deployment[b]
Carnegie Climate Governance Initiative	Promotes development of effective governance for climate-altering technologies, in particular for SRM and large-scale CDR[c]
Study on Gaps in the International Regulatory Framework on Geoengineering	Commissioned in 2010 by the CBD Secretariat, this study, conducted by the Ecologic Institute, explores gaps in the international regulatory framework for geoengineering to assess the extent to which the CBD framework can be applied to geoengineering[d]
Geoengineering Monitor	Provides "critical perspectives" on climate engineering to "serve as a resource for people around the world who are opposing climate geoengineering and fighting to address the root causes of climate change instead"[e]
Degrees Initiative	Supports developing countries and emerging economies in building their capacity to evaluate SRM alternatives and then participate in the dialogue about their governance[f]
Consortium for Science, Policy and Outcomes (CSPO)	Assists experts and decision-makers in benefiting from relevant insights and priorities of the public, particularly with respect to alternative governance approaches for SRM technologies[g]
International Risk Governance Center (IRGC)	Contributed a recent comprehensive report, *International Governance Issues on Climate Engineering: Information for Policymakers*, that was prepared with Swiss government support and offers a useful framework to guide the anticipated critical global decision process with respect to geoengineering research, policy, regulation, and possible use[h]
Geoengineering Research Governance Project	Published *A Code of Conduct for Responsible Geoengineering Research*, which tracks generally with the Oxford and Tollgate Principles and calls for a moratorium on the actual use of geoengineering, with the exception of responsible research, until there is an adequate scientifically based justification and due consideration of environmental and other secondary effects; also acknowledges the risk of not developing climate intervention given slow progress in mitigating climate change[i]
National Academies of Science, Engineering, and Medicine	Published a comprehensive report calling for the United States to establish a major transnational solar geoengineering research program and offering a blueprint for how to both structure the program and ensure that research is conducted responsibly by using various "governance mechanisms" that reflect earlier mainstream work[j]
Climate Overshoot Commission	A panel of global leaders on climate change offering principles and ideas to prevent overshoot (the global mean temperature reaching above the limits defined by the Paris Climate Agreement); calls for the development of CDR methods (though specific methods are not mentioned) and a moratorium on deployment and large-scale outdoor research on SRM methods[k]

[a] Rayner et al., "Oxford Principles." [b] Gardiner and Fragnière, "Tollgate Principles." [c] https://www.c2g2.net/. [d] Williamson and Bodle, *Update on Climate Geoengineering*. [e] Geoengineering Monitor, "Who We Are." [f] Degrees Initiative, "About." [g] CSPO, "Democratic Governance." [h] Florin et al., *International Governance Issues*. [i] Hubert, "Code of Conduct." [j] NRC, *Reflecting Sunlight*. [k] Climate Overshoot Commission, *Reducing the Risks*.

we surveyed. There are large uncertainties around this possibility too. These uncertainties point to a need for further research to comparatively assess potential positive and negative consequences. Thus, we derive two principles for these national security concerns:

- **Principle 1: The precautionary principle**—This principle from international law fits well with climate intervention and benefits national security. The benefits of any climate intervention method need to be weighed against all options and assessed for risk to mitigate irreversible harm. Resolving climate change impacts has benefits to national security, and climate intervention methods could play important roles in that resolution. However, unknowns and potential negative impacts to national security demand caution. Adoption of this principle may delay or even preclude the use of some methods.
- **Principle 2: Rigorous assessment inclusive of national security equities**—Lack of knowledge still plagues many of the proposed climate intervention methods, especially those that could have outsized consequences for national security, such as SAI. This principle extends the fourth Oxford Principle of independent assessment of impacts[96] to emphasize the national security elements in these assessments.

Effects of climate intervention methods, such as injecting aerosol into the atmosphere (SAI) and fertilizing the ocean with iron (OIF), can damage civilian systems across borders. For example, OIF could cause toxic algal blooms in multiple countries' maritime territories. This risk calls for greater awareness of maritime health across countries. As discussed, geopolitical conflict is another risk of implementing climate intervention methods. Because most nation-states could crudely implement SAI and OIF and implementation could affect large geographic areas, unilateral action could foster conflict. Inequitable distribution of costs related to climate intervention is yet another possibility, and this could also foster conflict. These implications illuminate the need for collaboration among nations to alleviate potential tensions around climate intervention. For example, engagement with China on climate intervention principles could increase transparency (refer to Appendix C). This leads to the next principle:

- **Principle 3: International collaboration**—Collaborative climate intervention research and development, deployment, and regulation can expand international buy-in for climate intervention (if warranted), increase geopolitical stability, and mutually promote the objectives of multiple nations.

As discussed, SAI and OIF could be at least crudely implemented by most nations, some non-state entities, and even some individuals in certain cases. Unilateral actors could foster conflict and diplomatic disputes by pursuing climate intervention clandestinely against the wishes of other actors. Visibility of unauthorized methods could help discourage actors from trying to implement a measure or could stop a deployment at its beginning. For example, the earlier-described 2012 Haida Salmon Restoration Corporation (HSRC) incident in the Pacific Northwest upset authorities, but it was quickly discovered. Even if there is tentative agreement on an acceptable climate intervention method to deploy, the way in which a method is researched or deployed could signal ambiguous intent. This brings us to another principle:

- **Principle 4: Observability and transparency**—Prioritizing means that can be easily monitored

[96] "Principle 4: Independent assessment of impacts. An assessment of the impacts of geoengineering research should be conducted by a body independent of those undertaking the research; where techniques are likely to have transboundary impact, such assessment should be carried out through the appropriate regional and/or international bodies. Assessments should address both the environmental and socio-economic impacts of research, including mitigating the risks of lock-in to particular technologies or vested interests" (Rayner et al., "Oxford Principles").

and observed could allay national security concerns and better forge international agreement. As the 2012 Pacific Northwest OIF incident demonstrated, unilateral incidents can be better managed when methods are easily monitored. Furthermore, governance in general would be enhanced if supported by a monitoring regime. Admittedly, international monitoring regimes can be difficult to establish. A role for civil society in monitoring regimes may prove helpful, as would monitoring capabilities that can be used outside of potentially inaccessible territory. Making sensing as easy as possible may simplify means of influencing climate intervention.

The Pacific Northwest OIF incident also showed that the potential interest in climate intervention extends beyond nation-states. We discussed the potential for non-state actors, including environmentalists and philanthropists as well as corporate and business interests, to engage in climate intervention. These actors and their activities can also have security implications. To manage competing interests, we can borrow another principle from the Oxford Principles:

- **Principle 5: Climate intervention as a public good—**The first Oxford Principle[97] in particular supports national security. Climate intervention pursuits need to balance government regulation and private participation. The 2012 Pacific Northwest OIF incident raised questions about the dangers of unrestrained implementation without a consensus.

We also noted that, in the area of civilian systems, the two climate intervention methods we investigated have limitations. SAI, for example, does not address the risk to carbon dioxide concentrations in the atmosphere and some of the non-heat-related effects, such as ocean acidification. OIF may have limited impact depending on how it is implemented. And, pursuing only SAI or OIF may undermine government efforts in climate change adaptation and mitigation. These methods' non-heat-related limitations would necessitate use of other or additional methods to address climate change. Thus, a sixth principle:

Because research and implementation of climate intervention has the potential to affect national security, the national security community should be part of the conversation.

- **Principle 6: Moral hazard mitigation—**Calls for climate intervention, even in the national security space, may draw investment away from mitigation and adaptation strategies, which are also crucially important to national security.

As noted, new civilian systems and infrastructure, such as delivery and sustainment systems, may be needed to support SAI and OIF. We would then need to defend and protect this new infrastructure. Depending on how the climate intervention technique is implemented with other climate change–fighting strategies, we may also need to counterbalance a potential dependence on this infrastructure. This brings us to the following principle:

- **Principle 7: Dependency hazard mitigation—**The potential for termination shock has been a prominent argument against climate intervention. Because preventing termination shock is a national security interest, climate intervention systems and infrastructure would be considered critical infrastructure that requires protection.

[97] "Principle 1: Geoengineering to be regulated as a public good. While the involvement of the private sector in the delivery of a geoengineering technique should not be prohibited, and may indeed be encouraged to ensure that deployment of a suitable technique can be affected in a timely and efficient manner, regulation of such techniques should be undertaken in the public interest by the appropriate bodies at the state and/or international levels" (Rayner et al., "Oxford Principles").

Recommendations, Conclusions, and Potential Paths

In light of the national security implications and adapted principles discussed in this report, we close by offering the following recommendations:

- Consistent with the characterization of climate intervention as a global good, develop and implement a synergistic framework of public and private-sector roles and responsibilities, along with a robust system of governance. The Office of Science and Technology Policy recommendation that the US Global Change Research Program (USGCRP) coordinate is appropriate, and coordination should include DOD equities, as it does for climate change issues writ large. Engagement with the United Nations will also be important.
- Prioritize and advocate for climate intervention methods that are easy to monitor and explore ways to make otherwise hard-to-detect methods more easily detectable. Organizations such as USGCRP and some of the agencies it coordinates (particularly NOAA and NASA) may be in strong positions to advance the need for detectability.
- Focus, organize, and resource the US Intelligence Community to closely and comprehensively monitor climate intervention activities.
- Recognize the potential harms of terminating a climate intervention on which the global environment could become dependent and develop ways to mitigate risks. This research and analysis could be led by USGCRP and the agencies it coordinates.
- In developing mitigation measures, explore the vulnerabilities of and required protection for climate intervention–related infrastructure. The Cybersecurity and Infrastructure Security Agency could lead this effort.

Climate intervention encompasses a wide variety of methods to address the effects of some of the worst climate change scenarios. While some climate intervention methods are noncontroversial and are of little concern, others, such as SAI or OIF, have the potential to harm the environment, economic activity, and human health, potentially leading to conflict. Furthermore, potential changes shaped by climate intervention could affect the operational environment, critical infrastructure, and homeland security along the same lines as climate change itself. As climate intervention is increasingly seen as a possible solution or part of the solution to the climate change crisis, discussion of intervention will likely increase in the not-too-distant future. Because research and implementation of climate intervention has the potential to affect national security, the national security community should be part of that conversation.

Quite a few paths can extend from this original examination of the intersection of climate intervention and national security. The implications for the operational environment, critical infrastructure, and situational awareness in particular present opportunities for more technical analysis to explore the degree of impact and to determine ways to ameliorate the challenges. Because sensing and monitoring is both a challenge and a way to support governance, a natural next step might be to examine ways to sense certain controversial methods and study the framework behind how the information could be acted on. Another step, in the area of policy, could be a deeper look at how the particular laws and norms around sea governance and other areas could apply to a climate intervention governance regime. As the march to ever-warmer global average temperatures continues, these and other avenues can help to address, manage, and regulate this emerging and consequential approach to climate change.

Appendix A Review of Climate Intervention Methodologies

This appendix provides an overview of solar radiation management (SRM) and carbon dioxide removal (CDR) methods. This information is summarized in Table 1 and Table 2 in the main report.

Stratospheric Aerosol Injection

Stratospheric aerosol injection (SAI) involves introducing liquid or solid particles[98] into the atmosphere so that they can reflect a small fraction of incoming sunlight back into space. It is one of the leading and most-studied proposed SRM methods, as it closely mimics the effects of large volcanic eruptions. For example, the 1991 eruption of Mount Pinatubo in the Philippines spewed approximately thirty-three billion pounds of mainly sulfur dioxide into the atmosphere. These particles remained in the atmosphere for about two years, resulting in heterogeneous cooling by approximately 0.6 degrees Celsius for the following fifteen months. Theory and modeling estimates indicate that increasing the number of aerosols in the stratosphere (about eight to eighteen kilometers above Earth's surface) would effectively reduce the amount of sunlight reaching the planet and result in a net cooling effect of the atmosphere below the layer of suspended particles. Additionally, particles suspended at lower altitudes in the stratosphere are predicted to have a lifetime on the order of years, as opposed to days or weeks, implying that a smaller proportion of materials would be required to produce a similar amount of cooling. The estimated implementation costs are approximately $2 billion to $11 billion annually.[99] Researchers speculate that, of the four main SRM methods, SAI has the greatest potential to realize the largest global benefits with the fewest risks and at a cost within reach.[100]

Most research to date has focused on two modeling efforts. First, as part of the Geoengineering Model Intercomparison Project (GeoMIP),[101] researchers modeled how reducing the amount of sunlight reaching Earth's surface affects both global mean temperature and precipitation patterns. The majority of models compared in GeoMIP agree that reducing atmospheric sunlight absorption would be sufficient to return the global average surface temperature to a preindustrial state. The sunlight reduction may also decrease precipitation levels, particularly in the warm tropic regions of the world. Second, researchers simulated a variety of effects of injecting increasing loads of sulfate-based aerosols into the stratosphere,[102] exploring homogeneous versus inhomogeneous sulfate aerosol distribution, sulfate aerosol particle size, sulfate

[98] A range of reflective aerosol materials have been proposed, including sulfate (sulfuric acid and sulfur dioxide) aerosols, calcite (calcium carbonate), titania (titanium dioxide), alumina (aluminum oxide), and diamond particles, among others.

[99] Rigorous cost analyses have not been conducted for this method, however. Current efforts mainly focus on annual costs for delivery of material into the atmosphere/stratosphere to reflect approximately one to five watts per square meter of solar radiation. Smith and Wagner, "Stratospheric Aerosol Injection Tactics"; and SilverLining, *Ensuring a Safe Climate*.

[100] NRC, *Reflecting Sunlight*.

[101] Kravitz et al., "Climate Model Response."

[102] Rasch, Crutzen, and Coleman, "Exploring the Geoengineering of Climate"; Heckendorn et al., "Impact of Geoengineering Aerosols"; Niemeier, Schmidt, and Timmreck, "Dependency of Geoengineered Sulfate Aerosol"; and Pitari et al., "Stratospheric Ozone Response."

aerosol geographic distribution, and the risks of dependence on and abrupt termination of SAI.[103] Although results from these efforts largely suggest that SAI has the potential to reduce the effects of local and global climate change, researchers have identified several risks associated with sulfate use:

- Ozone loss due to increased sulfuric acid concentration in the stratosphere[104]
- Difficulties in producing sufficient negative radiative forcing[105] owing to a loss in efficiency at higher sulfate concentrations[106]
- Stratospheric heating that would increase water vapor content, thereby exacerbating ozone loss and positive radiative forcing
- Increased diffuse radiation,[107] which could potentially alter atmospheric chemistry and ecosystem functioning[108]

More recently, researchers modeled injecting solid aerosol particles, such as alumina (aluminum oxide) or diamond, as alternatives to sulfate aerosols because of their improved scattering properties.[109] Preliminary results detail that an annual injection of four metric tons of alumina particles with radii of approximately 240 nanometers would provide the most radiative forcing (approximately 1.3 watts per square meter) without aggregation or sedimentation.[110] Similar radiative forcing can be achieved by injecting 160 nanometer-sized diamond particles at a rate of two metric tons per year. In both cases, researchers determined that injection of an equivalent mass of solid or aerosol sulfate particles can achieve a negative radiative forcing of approximately minus two watts per square meter, although stratospheric heating, ozone depletion, and diffuse radiation scattering is more severe with the sulfate materials. Ultimately, modeling shows that solid particles may provide advantages over sulfate aerosols, but further study on their radiative properties and reaction kinetics under stratospheric conditions is warranted.

103 Ricke, Morgan, and Allen, "Regional Climate Response"; and Ricke et al., "Effectiveness of Stratospheric Solar-Radiation Management." Simulation results for SAI's effect on global temperature and precipitation reductions were found to be broadly consistent with GeoMIP results. Proposed aerosol materials have an atmospheric lifetime of about one year or less, implying that injection would need to be renewed continuously to maintain global mean temperature and precipitation effects.

104 The increased sulfuric acid content is the result of hydrolysis reactions between sulfate aerosols and existing water vapor in the stratosphere.

105 Radiative forcing is defined as the balance between the receipt of incoming energy from the sun and the loss of energy back into space. Warming results when Earth receives more incoming energy than it radiates (positive radiative forcing), whereas cooling occurs when Earth loses more energy to space than it receives from the sun (negative radiative forcing).

106 Heckendorn et al., "Impact of Geoengineering Aerosols."

107 Diffuse radiation describes solar radiation that has been absorbed, scattered, or reflected by atmospheric molecules or particles. Direct radiation, on the other hand, describes solar radiation that reaches Earth's surface without being diffused.

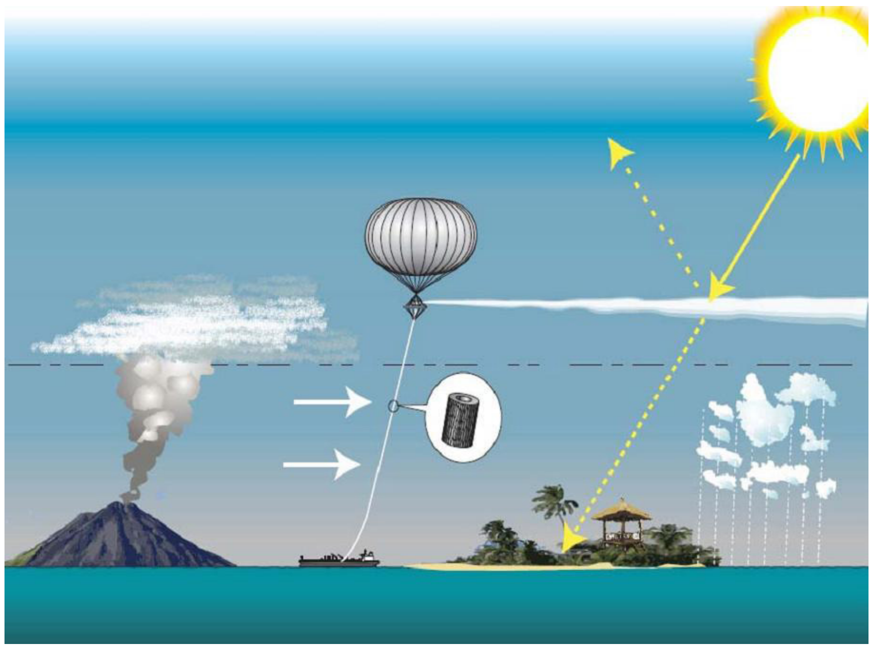
108 Wilton, Hewitt, and Beerling. "Simulated Effects."

109 Weisenstein, Keith, and Dykema, "Solar Geoengineering Using Solid Aerosol in the Stratosphere."

110 Aggregation occurs when the interparticle forces that separate and stabilize suspended particles become weakened and, in turn, begin to clump together. Sedimentation occurs when suspended particles become subject to gravitational forces (in some cases due to aggregation) and fall or settle out of solution.

Several outdoor experiments investigated the feasibility of injecting aerosols into the stratosphere. Two major experiments are Stratospheric Particle Injection for Climate Engineering (SPICE)[111] and Stratospheric Controlled Perturbation Experiment (SCoPEx).[112]

SPICE (Figure A-1), a 2010–2012 UK government–funded research project, explored the viability of injecting aerosols into the atmosphere. The proposed delivery system, consisting of a ship-tethered hose lofted by a balloon, would have pumped approximately 150 liters of pure water into the atmosphere at an altitude of approximately one kilometer above a deserted field. SPICE was canceled primarily because several of its researchers filed a patent separately, spurring perceptions of a conflict of interest, but lack of government regulation was an additional concern.[113]



Credit: Hughhunt, CC BY-SA 3.0 (https://creativecommons.org/licenses/by-sa/3.0), via Wikimedia Commons

Figure A-1. The Proposed SPICE Experiment

SCoPEx, initially launched in 2019 by researchers at Harvard University, aims to improve estimation of SAI's physical impacts on moderating climate change. The researchers propose to do this by understanding the optical properties of different aerosol materials and the microphysical properties associated with introducing particles into the stratosphere. The experiment involves delivering a high-altitude balloon (equipped with a water-filled container) approximately twenty kilometers into the atmosphere. One hundred grams to two kilograms of water will be released from the balloon to create a plume approximately one kilometer

[111] Hale, "Geoengineering Experiment Cancelled"; Marshall, "Field Test Cancelled"; and Watson, "Testbed News."

[112] Geoengineering Monitor, "Stratospheric Aerosol Injection"; Keutsch Group at Harvard, "SCoPEx"; and SCoPEx Advisory Committee, "About."

[113] Hale, "Geoengineering Experiment Cancelled."

long and one hundred meters in diameter.[114] The balloon will then be used to measure resulting changes in the plume, such as changes in air density, atmospheric chemistry, and light scattering. The research team formally requested that the SCoPEx advisory committee review plans for a proposed June 2021 platform test in Sweden, but in March 2021 the committee recommended that the platform test be suspended until a more thorough societal engagement process could be conducted and issues related to conducting climate intervention research in Sweden could be addressed. In October 2022, peer reviewers selected by the advisory committee conducted a scientific merit review of the SCoPEx research plan, and the committee produced a summary report based on the reviewers' evaluation. A spring 2024 update from Harvard notes that the SCoPEx principal investigator had ceased work on the experiment and that the experimental platform was expected to be repurposed for non-geoengineering-related scientific research.[115]

The research shows that SAI offers several key benefits over other climate intervention methods. First, there is evidence that the technology would work. SAI would likely mimic natural processes, such as the 1991 Mount Pinatubo eruption mentioned earlier, which decreased Northern Hemisphere surface temperatures by 0.5 to 0.6 degrees Celsius.[116] Moreover, modeling indicates that it could effectively reduce the amount of sunlight reaching Earth's surface.[117] This evidence has led to an international consensus that the method could be effective. In 2018, the United Nations Intergovernmental Panel on Climate Change concluded that "SAI is the most-researched SRM method, with *high agreement* that it could limit warming to below 1.5°C."[118] Additionally, the required technology for implementation (i.e., particle production and delivery) has already been developed and can be easily leveraged.

There are also concerns related to SAI. The panel warned that there remain major uncertainties about the social, environmental, and ecological impacts of SAI implementation. Although sulfate particles are natural, they could potentially affect asthma sufferers if they return to ground level in significant amounts. Moreover, little is known about the toxicity of proposed alternative particle materials, and there is no consensus on acceptable exposure levels. Ensuring particles stay aloft, however, would minimize these effects.

Parties to the October 2010 Convention on Biological Diversity (CBD) have concerns about the effects of SAI on the biological diversity of our planet[119] and have instituted a moratorium on climate intervention.[120]

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114 Planned experiments include injecting other kinds of aerosol materials (calcium carbonate, sulfates, etc.) into the plume to observe their reflective properties.

115 Shaw and Stock, "An Update on SCoPEx."

116 Self et al., *Atmospheric Impact*.

117 Kravitz et al., "Climate Model Response."

118 Masson-Delmotte et al., *Global Warming of 1.5°C*, 350.

119 CBD, "Draft Decisions."

120 At the October 2010 CBD Conference, attendees issued a moratorium on geoengineering and specified the following considerations with respect to the effects on biodiversity: (1) reducing the impacts of climate change on biodiversity and biodiversity-based livelihoods—invited "parties, other Governments and relevant organizations to submit information on synthetic biology and geo-engineering in accordance with the procedures of decision IX/29, for the consideration by the Subsidiary Body on Scientific, Technical and Technological Advice, while applying the precautionary approach to the field release of synthetic life, cell or genome into the environment"; (2) assessing the impact of climate change on biodiversity—"ensure, in line and consistent with decision IX/16 C, on ocean fertilization and biodiversity and climate change, and in accordance with the precautionary approach, that no climate related geo-engineering activities take place until there is an adequate scientific basis on which to justify such activities and appropriate consideration of the associated risks for the environment and biodiversity and associated social, economic and cultural impacts"; and (3) gathering information for review—issued a request for the executive secretary to "compile and synthesize avail-

While observations show that volcanic eruptions likely increase forest growth rates by increasing diffuse solar radiation, their effects on crop yields and other plant growth are uncertain.[121] Modeling has detailed that sulfate aerosol particles (in combination with chlorofluorocarbon gases) could potentially deplete the ozone if high enough quantities drift into or are injected into stratospheric clouds. Additionally, implementation would not directly lower atmospheric carbon dioxide concentration or prevent ocean acidification.

Finally, there are concerns related to the production or procurement of proposed aerosol materials. For example, mining for raw materials subjects workers to harsh working conditions and can deplete the habitat and food of local wildlife, significantly erode soil, contaminate water with toxic mine tailings, and potentially expose humans and wildlife to radioactive materials (refer to Appendix B for details).[122]

Marine Cloud Brightening

Low-lying stratocumulus clouds can act as natural reflectants by efficiently scattering incoming sunlight back into space, leading to speculation that modest changes in cloud lifetime or areal extent might be an effective method to cool the planet.[123] Thus, the premise of marine cloud brightening (MCB) involves the deliberate introduction of benign materials, such as sea salt, into clouds to act as condensation nuclei, thereby increasing the number of droplets that can in turn reflect more sunlight back into space. Commercial cargo ship tracks provide evidence that particle injection can increase cloud albedo (i.e., the fraction of reflected light); as ships emit aerosol particles in their wake, bright areas of clouds form.[124] Although this process is best understood for clouds that lie at the lowest 1.5 kilometers of the atmosphere and contain liquid water as opposed to ice, researchers have found it difficult to model the processes to control cloud droplet formation. Because of this, the capacity for MCB to compensate for large-scale climate change remains largely uncertain. Additionally, the effects would likely be spatially heterogeneous because of cloud location.[125] Deployment costs for MCB are poorly characterized, but the technology and field experiments for an MCB research program (over a seven- to ten-year time frame) are estimated to cost approximately $40 to $50 million, with total costs speculated to be on the order of approximately $11 billion annually.[126]

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able scientific information on the possible impacts of geo-engineering techniques on biodiversity and make it available for consideration at a meeting of the Subsidiary Body on Scientific, Technical and Technological Advice prior to the eleventh meeting of the Conference of the Parties." See CBD, Decision X/33. In follow-on conferences in 2012 and 2016, the attendees further encouraged development of non-geoengineering methods to fight climate change and called for more information. The United States is not a party to the convention.

121 Fan et al., "Crop Yields"; and Pongratz et al, "Crop Yields." The danger of overcompensating should also be considered, as with the significant cooling the Earth experienced in 1816 because of volcanic activity.

122 Most SAI research and atmospheric modeling focuses almost exclusively on injecting aqueous sulfate-based aerosol materials into the stratosphere, but researchers are increasingly considering solid aerosol materials such as alumina (aluminum oxide), diamond, calcite (calcium carbonate), and titania (titanium dioxide). Appendix B details these materials and the environmental concerns related to their production or procurement.

123 Slingo, "Earth's Radiation Budget."

124 Hobbs et al., "Emissions from Ships."

125 Russell et al., "E-PEACE." Low-lying stratocumulus clouds over dark ocean surfaces would be most effective at scattering sunlight back into space. These clouds cover approximately 20 to 40 percent of the world's ocean as a fraction of the daytime annual average.

126 Smith and Wagner, "Stratospheric Aerosol Injection Tactics"; and SilverLining, *Ensuring a Safe Climate*.

As previously described, comparative modeling via GeoMIP suggests that either SAI or MCB could reduce the global mean temperature to that of the preindustrial state while also decreasing precipitation levels.[127] Other research has characterized uncertainties associated with MCB, including measuring the effects of multilayered clouds at the marine atmospheric boundary layer[128] in coastal areas[129] and along ship tracks in the Pacific Ocean.[130] To collect these measurements, researchers used ship-based cloud radar to obtain information on the structure of stratocumulus clouds at the boundary layer. Additionally, several proof-of-concept experiments measured the effect of aerosols on stratocumulus cloud albedo. These experiments provide observational evidence that particles emitted along ship tracks can modify cloud albedo, as well as the frequency at which these modifications occur.[131] Last, studies show that only a small fraction of clouds are affected by controlled particle emissions (this is true even for clouds that were predicted to be highly susceptible to modification). They also demonstrate that particles can last about five to seven days within the troposphere, though ship tracking experiments suggest more modest lifetimes of about one to three days.[132] Given that the magnitude of cooling depends on the areal extent of and particle persistence within stratocumulus clouds, researchers have determined that particle injection would need to be renewed more or less continuously.

As part of the Eastern Pacific Emitted Aerosol Cloud Experiment (E-PEACE), in July–August 2011, University of California San Diego researchers conducted the first known open-air MCB trial off the coast of Monterey, California.[133] Their main aim was to collect data on aerosol cloud–radiation interactions to supplement MCB modeling. The twelve-day experiment involved the controlled release of smoke particles[134] from the deck of a research vessel,[135] salt aerosol from an aircraft,[136] and exhaust from container ships transiting across the study region. The researchers then used embedded aircraft, ship, and satellite observations[137] to

- measure particle and cloud droplet number, mass, composition, and water uptake distributions;
- investigate simulation results for modeling studies;
- test the ability to quantitatively predict cloud dynamical responses to increases in particle concentrations; and
- measure the changes in sunlight reflectance due to the emitted particles effects' on marine stratocumulus clouds.

127 Kravitz et al., "Climate Model Response."

128 The location where the atmosphere directly contacts the ocean.

129 Russell et al., "E-PEACE"; and Schroder et al., "Size-Resolved Observations."

130 ARM, "MAGIC."

131 Coakley et al., "Ship Tracks." Researchers determined that cloud modification occurs about 50 percent of the time during cloudy days in the northeastern Pacific regions.

132 Coakley, Bernstein, and Durkee, "Ship-Stack Effluents."

133 Russell et al., "E-PEACE"; and Geoengineering Monitor, "Geoengineering Map."

134 The smoke particles produced tracks that could be measured by satellite and had drop composition characteristic of organic smoke.

135 *Point Sur* research vessel.

136 Center for Interdisciplinary Remotely-Piloted Aircraft Studies (CIRPAS) Twin Otter aircraft.

137 A-train satellites and Geostationary Operational Environmental Satellite (GOES).

These studies revealed that smoke and ship emissions are effective at modifying cloud albedo and that salt nuclei can increase rates of drizzle production.

Researchers from Southern Cross University and the Sydney Institute of Marine Science performed a second open-air experiment in the open ocean, this one beside Broadhurst Reef near Australia in March 2020. During the four-day trial, part of the Australian Reef Restoration and Adaptation Program, they used a prototype machine to pump seawater through a filter and spray it out of small nozzles that produced fine water droplets. These water droplets were then propelled into the atmosphere by a fan, at which point the water evaporated, leaving behind salt particles that other water droplets could condense on, thereby forming brighter and more reflective clouds. Shortly afterward, researchers at the Sydney Institute of Marine Science and the University of Sydney announced larger-scale trials planned for the next few years, with aims to protect the Great Barrier Reef from coral bleaching. These trials would employ MCB on a larger scale (that is, they would cover larger areas and use a bigger aerosol-generating machine), creating larger and more reflective clouds above the Great Barrier Reef to cool the water underneath.[138] However, a coalition of nearly two hundred environmental groups protested these trials, arguing that the experiments would violate the 2010 United Nations moratorium on geoengineering and that MCB ultimately fails to address fossil fuel emissions, which are believed to be the underlying cause of rising ocean temperatures and coral bleaching.[139] While several of these trials were ultimately conducted in March 2021, details on their exact location, scale, and time period have not yet been made public.

Cirrus Cloud Thinning

High-altitude cirrus clouds are almost completely composed of ice crystals and can be found in the upper half of the troposphere. Since they can both absorb and emit longwave thermal (infrared) radiation from the lower atmosphere and at the same time emit small amounts of shortwave (solar) radiation into space, they are believed to have an overall net warming effect on the planet. To counteract this, researchers have proposed cirrus cloud thinning (CCT), which involves injecting ice-nucleating agents[140] into regions where cirrus clouds form to "thin" them and increase the emission of longwave radiation into space. This additional ice crystal growth would deplete available water vapor and hypothetically increase cloud opacity, frequency of occurrence, areal extent, or duration, resulting in a cooling effect on the planet.[141] Published estimates suggest that this increased emission could potentially offset any warming due to positive radiative forcing from excess carbon dioxide in the atmosphere[142] and could continuously affect high-latitude

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[138] Modeling results show that approximately eight hundred to one thousand misting stations, each containing three thousand nozzles, are required to cover the length of the Great Barrier Reef and reduce radiation by about 6.5 percent. Tollefson, "First Sun-Dimming Experiment."

[139] Galey, "Ocean Geoengineering Tests."

[140] Example nucleating agents include inorganic compounds such as bismuth iodide and silver iodide. Because of the inorganic agents' toxicity, researchers and companies such as Snomax International have been increasingly examining more benign alternatives, such as ice-nucleation proteins, which are considered nontoxic, nonpathogenic, and biodegradable in the presence of ultraviolet light. Despite these attributes, these proteins have increased costs and shorter lifetimes (due to biodegradability) than their inorganic compound counterparts. See https://www.snomax.com/.

[141] Mitchell and Finnegan, "Modification of Cirrus Clouds."

[142] Storelvmo et al., "Potential"; and Storelvmo, Boos, and Herger, "Cirrus Cloud Seeding."

locations around the globe.[143] Since CCT does not have a natural analogue, significant experimentation is still required to examine several key aspects:

- Materials that can best catalyze ice nucleation
- Delivery mechanisms and technologies
- Cost and feasibility of regulating regional or global temperatures

Because of uncertainties surrounding CCT's impact on atmospheric circulation and whether the predicted behaviors would actually occur, this method receives less funding than SAI and MCB.

Research into the effects of CCT implementation is limited to climate modeling (including realistically representing cirrus clouds), and there is no consensus on which materials would most effectively seed cirrus clouds. Additionally, there is limited understanding of the physical and dynamic processes influencing the formation, maintenance, and dissipation of cirrus clouds. Thus, further research is needed to better understand the feasibility of implementation of this method and its efficacy at reducing the effects of local or global climate change.

Surface Albedo Modification

Surface albedo modification (SAM) encompasses a variety of methods proposed to increase the albedo of Earth's surface. Potential methods include

- planting genetically engineered reflective crops over large swaths of land;[144]
- painting highly reflective coatings onto surfaces, such as human settlements, roads, or desert landscapes;[145] or
- physically generating reflective foam on ocean water surfaces.[146]

Of all the techniques to manage solar radiation, SAM probably contributes the least to reducing regional or global mean temperature because of its presumed low effectiveness and high costs. Although SAM methods are easily reversible (e.g., repainting roofs or removing reflective crops), significant uncertainties about their effectiveness persist because of the limited research in this area. Current estimates suggest that these methods are limited in the maximum amount of global cooling they can achieve,[147] so they are not expected to adequately compensate for any significant fraction of the warming produced by greenhouse gas emissions. On the other hand, SAM methods raise minimal transboundary concerns, since they would be confined to the implementing country's territory.

[143] Shepherd et al., *Geoengineering the Climate*.

[144] Ridgwell et al., "Tackling Regional Climate Change"; and Hamwey, "Active Amplification."

[145] Akbari, Matthews, and Seto, "Long-Term Effect"; Lenton and Vaughan, "Radiative Forcing Potential"; Gaskill, "Summary of Meeting"; and Shepherd et al., *Geoengineering the Climate*.

[146] PSAC, *Restoring the Quality of Our Environment*; and Seitz, "Bright Water."

[147] They are limited because they cannot compensate for a significant fraction of the warming produced by greenhouse gas emissions.

Land Use Management

Another proposed way to remove atmospheric carbon dioxide is to implement new land use policies and proactively change landscapes to increase natural carbon uptake from the atmosphere.[148] This can be accomplished through reforestation (restocking trees in existing or recently deforested forests) or afforestation (cultivating trees in areas where there have been no forests in the last fifty years). Another set of techniques involves changing the use practices for agricultural land—for example, by growing cover crops or using crop residues or low- or no-till systems.

There has been some research on the effectiveness of certain land use management techniques, as well as some cost estimates. The Intergovernmental Panel on Climate Change releases annual estimates of net carbon dioxide taken up as a result of afforestation and reforestation,[149] and costs have been estimated for different levels of uptake. One estimate states a cost of $100 per ton at a mitigation level of 10.6 gigatons of carbon dioxide per year, but estimates vary widely.[150] Overall, changes to land use management are considered inexpensive.

Land use management for CDR presents some potential drawbacks. Reforestation and afforestation efforts could be constrained by competition with agriculture for land;[151] these two categories of land use would have to be balanced. In some cases, conflict or debate could ensue.

Accelerated Weathering

Rather than modifying land use management, other CDR methods involve novel ways of extracting carbon dioxide from the atmosphere. Accelerated weathering[152] leverages chemical reactions to trap carbon dioxide in minerals (such as carbonates and silicates), which are then stored in rock formations on land or dissolved in the ocean. These naturally occurring reactions are accelerated when high concentrations of carbon dioxide are transported to the needed rock formations to create the minerals or, inversely, when precursor minerals are transported to areas of high carbon dioxide concentrations.

Some accelerated weathering research has been conducted conceptually or in the laboratory, but not at the scale needed for widespread implementation. For example, researchers assessed the life cycle of a proposed accelerated weathering model.[153] They found that accelerated weathering had potential to reduce atmospheric carbon dioxide, but the energy required to capture and transport the carbon dioxide to rock formations may offset any reductions. The chemistry is well understood, and the engineering involved can leverage established research areas, which could make cost estimates more certain. The sociopolitical risk should be lower for the land-based variant of this method.

Despite these positives, this method comes with some known difficulties. For example, accelerated weathering of calcium carbonate would require approximately 2.3 times more calcium carbonate than the mass

148 NRC, *Carbon Dioxide Removal*.

149 NRC, *Carbon Dioxide Removal*; and Watson et al., *Land Use*.

150 Edenhofer et al., *Climate Change 2014*.

151 Zeng et al., “Economic and Social Constraints.”

152 NRC, *Carbon Dioxide Removal*.

153 Kirchofer et al., “Impact of Alkalinity Sources.”

of carbon dioxide extracted.[154] More research and development is needed to obtain the required mass of minerals for this method. Additionally, moving minerals to high concentrations of carbon dioxide would require a large transportation footprint. Cost is also a challenge: the life-cycle assessment described previously estimated an upper-bound cost of $1,000 per ton of carbon dioxide extracted.[155]

There are other potential drawbacks and constraints to this method. While depositing carbon in rock formations poses limited environmental and sociopolitical risks, deposition in the ocean presents more ecological and economic risk. Depositing these minerals in the ocean at scale could harm ocean ecology. Legally, the London Convention and London Protocol limit what can be deposited in the ocean; these legal limitations could apply to the products of this method.[156] Yet, economics may constrain this method to ocean deposition and locating facilities on coasts.

Ocean Iron Fertilization

Ocean iron fertilization (OIF) is based on the idea that phytoplankton uptake carbon dioxide for photosynthesis. With this method, iron compounds are strategically introduced into the ocean to seed the growth of phytoplankton in new areas, causing blooms that uptake more carbon dioxide. When the phytoplankton die, the carbon is deposited deeper in the ocean.

About a dozen small OIF field experiments have been conducted over the past three decades.[157] In one of the most recent experiments, in 2012, an entrepreneur dumped iron compounds off the Pacific Northwest coast, seeking to gain carbon credits by causing plankton growth. This experiment was conducted with no government oversight.[158] Satellite imaging quickly detected the resultant bloom (demonstrating the ease of detection for this climate intervention method).[159] This is a real-life example of the concern about unilateral actors with no government or international oversight attempting a climate intervention method.

Still, there are many questions about the efficacy of OIF because of the limited scope and duration of these experiments and the absence of long-term carbon sequestration evidence.[160] At this point, researchers rely mostly on models, and the method's overall effectiveness remains largely unknown. Regarding costs, a recent estimate notes the upper-bound costs to be about $450 per ton of carbon dioxide removed.[161] However, the estimators acknowledge that there are many unknown variables and high uncertainties.

As a climate intervention method, OIF presents two advantages. First, if deployed as part of a portfolio of intervention methods, it would need to be deployed only to certain iron-limited regions of the world, such

154 NRC, *Carbon Dioxide Removal.*

155 Kirchofer et al., "Impact of Alkalinity Sources." This estimate was produced in 2012 and assumed that the electricity needed for this process would come from coal.

156 Convention on the Prevention of Marine Pollution; and London Protocol.

157 OCB Program, "Ocean Fertilization."

158 Fountain, "Rogue Climate Experiment"; and Tollefson, "Ocean-Fertilization Project."

159 Rabitz, "Going Rogue?"

160 NRC, *Carbon Dioxide Removal.*

161 NRC, *Carbon Dioxide Removal.*

as the Southern Ocean (its effectiveness would be limited to these areas).[162] Second, the required materials are easily obtainable.

The method has several potential disadvantages, however. Its overall effectiveness is questionable. Recent estimates put annual uptake at only about 3.7 gigatons.[163] In addition, there are international legal concerns with adding chemicals to the ocean. As mentioned, the London Convention and London Protocol regulate what can be deposited in the oceans, and the CBD urges no ocean fertilization (except for small research projects) until scientific justification and regulation are in place.[164] Phytoplankton blooms would be hard to control, potentially drifting into multiple nations' territorial waters. Furthermore, researchers question how the emission of aerosols from plankton, such as aerosols containing dimethyl sulfide, would affect the environment,[165] and plankton blooms may contain toxic species.[166] Finally, iron addition may reduce nutrients (although it may also increase fish populations).[167]

Direct Air Capture and Sequestration

Direct air capture and sequestration (DACS) involves the industrial-scale extraction of carbon dioxide directly from the air followed by sequestration at an appropriate place. In this process, solvents are used to extract carbon dioxide from the air through absorption or adsorption.[168] The carbon dioxide is then concentrated as a pure stream that can be either used for industrial purposes or sequestered underground or in other locations. This method differs from carbon capture and sequestration in that rather than being captured at a point source such as a factory smokestack, the carbon dioxide is extracted at a much lower concentration from ambient air.

Not only has this method been researched for more than twenty years, but within the last several years, direct air capture (DAC) facilities have been built. Primarily, two types of sorbents have been used in research: aqueous sorbents made with an alkaline substance[169] or amines on a porous support.[170] Companies such as Climeworks[171] and Carbon Engineering[172] have built DAC facilities of different sizes and capacities all over the world.[173] According to the International Energy Agency, as of September 2024, there are twenty-seven DAC plants spread globally.[174]

162 NRC, *Carbon Dioxide Removal*.

163 NRC, *Carbon Dioxide Removal*.

164 Convention on the Prevention of Marine Pollution; London Protocol; CBD, Decision IX/16; and CBD, Decision X/33.

165 Behrenfeld et al., "NAAMES."

166 Trick et al., "Iron Enrichment."

167 Williamson et al., "Ocean Fertilization."

168 NRC, *Carbon Dioxide Removal*; and Lackner, Ziock, and Grimes, "Carbon Dioxide Extraction."

169 Holmes and Keith, "Air-Liquid Contactor"; and Stolaroff, Keith, and Lowry, "Carbon Dioxide Capture."

170 Lu et al. "Carbon Dioxide Capture."

171 https://climeworks.com/.

172 https://carbonengineering.com/.

173 Beiser, "Quest to Trap Carbon in Stone."

174 Budinis, *Direct Air Capture*.

Varying costs have been projected for this method. Upper-bound costs of $1,000 per metric ton of carbon dioxide have been estimated, not including the cost of compressing and sequestering the gas.[175] Climeworks estimates it costs about $750 per ton of carbon dioxide captured.[176] Overall, DACS is viewed as more expensive than other climate intervention methods.[177]

Despite being considered more expensive than other methods, the technique does have some advantages. The concept's technical development is maturing, even if economic viability is still an issue. Facilities can be positioned near sequestration areas or other areas convenient for application, such as oil wells. The choice of placement can decrease some of the cost and hazards of transporting captured carbon dioxide to a distant location. Two potential dangers of DACS (which are shared with bioenergy with carbon capture and sequestration, or BECCS, discussed in the next subsection) are the potential for seismic activity and subsequent leaking of captured carbon; both require more study.[178]

Compared with the other climate intervention methods, DACS is less controversial and is receiving more support. Many countries have passed policies supporting and incentivizing DACS.[179] In the United States, the 2022 Inflation Reduction Act updated the tax code to increase tax credits for carbon capture, supporting more development.[180] This support may have to do with the sense that a scalable CDR method is necessary to prevent exceeding the Paris Climate Agreement levels. Still, there is some concern that development of DACS, as with all climate intervention methods, will undercut efforts to mitigate emissions.[181]

Bioenergy with Carbon Capture and Sequestration

Somewhat similar to DACS, bioenergy with carbon capture and sequestration (BECCS) involves directly extracting carbon dioxide from the air. However, rather than capturing low concentrations of carbon dioxide from any location, BECCS captures carbon at the point source of bioenergy plants. These plants that burn biomass would replace fossil fuel–burning plants, and their emissions would be immediately scrubbed and sequestered. The carbon captured in the biomass would then in effect be removed from Earth's atmospheric system.

Research on this method has focused on modeling and estimating the amount of carbon dioxide that would be taken up.[182] BECCS is viewed as more cost effective than DACS up to a certain point of removal. Estimates suggest costs of around $100 per ton of carbon dioxide removed, assuming the method is similar to current carbon capture and sequestration methods for plants that do not produce bioenergy.[183] Furthermore, the costs of BECCS may be more certain, because it uses existing technology.

175 House et al., "Economic and Energetic Analysis."

176 Beiser, "Quest to Trap Carbon in Stone."

177 NRC, *Carbon Dioxide Removal*.

178 NRC, *Carbon Dioxide Removal*.

179 Budinis, *Direct Air Capture*.

180 Bettenhausen, "Inflation Reduction Act."

181 Gertner, "Dream of Carbon Air Capture."

182 Smith and Torn, "Ecological Limits."

183 NRC, *Carbon Dioxide Removal*; and Rubin and Zhai, "Cost of Carbon Capture and Storage."

There are several drawbacks to this method.[184] First, its success depends on the world adopting bioenergy as a large percentage of its energy sources. Like land use management, BECCS would call for a large allocation of land for growing certain vegetation (in direct competition with afforestation and reforestation). The crops needed for bioenergy would also displace crops for food; land use would need to be smartly balanced between crops for food and crops for energy. Finally, similar to DACS, BECCS raises concerns about potential seismic activity and leaking of captured carbon from sequestration.

Summary

Managing solar radiation (SRM) and removing carbon dioxide (CDR) represent two broad families of climate intervention that address the issue in fundamentally different ways. SRM would alter Earth's radiation budget to implement cooling and would not decrease greenhouse gas in the atmosphere at all. CDR would actively try to decrease greenhouse gas concentrations already present in the atmosphere. SRM promises relatively quick effects, while CDR takes longer to result in temperature change. Methods within both families vary in estimated cost. More information on methods and estimated costs can be found in the National Research Council publications *Reflecting Sunlight*[185] and *Carbon Dioxide Removal*.[186]

[184] NRC, *Carbon Dioxide Removal*.

[185] NRC, *Reflecting Sunlight*.

[186] NRC, *Carbon Dioxide Removal*.

Appendix B Materials for Stratospheric Aerosol Injection

Most stratospheric aerosol injection (SAI) research and atmospheric modeling focuses almost exclusively on injecting aqueous sulfate-based aerosol materials into the stratosphere. However, researchers have increasingly considered solid aerosol materials such as alumina (aluminum oxide), diamond, calcite (calcium carbonate), and titania (titanium dioxide). These materials are of interest for their

- high refractive index (i.e., they scatter more light);
- relatively low density (ideal for stratospheric suspension);
- minimal absorption in the solar and thermal infrared spectral regions;
- well-understood surface chemistries under stratospheric conditions; and
- ability to be produced at a sub-micron size regime (ideally about fifty to two hundred nanometers in diameter).[187]

Despite these promising attributes, however, these materials pose several environmental concerns related to their production or procurement (i.e., mining). The proposed materials and their respective environmental concerns are described below.

Sulfates

Sulfate-based aerosols (e.g., sulfuric acid or sulfur dioxide) have most commonly been proposed for SAI,[188] though scientists have increasingly found that these chemicals could potentially contribute to ozone depletion. Sulfuric acid is a caustic mineral acid typically used as a commodity chemical in the production of fertilizers, detergents, pharmaceuticals, and insecticides, among other things. Sulfur dioxide is a toxic gas primarily used as a precursor to sulfuric acid. Other applications of sulfur dioxide include as a preservative for dried fruits and as a reagent/solvent in laboratory-based chemical reactions. The main component of sulfates is sulfur, which is currently produced from petroleum, natural gas, and other fossil fuels as a side product of industrial processes such as oil refining. Approximately eighty-two million metric tons of sulfur were produced worldwide in 2023.[189] Outside of industrial production, sulfur is obtained from mining surface deposits at volcano sites. During these excavations, miners are subject to dangerous working conditions, such as toxic smoke exposure (sulfur dioxide, hydrogen sulfide, etc.) and they are generally equipped with minimal protective equipment.

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187 Weisenstein, Keith, and Dykema, "Solar Geoengineering Using Solid Aerosol in the Stratosphere."

188 The main gases released during volcanic eruptions include water vapor, carbon dioxide, and sulfur dioxide. Thus, sulfates were most commonly proposed for SAI since their stratospheric injection would most closely mimic the materials expelled during an eruption. Preliminary modeling suggests that a negative radiative forcing of two watts per square meter can be achieved by injecting two to four metric tons of solid or aerosol sulfate particles into the stratosphere.

189 USGS, *Mineral Commodity Summaries 2024*. According to the US Geological Survey, the top five producers of sulfur in 2023 are China (19 million metric tons), the United States (8.6 million metric tons), Saudi Arabia (8 million metric tons), Russia (7 million metric tons), and the United Arab Emirates (5.4 million metric tons).

Alumina

Alumina is a naturally occurring metal oxide material primarily used as a precursor for aluminum. It has a variety of industrial applications, including in sunscreens, cosmetics, catalysis, and glass, among others. The global production capacity of alumina was approximately 140 million metric tons in 2023.[190] Alumina was chosen as a potential solid aerosol candidate for several reasons:

- There is prior research and knowledge on its impacts to stratospheric chemistry.[191]
- It is speculated to have fewer technology-specific risks than sulfate aerosols for appropriately sized particles.[192]
- There are established processes to produce nanoparticles for industrial applications.
- It has a relatively high refractive index (n = 1.77).

Additionally, preliminary modeling indicates that the injection of 240 nanometer-sized alumina particles at a rate of four metric tons per year would generate a negative radiative forcing of approximately 1.3 watts per square meter.[193] Despite these positive characteristics, alumina contains absorption bands within the infrared (thermal) region of the electromagnetic spectrum that would contribute to positive radiative force and, in turn, some heating of the lower stratosphere.[194]

Alumina production generally involves extraction and refining from the bauxite ore via the Bayer process. Bauxite is generally mined from various tropical and subtropical regions, including Asia (China, India, Indonesia, Vietnam, etc.), Central and South America (Venezuela, Brazil, Jamaica, Guyana, Suriname, Guinea, etc.), Russia, Africa, Iceland, and Australia.[195] Bauxite is typically extracted from the earth via strip-mining or open-cast mining. During these processes, large swaths of soil are excavated relatively close to the earth's surface, and all native vegetation in the mining region is removed, significantly eroding soil and depleting habitats and food for local wildlife. Additionally, caustic red sludge and toxic mine tailings (remaining after waste is deposited into mine pits) can seep into aquifers and contaminate local water sources.

Diamond

Diamond, a mineral composed completely of carbon, has been proposed as a potential solid aerosol candidate for several reasons:

- It has a very high index of refraction (n = 2.4).
- It offers negligible absorption in both solar and thermal infrared spectral regions.

[190] Alumina is a major component of NASA shuttle rocket exhaust plumes.

[191] Danilin et al., "Global Stratospheric Effects"; Jackman, Considine, and Fleming, "Global Modeling Study"; and Ross and Schaefer, "Radiative Forcing."

[192] Keith et al., "Stratospheric Solar Geoengineering without Ozone Loss."

[193] Weisenstein, Keith, and Dykema, "Solar Geoengineering Using Solid Aerosol in the Stratosphere."

[194] Weisenstein, Keith, and Dykema, "Solar Geoengineering Using Solid Aerosol in the Stratosphere."

[195] The largest producers of bauxite are China and Australia.

- Diamond nanoparticles (nanodiamond) are considered biologically and environmentally benign.[196]

Similar to alumina, researchers have speculated that diamond-based particles may have fewer technology-specific risks than sulfate aerosols for appropriately sized particles.[197] Additionally, preliminary modeling results suggest that the injection of two metric tons per year of particles with radii of approximately 160 nanometers would provide radiative forcing of approximately 1.3 watts per square meter.[198]

The majority of natural industrial diamond is created as a byproduct of mining gem-quality diamond.[199] Gem-quality diamond is typically extracted from the kimberlite ore, a plutonic igneous rock that sometimes contains diamonds embedded within its rock matrix. Three main methods are used for diamond extraction:

(1) Pipe mining

- Open-pit pipe mining involves removing layers of sand and rock found just above the kimberlite ore. After the ore is broken up by blasting, it is loaded and transported to a primary ore crusher where the diamond is extracted.
- Underground pipe mining involves the construction of two tunnels through the earth's crust to reach the kimberlite pipe. The tunnels are constructed one above the other and are connected by funnels. Mining begins at the top-level tunnel by blasting the kimberlite ore, which falls through the funnels and collects in the lower-level tunnel. Loaders can then collect the broken ore and bring it back to the surface for diamond extraction.

(2) Alluvial mining

- Alluvial mining involves the mining of streambed deposits that contain rough diamonds (originating from kimberlite pipes) embedded within the gravel layer of other materials, such as mud, clay, and underwater plant life. A wall is constructed to allow the water to pool, at which point the gravel is collected, hauled to the surface, and prepared for diamond extraction.

(3) Marine mining

- Marine mining involves extracting diamond from the underwater seabed. Ships equipped with a specialized crawler suck gravel on the seabed through flexible hoses or pipes and a large-scale drill that excavates the diamonds from the obtained gravel. The richest known source of marine diamond deposits is off the coast of Namibia, which accounts for about 64 percent of Namibia's total diamond production.

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[196] Krueger, "Diamond Nanoparticles." Mechanical applications include use as a polishing material for surface finishing of watches, sapphires, hard disks, etc. Because of its biocompatibility, diamond has biological applications, including targeted drug delivery and labeling of bioactive compounds. Electrical applications can be envisioned for diamond, because of its semiconducting properties, and it has been proposed for applications such as quantum engineering and electrode coatings.

[197] Weisenstein, Keith, and Dykema, "Solar Geoengineering Using Solid Aerosol in the Stratosphere."

[198] Weisenstein, Keith, and Dykema, "Solar Geoengineering Using Solid Aerosol in the Stratosphere."

[199] USGS, *Mineral Commodity Summaries 2024*. According to the US Geological Survey, approximately forty-five million carats of diamonds were mined in 2023.

After the diamond is acquired, it can be converted into nanoparticles by a variety of methods, including

- detonation;[200]
- laser ablation;[201]
- high-energy ball milling of high-pressure high-temperature diamond microcrystals;[202]
- plasma-assisted chemical vapor deposition;
- autoclave synthesis from supercritical fluids;
- chlorination of carbides;
- ion irradiation of graphite;
- electron irradiation of carbon onions; and
- ultrasound cavitation.

The first three methods are used commercially.

Diamond mining has several environmental impacts:[203]

- Extensive removal of rock. Deep ground and seabed excavation requires the removal of large amounts of rock, in many cases several million times the amount of acquired diamond material. According to the United States Geological Survey,[204] the average stone in an engagement ring is the product of the removal of two hundred million to four hundred million times its volume of displaced earth. Additionally, the richest diamond mines in Africa produce approximately forty million parts waste per part extracted diamond material.
- Acid rock drainage from waste mine tailings, which cannot be stopped once started.[205] After mining, waste rock is piled onto land, and large quantities of tailings and processing chemicals are dumped into processing ponds. These waste byproducts can acidify the pond water. The acidic water can dissolve lead, copper, and zinc within the waste rock and, in turn, leach into groundwater and contaminate it. These waste products are stored in frozen dams in colder climates, but heavy metals could leach into the soil and water sources as the frozen ground thaws when temperatures warm. Ongoing threats persist:

200 Detonation is a commercial method to produce nanodiamonds. With this technique, explosives with a negative oxygen balance—e.g., a mix of 60 percentage by weight TNT ($C_6H_2(NO_2)_3CH_3$) and 40 percentage by weight hexogen ($C_3H_6N_6O_6$)—are detonated in a closed metallic chamber in an atmosphere of nitrogen, carbon dioxide, and liquid or solid water. After detonation, diamond-containing soot is collected from the bottom and the walls of the chamber.

201 Laser ablation is a commercial method to produce nanodiamonds. It involves etching a graphite target with a high-power pulsed laser in water.

202 High-energy ball milling of high-pressure high-temperature diamond microcrystals is a commercial method to produce nanodiamonds. It involves ball milling diamond microcrystals under an inert atmosphere (e.g., argon or nitrogen) into a fine powder containing particles with diameters smaller than two microns, followed by nanomilling of the resultant powder.

203 Diamond Nexus, "Forever Destructive."

204 USGS, "Geologic Environment."

205 US EPA, "Acid Mine Drainage Prediction"; and Wilt, "Disaster Looming."

waste rock and mine tailings remaining at the many abandoned mines throughout the world[206] are continuously contaminating the surrounding ecosystems, affecting the health and well-being of nearby plants, animals, and humans.[207]

- Habitat destruction due to rock and soil removal and water supply contamination.[208] For example, waste from diamond mine tailings in Zimbabwe has polluted both the Odzi and Save Rivers, which local animals rely on for drinking water. In Canada, there is fear that toxic heavy metals could be introduced into the local food chain if roaming animals eat the vegetation growing near mine tailing ponds.
- Although lab-grown diamonds are marketed as a sustainable alternative to mined diamonds, the environmental impact of their production is not entirely benign. For example, typical manufacturing processes such as chemical vapor deposition or high-pressure, high-temperature treatment require constant energy generation to maintain ideal reaction conditions. This energy is generally produced from large amounts of nonrenewable sources such as coal or fossil fuels, which are known to produce harmful greenhouse gases.

Calcite

Calcite is a carbonate-based mineral that makes up more than 4 percent of the earth's crust. Its most common forms are chalk, limestone, and marble. Calcite has been proposed as an alternative to sulfate aerosol particles,[209] since it could simultaneously reflect thermal radiation and counter ozone loss by neutralizing acids that result from anthropogenic (human-generated) emissions.[210] Preliminary modeling indicates that a radiative forcing of approximately two watts per square meter can be achieved by injecting 5.6 metric tons per year of particles with radii of approximately 275 nanometers.[211]

Most calcite used for industrial purposes is extracted by mining or quarrying. This includes surface mining, which involves removing overlying rock and soil to expose the underlying calcite ore. After it is exposed, the ore is drilled, blasted, and transported by truck to the processing plant. Calcite deposits located deep underground are extracted by underground mining methods, such as shaft mining or room and pillar mining. These techniques involve creating underground tunnels and shafts where the ore can be accessed and extracted. The ore is then processed via various techniques, such as crushing, grinding, and sorting, depending on its final application and use.

Scientific studies into these extraction techniques reveal several environmental implications:[212]

- Loss of forest cover

206 For example, there are approximately ten thousand abandoned diamond mines in Canada (Diamond Nexus, "Forever Destructive") and over six thousand abandoned coal, diamond, and other mineral mines in South Africa (Trenchard, "Diamond Diggers").

207 Coumans, "Mining in Canada;" and AFP, "Gang Wars Erupt."

208 Mambondiayni, "Pollution Fallow"; Martin and Burgess, "Namaqualand-Richtersveld Steppe"; and Wilt, "Disaster Looming."

209 Gibbs, "Umbrella to Combat Warming"; and Keith et al., "Stratospheric Solar Geoengineering."

210 Wilt, "Disaster Looming."

211 Keith et al.. "Stratospheric Solar Geoengineering without Ozone Loss."

212 Larmare and Singh, "Limestone Mining."

- Pollution of water, soil, and air (e.g., via mine water runoff into streams and rivers)
- Water scarcity (water sources are dried up or contaminated)
- Depletion of natural flora and fauna and a reduction in biodiversity
- Soil erosion (the loss of top fertile soil alters soil quality in surrounding areas by changing its physical, chemical, and microbiological properties)
- Instability of soil and rock masses
- Changes in landscape, degradation of agricultural land, and encroachment of waste into agricultural land
- Destruction of habitats
- Noise pollution (from, e.g., drilling of blast holes, blasting of rock beds using explosives, and transportation)
- Generation of dust particulates in the air (which leads to health problems, such as respiratory tract infections from dust inhalation)
- Subsidence (limestone in underground mines can dissolve in water and be carried away, creating caves that can become weak and collapse; mining can lower the water table, which removes the support of rock that overlies water-filled caverns, creating sinkholes)

Titania

Titania is a naturally occurring titanium oxide mainly sourced from the ilmenite ore.[213] Common industrial applications include pigments, coatings,[214] sunscreens,[215] and water purification,[216] among others. Titania has been proposed as a potential solid aerosol candidate because of its high refractive index (n = 2.5, which is close to the optimal value for SAI) and low density (4,250 kilograms per cubic meter). In terms of titania's potential SAI performance,[217] scientists have calculated that a mass of about ten megatons of titanium dioxide particles with radii of approximately seventy nanometers would be required to achieve the same effects as the sulfate particles dispersed during the Mount Pinatubo eruption. This amounts to a factor of approximately three times less in mass and approximately seven times less in volume than sulfate particles in the stratosphere to achieve a similar level of albedo reflectance. Despite this, titania delivery and injection would likely necessitate transporting a larger mass and volume than required for sulfate particles because of the need for a carrier gas or liquid. Additionally, titania's feasibility for SAI is more uncertain than sulfate's feasibility because titania does not naturally occur in the stratosphere.

213 According to the US Geological Survey, the global production capacity of titanium dioxide was approximately 9.6 million metric tons in 2023.

214 USGS, *Mineral Commodity Summaries 2024*.

215 Lowe and Shaath, *Sunscreens*.

216 Tanos et al., "Modification of Titanium Dioxide-Based Catalysts."

217 Pope et al., "Stratospheric Aerosol Particles."

Ilmenite is extracted from the earth by either dry or wet mining.[218] Dry mining involves the extraction of heavy mineral ores from shallow, free-flowing, and hollow deposits and requires transportation, such as trucks, loaders, excavators, or scrapers, to recover the ore. Once obtained, the ore is then delivered to a wet concentration plant. Wet mining involves the use of high-pressure water to dredge the ore from the ground and is preferred for large ore bodies with low clay content. In preparation for wet mining, the topsoil and subsoil are removed, stripped, and stockpiled, at which point scrapers or trucks collect and transport the ore from the mining plant. The ore is then screened to remove excess rock or debris, and oversized items are returned to the pit to be conveyed to the concentration plant. Of the two, wet mining produces a higher-grade heavy mineral concentrate. Environmental concerns associated with these mining methods include

- radiation hazards due to the release of radioactive materials, such as radionuclides, dust, metals, and rare-earth elements;
- pollution of groundwater resources;
- dredging operations in fragile coastal areas; and
- deforestation.[219]

Table B-1 compares these proposed SAI materials' advantages, disadvantages, and SAI characteristics.

Table B-1. Comparative Summary of Proposed SAI Materials Characteristics

Proposed Material	Advantages	Disadvantages	SAI Characteristics
Sulfate[a,b,c,d]	• Most closely mimics the materials expelled during volcanic eruptions • Most widely studied material for SAI	• Could potentially contribute to ozone depletion • Increased diffuse radiation scattering, which could potentially alter atmospheric chemistry and ecosystem functioning	• Particle size: various • Injection rate: 2–4 t/year • Radiative forcing: –2 W/m^2
Alumina[e]	• Existing research and knowledge on its impacts to stratospheric chemistry • Speculated greater reduction in technology-specific risks than sulfate aerosols • Established production of nanoparticles for industrial applications • Relatively high refractive index (n = 1.77)	• Can absorb infrared (thermal) radiation, which would contribute to heating of lower stratosphere • Environmental impacts, such as significant soil erosion, loss of habitat and food for local wildlife, local water contamination due to caustic red sludge and toxic mine tailings	• Particle size: 240 nm • Injection rate: 4 t/year • Radiative forcing: –1.3 W/m^2

(continues)

218 Farjana et al., "Sustainable TiO_2 Production."

219 Weisenstein, Keith, and Dykema, "Solar Geoengineering Using Solid Aerosol in the Stratosphere"; and Farjana et al., "Life-Cycle Environmental Impact Assessment."

Table B-1 *(continued)*

Proposed Material	Advantages	Disadvantages	SAI Characteristics
Diamond[f]	• High refractive index that is close to optimal value for SAI (n = 2.4) • Negligible absorption in both solar and thermal infrared spectral regions • Speculated greater reduction in technology-specific risks than sulfate aerosols • Particles are considered biologically and environmentally benign	• Limited studies on radiative properties and reaction kinetics under stratospheric conditions • Environmental impacts, such as extensive rock removal, ecosystem contamination due to acid rock drainage, and habitat destruction	• Particle size: 160 nm • Injection rate: 2 t/year • Radiative forcing: –1.3 W/m^2
Calcite[e]	• Can reflect thermal radiation • Can counter ozone loss by neutralizing acids that result from human-generated emissions	• Limited studies on radiative properties and reaction kinetics under stratospheric conditions • Environmental impacts, such as water, soil, and air pollution; natural flora and fauna depletion; habitat destruction; and subsidence	• Particle size: 275 nm • Injection rate: 5.6 t/year • Radiative forcing: –2 W/m^2
Titania[g]	• High refractive index that is close to optimal value for SAI (n = 2.5) • Requires ~3 times less in mass and ~7 times less in volume of material than sulfate aerosols to achieve a similar level of albedo reflectance • Feasibility for SAI is uncertain since titania does not occur naturally in the stratosphere	• The need for a carrier gas or liquid would likely necessitate transporting larger mass and volume than required for sulfate aerosols • Limited studies on radiative properties and reaction kinetics under stratospheric conditions • Environmental impacts, such as radiation hazards, groundwater pollution, and deforestation	• Researchers calculated that a mass of ~10 Mt of titanium dioxide particles with radii of ~70 nm would be required to achieve the same effects as sulfate particles dispersed during the Mount Pinatubo eruption

[a] Rasch, Crutzen, and Coleman, "Exploring the Geoengineering of Climate." [b] Heckendorn et al., "Impact of Geoengineering Aerosols." [c] Niemeier, Schmidt, and Timmreck, "Dependency of Geoengineered Sulfate Aerosol." [d] Pitari et al., "Stratospheric Ozone Response." [e] Keith et al., "Stratospheric Solar Geoengineering without Ozone Loss." [f] Weisenstein, Keith, and Dykema, "Solar Geoengineering Using Solid Aerosol in the Stratosphere." [g] Pope et al., "Stratospheric Aerosol Particles and Solar-Radiation Management."

Appendix C China and Climate Intervention

The main report presents several hypothetical profiles of actors who might engage in climate intervention. Here we present research on how a specific nation-state—China—is thinking and working in areas related to climate intervention. This brief nation-state profile includes an overview of Chinese climate intervention efforts to date, highlighting that questions about response and influence are important, rather than speculative and fanciful thought exercises, given the growing urgency to combat climate change. Analogous US thinking can be found in the Office of Science and Technology Policy research plan[220] and scientific work presented in Appendix A.

> "One of the key characteristics of China's socialist modernization is human-nature harmony."
>
> *—President Xi Jinping*[221]

Since China's economic reform and opening in the late 1970s, the country's historically unprecedented economic growth rate has come at the great expense of its environment. China is now the world's largest carbon emitter, responsible for approximately 30 percent of global carbon emissions.[222] Its average annual economic growth rate of 9.4 percent from 1978 to 2018 resulted in strong fossil fuel consumption, which has become the main driver of its carbon emissions.[223] The environmental costs have been astronomical as well: analysts estimate that environmental degradation costs were between 2 and 3 percent of China's gross domestic product.[224] Recently, the Chinese government has begun to reprioritize climate and environmental considerations in its future economic growth strategy. It now emphasizes the need for sustainable development that values both economic growth and environmental protection, a significant reframing away from a previous "growth at all costs" mindset. President Xi Jinping is spearheading this shift toward restoring the country's environment through his "new development philosophy," termed "ecological civilization (eco-civilization)," which advocates for low-carbon, sustainable economic development.[225]

This new philosophy of decoupling economic growth from carbon emissions is bold. For a country like China, a self-proclaimed developing country with significant high-emissions industries and the world's largest population, this attempt is objectively unprecedented. In line with this new philosophy, President Xi's government has publicly announced significant climate-related milestones. Most important is the pledge to peak carbon dioxide emissions before 2030, achieve carbon neutrality before 2060, and lower carbon dioxide emissions per unit of gross domestic product by over 65 percent from the country's 2005 level.[226] This is in addition to other measures to mitigate energy usage and consumption, such as increasing non-fossil fuels in primary energy consumption to around 25 percent, especially through solar and

220 OSTP, *Congressionally Mandated Research Plan*.

221 Xi Focus-Quotable Quotes.

222 Sandalow et al., *Guide to Chinese Climate Policy 2022*.

223 Zheng et al., "Drivers of Change."

224 Ma et al., "Valuation of China's Environmental Degradation."

225 Greenfield and Ni, "'Ecological Civilization.'"

226 Huaxia, "Remarks by Chinese President."

wind capacity, as well as environmental objectives, such as increasing forest stock volume by six billion cubic meters.[227]

As a direct result of reprioritizing "sustainable" development, Chinese officials are accelerating a broad range of activities to improve the environment and mitigate climate change. These will potentially impact US security considerations. This section describes examples of China's activities related to stratospheric aerosol injection (SAI), marine cloud brightening (MCB), cirrus cloud thinning (CCT), and surface albedo modification (SAM) that could potentially affect US security considerations.

China's climate intervention efforts are varied and nascent. Although China's government supports climate intervention through official funding for burgeoning research efforts at numerous national and provincial laboratories, larger-scale efforts do not yet exist. As of this writing in 2024, China's support for climate intervention largely focuses on state-funded research. In 2017, an *MIT Technology Review* writer proclaimed that China has one of the "largest federally funded geoengineering research programs in the world," although he went one to say that this funding only totaled $3 million.[228] In 2015, Chinese media discussed the funding of the country's first formal geoengineering project through Beijing Normal University, a four-year study on using geotextile cloth to prevent glacial melt on Sichuan's Dagu glacier.[229] This study was part of the prestigious government-supported National Key Basic Research Program.[230]

China is an active participant in frontier research on global climate intervention topics, such as solar radiation management (SRM), largely through participation in international modeling efforts to examine potential effects. Numerous national and provincial laboratories in China study geoengineering topics, including

- the Chinese Academy of Sciences (analogous to the US National Academy of Sciences);
- the Key Laboratory of Geoscience Big Data and Deep Resource of Zhejiang Province at Zhejiang University;
- the Joint Center for Global Change Studies at Beijing Normal University; and
- the State Key Laboratory of Earth Surface Processes and Resource Ecology at Beijing Normal University.

Published research (Table C-1) by Chinese authors indicates that this field is of growing interest.

China's carbon dioxide removal (CDR) projects are more advanced than its SRM forays. Chinese CDR projects began first, in the early 2000s. More recently, Chinese state-owned petroleum companies publicized a series of larger-scale experimental CDR projects. In January 2022, Chinese state-owned energy company Sinopec announced the completion of China's first megaton carbon capture, utilization, and storage (CCUS) facility, which has an annual capacity of two hundred thousand metric tons.[231] It plans to develop another megaton CCUS demonstration project within the next five years.[232] According to IHS Markit, China is home to the greatest number of operational CCUS pilots globally. China is also starting to

227 Huaxia, "Remarks by Chinese President."

228 Temple, "Geoengineering Research Programs."

229 Zizhu, "Has 'Geoengineering' Arrived in China?"

230 Long et al., "Research Efforts in China."

231 Sinopec, "Megaton Scale Carbon Capture Project."

232 Sinopec, "Megaton Scale Carbon Capture Project."

Table C-1. Representative SRM Publications by Chinese Authors

Technology Area	Publication Authors and Title	Description
SAI	Liu, Lang, and Jiang, "Impact of Stratospheric Aerosol Intervention Geoengineering on Surface Air Temperature in China: A Surface Energy Budget Perspective"	Simulation of Chinese use of SAI in 2030–2069 time frame, with results showing surface cooling
	Xia et al., "Solar Radiation Management Impacts on Agriculture in China: A Case Study in the Geoengineering Model Intercomparison Project (GeoMIP)"	Simulation of effects of SAI on Chinese rice and maize production, showing little impact on rice and potential increases in maize
MCB	Zhao et al., "Climate More Responsive to Marine Cloud Brightening than Ocean Albedo Modification: A Model Study"	Comparison of effectiveness of MCB with ocean albedo modification in the National Center for Atmospheric Research (NCAR) Community Earth System Model, finding both have similar impact dependent on clouds and precipitation
CCT	Cao et al., "Simultaneous Stabilization of Global Temperature and Precipitation through Cocktail Geoengineering"	Research modeling that concludes a "cocktail" of both SAI and CCT may lead to the best climate response
SAM	Guo et al., "Multi-decadal Analysis of high-Resolution Albedo Changes Induced by Urbanization over Contrasted Chinese Cities Based on Landsat Data"	Analysis of Chinese cities' changing albedo values, shown in land satellite imagery, as a result of urbanization from 1986 to 2016

pursue CCUS demonstration projects beyond its borders. In an experimental project in the South China Sea, the China National Offshore Oil Corporation plans to store nearly one and a half million tons of carbon dioxide, including injecting up to three hundred thousand tons of carbon dioxide per year into seabed reservoirs.[233] In addition, similar to their work in SRM, Chinese scientists are also participating in transnational studies with the United States, Europe, and others that aim to build a common modeling framework of Earth systems to explore the potential future impact of CDR.[234]

The Chinese government has funded an initial wide-ranging set of studies of SRM technologies and has implemented large-scale pilot projects for CDR. These activities can be easily justified in a new political context that emphasizes sustainable development and combating climate change and environmental degradation.

Some potentially problematic themes emerge, however, specifically with regard to CDR, which has been more mature than SRM in China to date. The first is that although these technologies are still immature, their adoption could be prematurely institutionalized into China's future national carbon mitigation strategies by the design of the country's economic and political system.[235] This has been true for CDR, although not yet for SRM. For example, China is deploying large-scale CDR activities through CCUS technology pilot projects that were first studied in China in 2006 and increasingly emphasized since the country's 12th Five-Year Plan in 2013.[236] Given China's prospective economic planning practices, where investments are made in five-year increments, CCUS has been essentially codified in Chinese future planning. A second problem highlighted in China's CDR activities is their deployment in contested regions, such as the South

233 Xu and Patton, "Offshore Carbon Capture Project."

234 Keller et al., "CDRMIP."

235 Jiang et al., "CCUS Policy."

236 Jiang et al., "CCUS Policy."

China Sea. Although China National Offshore Oil Corporation's offshore CCUS is in Chinese territory at Enping 15-1 oil field, the South China Sea is a generally contested area with overlapping territorial claims. There is no governance mechanism to control for potential harm from Chinese incursions into surrounding areas. China's efforts in the South China Sea indicate that the country is not averse to deploying climate intervention and mitigation strategies in contested regions or necessarily concerned with how such deployment may affect other regional countries.

Members of the Chinese government and academic community have been circumspect about articulating explicit public support for geoengineering. Some studies, though, have found less divergence between US and Chinese expert views on future geoengineering activities. Small comparative studies of qualitative interviews with Chinese and American solar geoengineering experts, for example, show that "experts have strikingly consistent judgments on the trends of climate change, funding, and makeup of SG [solar geoengineering] research program, and potential deployment."[237] John Moore, who runs China's first national geoengineering program at Beijing Normal University and therefore has intimate knowledge of Chinese views on the matter, stated that China would not engage in disruptive climate geoengineering projects unilaterally as a first-mover.[238]

Nonetheless, all attempts to forecast Chinese activities are speculative at best. Thus, the US government should prioritize attempts to engage China in discussions around key principles for governance on experimentation with geoengineering and revolutionary climate science. Despite China's evolving climate governance priorities, scholars highlight that the country's objectives will always be nested within its own national priorities, strategic and economic development, and underlying national governance considerations.[239] It will be important for American policymakers to operate within those constraints and to search for the opportunities therein to start dialogue on geoengineering principles.

237 Dai et al., "Consistent Views."

238 Moore et al., "Will China Be the First?"

239 Teng and Wang, "Evolution of Climate Governance."

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