Solar Geoengineering and Climate Change

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Solar Geoengineering and Climate Change

SUMMARY

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Solar geoengineering (SG) refers to a set of methods aimed at cooling the Earth in order to counteract the warming effects of increases in greenhouse gases (GHGs). Interest in SG has developed due to concerns that current strategies of climate change mitigation, primarily through GHG emissions reductions, may not be sufficient to stabilize global temperatures at levels quickly enough to avoid adverse climate impacts resulting from global warming.

The Earth's energy budget is the ratio of energy entering the Earth's climate system in the form of shortwave solar radiation and the energy leaving the Earth's climate system either as reflected shortwave radiation energy or reradiated longwave heat radiation energy. SG methods seek to offset global warming by either reducing the amount of energy coming into the system from the sun, or increasing the amount of energy lost from the system to space.

Three SG methods are discussed in this report: stratospheric aerosol injection (SAI), marine cloud brightening (MCB), and cirrus cloud thinning (CCT).

SAI seeks to reproduce the cooling effect of volcanic eruptions by injecting sulfates into the stratosphere, to form a reflective aerosol. There is uncertainty about the method's degree of cooling, the potential effect on the Earth's climate, and concern about damage to the Earth's protective stratospheric ozone layer.

MCB seeks to increase the reflectivity of low-altitude oceanic clouds, reducing incoming solar energy and having a cooling effect, by spraying a mist of seawater into such clouds. Some studies indicate that MCB could offset the warming of a doubling of atmospheric CO_2 (a common metric of climate sensitivity) and others indicating that it could not. Some climate modeling studies suggest that MCB could affect global precipitation, with other studies yielding mixed regional effects.

CCT differs from SAI and MCB in that rather than decreasing the amount of incoming energy, CCT attempts to increase the amount of outgoing energy. High-altitude cirrus clouds prevent some longwave outgoing heat energy from reaching space. CCT adds an aerosol to the clouds to thin them, allowing more longwave heat energy to escape. Research on CCT effectiveness has produced mixed results, with some researchers finding a cooling effect and others not.

Although some international agreements include sections on geoengineering, there is no international agreement exclusively governing SG research and implementation. Governance of SG is an area of active discussion for researchers and policymakers.

As of the publication of this report, Congress has not passed legislation that exclusively regulates or governs SG research or implementation; however, there are aspects of some U.S. statutes that may be relevant. For FY2022, Congress appropriated funds for the Office of Science and Technology Policy (OSTP) to form an interagency task force in cooperation with other federal agencies, whose mandate includes the establishment of a research governance framework for publicly funded SG research. The OSTP has solicited public comments on rapid climate intervention research, including research on SG.

Some scientists have stated that the scientific understanding of SG is not currently sufficient to consider implementation. Some commentators have raised the concern that the perceived availability of SG may be seen as an alternative to mitigation strategies, such as emissions reductions, and delay or reduce efforts at such reductions.

Congressional deliberations on SG policy may include an evaluation of trade-offs between benefits and risks. On the one hand, SG may provide a cooling effect to offset global warming, reducing the risk of adverse climate change effects. On the other hand, risks associated with SG include possible damage to stratospheric ozone, reductions in precipitation, and reduction of ocean primary productivity. There is uncertainty about the climate response to SG, including the possibility of adverse impacts at global and regional levels. There may also be a risk of unilateral action on SG by countries or nonstate actors in the absence of U.S. law or an international agreement specifically addressing SG.

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Introduction

This report presents information on *solar geoengineering* (SG), a type of climate intervention for mitigating climate change.[1] SG is a set of proposed methods for limiting global warming by reducing the amount of solar energy entering the Earth's climate system or increasing the amount of energy leaving the Earth's climate system, and by doing so preventing global temperatures from increasing over time.[2]

Interest in the concept and methods of SG as a way of offsetting global warming has developed in part due to concerns that current strategies of climate change mitigation, through emissions reductions and reducing the atmospheric carbon dioxide (CO_2) concentration through carbon dioxide removal (CDR), may not be sufficient to stabilize global temperatures quickly enough to avoid adverse climate impacts.[3] In 2017, the U.S. Global Change Research Program (USGCRP) published its Fourth National Climate Assessment that stated the following:

> Limiting the global mean temperature increase through emissions reductions or adapting to the impacts of a greater-than-3.6°F (2°C) warmer world have been acknowledged as severely challenging tasks by the international science and policy communities. Consequently, there is increased interest by some scientists and policy makers in exploring additional measures designed to reduce net radiative forcing through other, as yet untested actions, which are often referred to as geoengineering or climate intervention (CI) actions.[4]

SG is distinct from the other principal methods of mitigating climate change—reducing emissions of greenhouse gases, and removing CO_2 from the atmosphere—that seek to influence global temperatures through changes in the concentrations of greenhouse gases (GHGs) in the atmosphere. SG, by contrast, seeks to influence global temperatures by managing the balance of incoming and outgoing energy. To do this, SG includes methods for increasing the reflectivity of the Earth and thereby reducing the absorption of incoming solar energy or by reducing the capacity of high-altitude clouds to retain outgoing energy in the form of heat. Either approach, if successful, would create a cooling effect, offsetting, to some extent, the global warming effect of increases in GHGs.

In a study published in 2021, the National Academies of Science, Engineering, and Medicine (NASEM) examined three SG methods, selected on the following basis:

> This particular study focuses specifically on atmospheric-based interventions—both because these strategies are a source of growing research interest and because they pose

[1] In addition to *solar geoengineering*, there are several terms in use for this group of methods, including *solar radiation management*, *solar radiation modification*, *albedo modification*, and *sunlight reflection*. See also Harvard's Solar Geoengineering Research Program, "Geoengineering," https://geoengineering.environment.harvard.edu/geoengineering.

[2] National Academies of Science, Engineering, and Medicine, *Reflecting Sunlight: Recommendations for Solar Geoengineering Research and Research Governance* (Washington, DC: The National Academies Press, 2021) (hereinafter NASEM 2021) provides the following description: "solar geoengineering (SG), which refers to attempts to moderate warming by increasing the amount of sunlight that the atmosphere reflects back to space or by reducing the trapping of outgoing thermal radiation" (p. 1).

[3] The White House Office of Science and Technology Policy: Legal, "Request for Input to a Five-Year Plan for Research on Climate Intervention," https://www.whitehouse.gov/ostp/legal/. See also Scientific American, "Solar Geoengineering Should Be Regulated, U.N. Report Says," February 28, 2023, https://www.scientificamerican.com/article/solar-geoengineering-should-be-regulated-u-n-report-says/.

[4] U.S. Global Change Research Program (USGRP*), Climate Science Special Report: Fourth National Climate Assessment*, Volume I, 2017, p. 401 (hereinafter USGCRP NCA4 2017).

> particularly large governance challenges, given the inherently transboundary, global nature of such interventions.[5]

The methods selected for examination by NASEM are presented in this report: stratospheric aerosol injection (SAI), marine cloud brightening (MCB), and cirrus cloud thinning (CCT). The report includes an overview of the techniques and a discussion of their potential for affecting global temperatures, as well as the potential risks and uncertainties associated with each technique.

Other methods of SG have been proposed, including space-based methods, and modification of the reflectance of land surfaces.[6] In addition to the NASEM selection criteria, the analysis in this report was limited to atmospheric methods due to the likely high costs and technical challenges of space-based methods relative to atmospheric methods, and concerns raised by researchers regarding the effectiveness of surface reflectivity modification.[7]

Although some international agreements, such as the Convention on Biodiversity and the London Protocol, include sections on geoengineering, there is no international agreement exclusively governing SG research and implementation.[8] Governance of SG is an area of active discussion by researchers and policymakers.

As of May 2023, Congress has not introduced or passed legislation that exclusively regulates or governs SG research or implementation. There are, however, aspects of some U.S. statutes that may be relevant to SG. For FY2022, Congress appropriated funds for the Office of Science and Technology Policy (OSTP) to form an interagency task force in cooperation with other federal agencies whose mandate includes the establishment of a research governance framework for publicly funded SG research.[9] On August 19, 2022, the OSTP posted a notice in the *Federal Register* soliciting public comments on rapid climate intervention research, including research on SG.[10]

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[5] NASEM 2021, p. 1

[6] D. G. MacMartin et al., "Solar Geoengineering as Part of an Overall Strategy for Meeting the 1.5°C Paris Target," *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, vol. 376, no. 2119 (2018), 20160454 (hereinafter MacMartin 2018). See also J. Lee et al., "Future Global Climate: Scenario-Based Projections and NearTerm Information" in *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, ed. Masson-Delmotte et al., (Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA), 2021, p. 553 (hereinafter IPCC AR6 WGI Chapter 4). See also Peter J. Irvine et al., "Climatic Effects of Surface Albedo Geoengineering," *Journal of Geophysical Research: Atmospheres*, vol. 116, no. D24 (2011).

[7] Roger Angel, "Feasibility of Cooling the Earth with a Cloud of Small Spacecraft near the Inner Lagrange Point (L1)," *Proceedings of the National Academy of Sciences*, vol. 103, no. 46 (2006), p. 17184. See also Peter J. Irvine et al., "Climatic Effects of Surface Albedo Geoengineering," *Journal of Geophysical Research: Atmospheres*, vol. 116, no. D24 (2011).

[8] United Nations Convention on Biological Diversity, May 22, 1992, 31 I.L.M. 818. See also 1996 Protocol to the Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter, November 7, 1996, 36 I.L.M. 7.

[9] U.S. Congress, House Committee on Appropriations, *Consolidated Appropriations Act, 2022 (H.R. 2471; P.L. 117-103): Provisions Applying to All Divisions of the Consolidated Appropriations Act*, committee print, 117th Cong.

[10] U.S. Global Change Research Program, "Request for Input to a Five-Year Plan for Research on Climate Intervention," https://www.globalchange.gov/content/request-input-five-year-climate-intervention-research-plan.

The Earth's Energy Budget

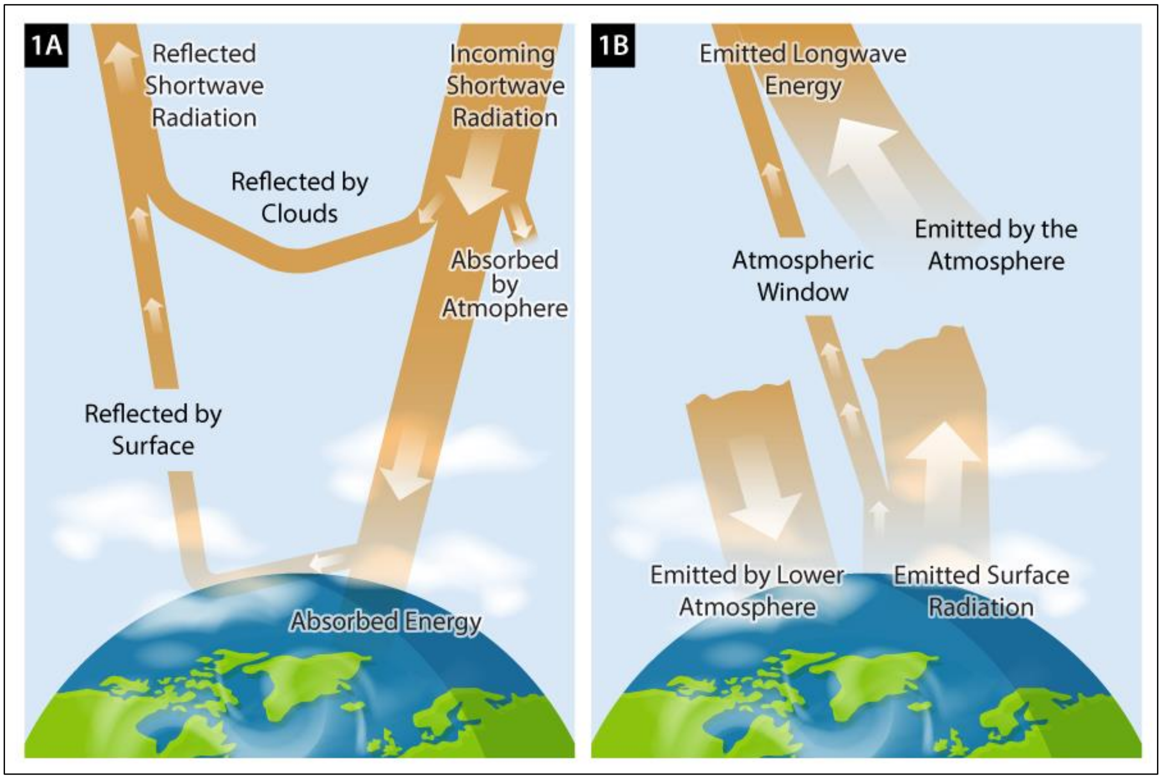
The methods of SG described in this report are intended to influence some of the energy components of the Earth's climate system, known as the *energy budget.* The Earth's energy budget is the balance between the energy coming into the Earth's climate system and the energy leaving the Earth's climate system (**Figure 1**).[11] This balance determines the Earth's climate, and when the gain and loss of energy are in balance, the Earth's climate is stable. When there is a change in the balance of the energy budget, the Earth's average temperature, and therefore climate, will change.[12]

Energy comes from the sun in the form of shortwave radiation, which includes visible light, and when it reaches the Earth's atmosphere a portion is reflected back into space, a portion is absorbed by the atmosphere itself, and a portion is transmitted through the atmosphere to the Earth's surface (**Figure 1A**). At the Earth's surface, a portion of the solar energy that has been transmitted through the atmosphere is reflected back into space and the remainder is absorbed. Some of the energy absorbed by the Earth's surface is reemitted back to the atmosphere as longwave (infrared or heat) radiation. Greenhouse gases (e.g., water vapor, CO_2, methane [CH_4]) do not absorb the incoming shortwave solar radiation but can absorb the longwave radiation emitted from the Earth's surface. Some of this heat energy is reemitted back toward the Earth's surface (**Figure 1B**). This absorption and reemission of longwave radiation or heat energy by the atmosphere keeps some energy from being lost directly into space and keeps the Earth's surface warmer than it would be without the atmosphere. This keeps the Earth's temperature within a range that can support human life.

[11] See glossary in Intergovernmental Panel on Climate Change, *The Physical Science Basis: Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (Cambridge, United Kingdom: Cambridge University Press, 2013): "The climate system is the highly complex system consisting of five major components: the atmosphere, the hydrosphere, the cryosphere, the lithosphere and the biosphere, and the interactions between them."

[12] When the *Earth's temperature* is referred to in this report, the phrase refers to the average temperature of the Earth.

Figure 1. The Earth's Energy Budget



Source: Adapted from images presented on the National Aeronautics and Space Administration (NASA) website, "The Earth's Radiation Budget," https://science.nasa.gov/ems/13_radiationbudget.

Note: The specifics of the Earth's energy budget are described in the text of the report.

When GHGs are added to the atmosphere through human-influenced (anthropogenic) emissions, the increased levels of GHGs in the atmosphere increase the amount of heat energy that can be absorbed and reemitted by the atmosphere. This leads to more heat energy trapped in the atmosphere and less of this energy transmitted back into space. In this case, incoming and outgoing energy are not in balance, the Earth warms, and the temperature of the Earth increases.

An imbalance of this kind between incoming and outgoing energy can be expressed mathematically and is termed *radiative forcing*.[13] When the incoming solar energy retained in the Earth's climate system is greater than the outgoing energy reemitted back to space, the radiative forcing is positive, and this has a warming effect for Earth. When outgoing energy is greater than the incoming solar energy retained in the Earth's climate system, then radiative forcing has a negative value, and this has a cooling effect for the Earth.

Solar Geoengineering: Selected Methods

There are several methods of SG, referred to as *atmospheric-based interventions*, identified by the NASEM as the focus of ongoing research. These methods—stratospheric aerosol injection (SAI), marine cloud brightening (MCB), and cirrus cloud thinning (CCT)—all involve the impact

[13] *Radiative forcing* has units of watts per square meter (W/m2) and is a measure of the movement of energy.

of aerosols in the atmosphere and are discussed in more detail below.[14] Research on these SG methods has primarily involved modeling studies.[15] However, the SG research has also included examining natural events like volcanic eruptions, and anthropogenic features like cloud aerosol pollution from ships, as real-world examples of the effects of adding aerosols to the atmosphere.[16] The effects of the natural and anthropogenic increases in organic aerosols in the atmosphere on cirrus cloud formation have also been studied.[17]

Stratospheric Aerosol Injection (SAI)

The SAI method is based on the observation that past volcanic eruptions, like the 1991 eruption of Mt. Pinatubo in the Philippines,[18] that emitted large quantities of sulfates (such as sulfur dioxide) into the stratosphere, led to a reduction in the amount of incoming solar energy, resulting in a short-term global cooling effect. The sulfate gases released during an eruption are converted into a dispersed aerosol of sulfuric acid. The aerosol reflects and thereby reduces the amount of incoming solar energy, resulting in short-term global cooling. In the case of the 1991 eruption of Mt. Pinatubo, this process resulted in a decrease of global temperatures by approximately 0.3°C for about three years.[19]

SAI as an SG method would require the dispersion of sulfates in the stratosphere to create manmade aerosol particles in order to make the atmosphere more reflective to incoming solar radiation energy and mimic the cooling effect observed after a large volcanic eruption.[20]A variety of methods have been proposed to add sulfates to the atmosphere, including "aircraft, rockets, artillery, and pipes elevated to high altitudes carrying aerosol precursors."[21]

Potential Cooling by SAI

Estimates of the degree of cooling that SAI could provide, and the quantity of sulfates needed for this cooling, have varied. A review of modeling study results for equivalent amounts of sulfate injected into the atmosphere have differed in the amount of cooling estimated between studies, by

[14] The National Institute for Occupational Safety and Health (NIOSH) defines an *aerosol* as "... a suspension of tiny particles or droplets in the air, such as dusts, mists, or fumes." See also NIOSH, "Aerosols," https://www.cdc.gov/niosh/topics/aerosols/default.html. See also NASEM 2021.

[15] NASEM 2021.

[16] D. Visioni et al., "Sulfate Geoengineering: A Review of the Factors Controlling the Needed Injection of Sulfur Dioxide," *Atmospheric Chemistry and Physics*, vol. 17, no. 6 (2017), p. 3879. See also M. S. Diamond et al., "Substantial Cloud Brightening From Shipping in Subtropical Low Clouds," *AGU Advances*, vol. 1, no. 1 (2020).

[17] Martin Wolf et al., "A Biogenic Secondary Organic Aerosol Source of Cirrus Ice Nucleating Particles," *Nature Communications*, vol. 11 (2020), p. 4834. See also K. Ignatius et al., "Heterogeneous Ice Nucleation of Viscous Secondary Organic Aerosol Produced from Ozonolysis of α-Pinene," *Atmospheric Chemistry and Physics*, vol. 16, no. 10 (2016), p. 6495.

[18] The eruption of Mount Pinatubo in the Philippines, in 1991, was the second-largest volcanic eruption of the 20th century. See also National Oceanographic and Atmospheric Administration (NOAA), "Mt. Pinatubo, Philippines: Facts," https://www.ngdc.noaa.gov/hazard/stratoguide/pinfeat.html.

[19] NASEM 2021.

[20] NOAA, "Layers of the Atmosphere," https://climate.nasa.gov/news/2919/Earths-atmosphere-a-multi-layered-cake/, includes the following definition of the *stratosphere*: "The stratosphere extends from 4 -12 miles (6-20 km) above the Earth's surface to around 31 miles (50 km). This layer holds 19 percent of the atmosphere's gases but very little water vapor." See also earlier studies: David Keith and Hadi Dowlatabadi, "A Serious Look at Geoengineering," *Eos, Transactions American Geophysical Union*, vol. 73, no. 27 (1992), p. 289; and M. I. Budyko, "Climatic Changes," *American Geophysical Union*, Waverly Press, 1977.

[21] NASEM 2021, p. 77.

a factor of three.[22] Based on observations of volcanic eruptions and some modeling studies, in order to maintain any potential cooling effects longer than a few years, the quantity of sulfate aerosol in the stratosphere would need to be replenished regularly.[23]

Potential Concerns/Drawbacks of SAI

Ninety percent of the atmosphere's ozone (O_3) is in the stratosphere, and this ozone provides protection from the harmful ultraviolet (UV) radiation from the sun.[24] Some research indicates that SAI using sulfates could cause depletion of the protective stratospheric ozone layer.[25] The 1991 eruption of Mt. Pinatubo provided evidence for this effect.[26] Other modeling studies on the effects of SAI on the ozone layer produced mixed results, with increases of ozone in some regions and decreases in others.[27]

Using sulfate aerosols may also increase water vapor content, and depending on where in the stratosphere the aerosols are introduced, could affect cloud formation.[28] Cloud formation could lead to warming of the stratosphere and could reduce the degree of cooling achieved by sulfate-based SAI.[29]

These concerns about sulfate-based SAI have led to research into alternative materials that could be aerosolized and used instead of sulfates, such as alumina and diamond.[30] There is uncertainty about the behavior of nonsulfate aerosols because they do not occur naturally in the stratosphere.[31]

Estimates of the degree of cooling that SAI could provide have varied. If SAI were implemented, there is some research that indicates an abrupt termination of SAI would lead to rapid warming of the planet, to the temperature level that it would have had if SAI had not been implemented and with the risk of adverse climate effects. These findings imply that SAI would need to be continued indefinitely at levels approximating an annual volcanic eruption like that of Mount

[22] D. Visioni et al., "Sulfate Geoengineering: A Review of the Factors Controlling the Needed Injection of Sulfur Dioxide," *Atmospheric Chemistry and Physics,* vol. 17, no. 6 (2017), p. 3879.

[23] NASEM 2021, p. 81. See also S. Kremser et al., "Stratospheric Aerosol—Observations, Processes, and Impact on Climate," *Reviews of Geophysics*, vol. 54, no. 2 (2016), p. 278.

[24] NASA, Goddard Space Flight Center, "NASA Ozone Watch," https://ozonewatch.gsfc.nasa.gov/facts/SH.html (accessed April 2023).

[25] S. Tilmes et al., "The Sensitivity of Polar Ozone Depletion to Proposed Geoengineering Schemes," *Science*, vol. 320, no. 5880 (2008), p. 1201 (hereinafter Tilmes 2008).

[26] Tilmes 2008.

[27] G. Pitari et al., "Stratospheric Ozone Response to Sulfate Geoengineering: Results from the Geoengineering Model Intercomparison Project (GeoMIP)," *Journal of Geophysical Research: Atmospheres*, vol. 119, no. 5 (2014), p. 2629.

[28] K. S. Krishnamohan et al., "The Climatic Effects of Hygroscopic Growth of Sulfate Aerosols in the Stratosphere," *Earth's Future*, vol. 8, no. 2 (2020).

[29] D. W. Keith et al., "Stratospheric Solar Geoengineering without Ozone Loss," *Proceedings of the National Academy of Sciences of the United States of America*, vol. 113, no. 52 (2016), p. 14910 (hereinafter Keith 2016).

[30] Keith 2016; see also J. A. Dykema et al., "Improved Aerosol Radiative Properties as a Foundation for Solar Geoengineering Risk Assessment," *Geophysical Research Letters*, vol. 43, no. 14 (2016), p. 7758.

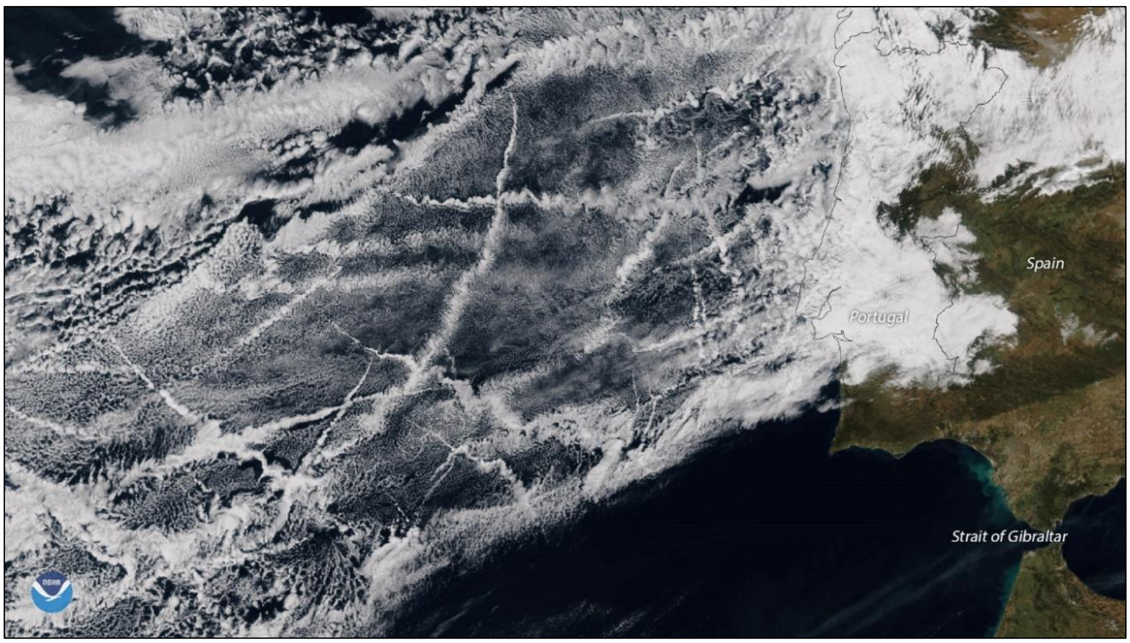
[31] J. A. Dykema, D. W. Keith, and F. N. Keutsch, "Improved Aerosol Radiative Properties as a Foundation for Solar Geoengineering Risk Assessment," *Geophysical Research Letters*, vol. 43, no. 14 (2016), p. 7758.

Pinatubo.[32] Some researchers have questioned the likelihood of such an abrupt halt to SAI.[33] Other researchers have suggested that SG methods such as SAI might be combined, on a temporary basis, with other climate mitigation strategies until atmospheric CO_2 concentrations reach levels consistent with global temperature stabilization targets.[34]

Marine Cloud Brightening (MCB)

MCB is a proposed method of cooling the Earth's climate by increasing the reflectivity or brightness of low-altitude marine clouds.[35] MCB is based on the observation that, in a cloud, smaller water droplets are more reflective than larger droplets and that by increasing the number of small droplets, a cloud can be made more reflective. This phenomena has been observed with "ship tracks," which are lighter lines within cloudy ocean areas produced by ships' emissions of aerosols. These emissions cause an increase in water droplets in cloudy areas the ships pass through (**Figure 2**).

Figure 2. Ship Tracks off the Iberian Peninsula



Source: National Oceanographic and Atmospheric Administration (NOAA), National Environmental Satellite Data and Information Service, "Ship Tracks off the Coast of the Iberian Peninsula," https://www.nesdis.noaa.gov/news/ship-tracks-the-coast-of-the-iberian-peninsula.

[32] K. E. McCusker et al., "Rapid and Extensive Warming Following Cessation of Solar Radiation Management," *Environmental Research Letters*, vol. 9, no. 2 (2014), 024005 (hereinafter McCusker 2014). See also NASEM 2021, p. 81.

[33] Andy Parker and Peter J. Irvine, "The Risk of Termination Shock From Solar Geoengineering," *Earth's Future*, vol. 6, no. 3 (2018), p. 456.

[34] D. G. MacMartin et al., "Solar Geoengineering as Part of an Overall Strategy for Meeting the 1.5°C Paris Target," *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, vol. 376, no. 2119 (2018), 20160454.

[35] J. Latham et al., "Marine Cloud Brightening," *Philosophical Transactions. Series A, Mathematical, Physical, and Engineering Sciences*, vol. 370 (2012), p. 4217 (hereinafter Latham 2012).

Note: Image acquired January 15, 2018, by the VIIRS instrument on board the Suomi NPP Satellite, showing ship tracks over the ocean to the west of the Iberian Peninsula.

The MCB technique would involve spraying a mist of submicrometer seawater particles into marine stratocumulus clouds.[36] The spray particles would form small droplets within the cloud; these droplets would increase the cloud's reflectivity, increasing the amount of incoming solar energy reflected back out into space. The method can be implemented only where appropriate marine cloud types occur, and the most extensive oceanic occurrence of these clouds is near the western coasts of North and South America and Africa.[37]

Potential Cooling Effects of MCB

Using climate models to estimate the potential effectiveness of MCB, some researchers have found that MCB could provide a cooling effect that would mitigate some of the warming effect caused by the increase in concentrations of atmospheric CO_2 from human activities.[38]

Some research indicates that MCB would be able to offset the warming effect of a doubling of atmospheric CO_2 as compared to levels before the industrial revolution; however, other studies indicate that while there would be some cooling effect, it would not be sufficient to offset this level of warming.[39]

Potential Concerns/Drawbacks of MCB

Some modeling studies of MCB have suggested it could alter precipitation patterns at global and regional levels, although studies have differed in their results.[40] For example, one modeling study indicated that MCB caused a 50% decrease in Amazonian precipitation.[41] Other modeling studies, however, found that precipitation in the Amazon was not sensitive to MCB, increased, or decreased.[42] Other modeling studies that examined the potential impacts of MCB on Arctic and

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[36] Latham 2012. A micrometer is one-millionth of a meter, or 0.001 millimeters.

[37] J. Latham et al., "Marine Cloud Brightening: Regional Applications," *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, vol. 372, no. 2031 (2014), 20140053 (hereinafter Latham 2014).

[38] Latham 2012. The experimental design of the study was described in the journal article cited as follows:

> The three simulations used in our current studies are (1) a control (CON) with carbon dioxide levels held at a 2020 projected level of 440 ppm; (2) a climate change (CC) simulation, where the carbon dioxide fraction increases by 1% p.a. until 2045, where it is held steady at 560ppm for the duration of the simulation, until 2090; and (3), an MCB simulation, which is the same as the [CC] simulation except that it includes seeding in the three stratocumulus regions defined above. All simulations were run for 70 model years with the final 20 years (2070–2090) used for analysis.

[39] Latham 2012. See also P. Forster et al., "The Earth's Energy Budget, Climate Feedbacks, and Climate Sensitivity" in *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (Cambridge, United Kingdom: Cambridge University Press, 2021), p. 943. See also Spencer Hill and Yi Ming, "Nonlinear Climate Response to Regional Brightening of Tropical Marine Stratocumulus," *Geophysical Research Letters*, vol. 39, no. 15 (2012); and A. Jones et al., "Climate Impacts of Geoengineering Marine Stratocumulus Clouds," *Journal of Geophysical Research: Atmospheres*, vol. 114, no. D10 (2009) (hereinafter Jones 2009).

[40] G. Bala et al., "Albedo Enhancement of Marine Clouds to Counteract Global Warming: Impacts on the Hydrological Cycle," *Climate Dynamics*, vol. 37, no. 5 (2011), p. 915 (hereinafter Bala 2011). As of the date of this report, atmospheric CO_2 concentration was below 430 ppm; see also NOAA, "Global Monitoring Laboratory: Trends in CO_2," https://gml.noaa.gov/ccgg/trends/.

[41] A. Jones et al., "Climate Impacts of Geoengineering Marine Stratocumulus Clouds," *Journal of Geophysical Research: Atmospheres*, vol. 114, no. D10 (2009) (hereinafter Jones 2009).

[42] Bala 2011; see also Spencer Hill and Yi Ming, "Nonlinear Climate Response to Regional Brightening of Tropical

Antarctic sea ice extent have also produced variable results.[43] As different models were used in these studies, direct comparison of results is challenging.

Researchers have identified a number of key knowledge gaps regarding the use of MCB to lower global temperatures. These include both the basic science relevant to the method, such as the current state of knowledge of cloud physical processes, and technological implementation challenges, such as the development of appropriate spray technology.[44]

As with SAI, some research indicates that an abrupt halt of MCB could result in global temperatures increasing to levels comparable to temperature levels occurring if MCB had not been implemented.[45]

Cirrus Cloud Thinning (CCT)

Wispy, high-altitude cirrus clouds help prevent longwave heat energy from leaving the Earth. CCT is a proposed method of reducing cirrus clouds, allowing more longwave heat energy to escape into space, which could compensate for some of the warming caused by anthropogenic GHG emissions.[46]

Cirrus clouds consist of ice crystals, and the extent to which these clouds persist in the atmosphere is determined in part by how quickly the clouds' ice crystals fall out of the atmosphere. CCT would involve adding an aerosol of insoluble particles to the cloud, which would form larger crystals than the smaller ice-only crystals. These larger crystals would fall out of the atmosphere more quickly than the naturally forming ice-only crystals, thus thinning the cirrus cloud and allowing more heat energy to escape.[47] One proposed CCT method would be to use specially adapted commercial aircraft to disperse nucleation, or seed, aerosols into cirrus clouds.[48]

Potential Effects of CCT on Global Temperatures

There is scientific debate about whether CCT would have the desired cooling effect. A 2009 peer-reviewed theoretical study indicated that CCT could provide a significant reduction in radiative forcing, although later studies have found a range of results.[49] One study, for example, found that CCT could provide a cooling effect with optimum ice nuclei seeding concentrations, but that higher concentrations produced a warming rather than a cooling effect.[50] Other studies did not

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Marine Stratocumulus," *Geophysical Research Letters*, vol. 39, no. 15 (2012).

[43] P. J. Rasch et al., "Geoengineering by Cloud Seeding: Influence on Sea Ice and Climate System," *Environmental Research Letters*, vol. 4, no. 4 (2009), 045112. See also B. Parkes et al., "The Effects of Marine Cloud Brightening on Seasonal Polar Temperatures and the Meridional Heat Flux," *ISRN Geophysics*, vol. 2012 (2012), p. 1.

[44] Knowledge gaps have been identified in Latham 2012 and in the Marine Cloud Brightening Project, "About Us," https://mcbproject.org/about-us/, including cloud-aerosol interactions and cloud physical processes; climate models' inability to adequately simulate some marine clouds; and designs for the necessary sea spray technology.

[45] Jones 2009.

[46] NASEM 2021.

[47] David L. Mitchell and William Finnegan, "Modification of Cirrus Clouds to Reduce Global Warming," *Environmental Research Letters*, vol. 4, no. 4 (2009), 045102 (hereinafter Mitchell and Finnegan 2009).

[48] Mitchell and Finnegan 2009.

[49] Mitchell and Finnegan 2009.

[50] T. Storelvmo and N. Herger, "Cirrus Cloud Susceptibility to the Injection of Ice Nuclei in the Upper Troposphere," *Journal of Geophysical Research: Atmospheres*, vol. 119, no. 5 (2014), p. 2375 (hereinafter Storelvmo and Herger 2014).

find CCT to be effective in providing a cooling effect or found that different models produced different degrees of cooling.[51] A scientific consensus on the effectiveness of CCT has not been reached.

Potential Concerns/Drawbacks of CCT

Researchers have identified a number of knowledge gaps with respect to the potential development of CCT, including how ice crystals in cirrus clouds nucleate and freeze, which aerosols are effective for this process, and how the technology for implementing CCT would work, among other challenges.[52] One researcher stated that "uncertainties in both observations and modeling of cirrus clouds place some doubt on all cirrus seeding studies."[53]

Concerns About SG

Uncertainties about SG include

- uncertainty about some of the underlying physical and chemical processes of SG methods,
- uncertainty regarding the technical feasibility of SG implementation,
- uncertainty that the proposed SG methods will be able to provide large-scale cooling effects even if successfully deployed, and
- uncertainty about the potential regional and global effects on the Earth's climate, apart from the possible cooling effects.

As of May 2023, no SG field experiments at scale have been carried out, and one effort to do so proved controversial and was canceled. Thus, most of the current understanding about SG comes from theoretical and modeling studies.[54]

Scientific and academic groups are divided over SG research and implementation in the United States and other countries.[55] In January 2022, an international coalition of scientists and scholars launched an effort advocating for a solar geoengineering non-use agreement in an "open letter." The open letter advocates for the adoption of an official policy of SG non-use, including a

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[51] J. E. Penner et al., "Can Cirrus Cloud Seeding Be Used for Geoengineering?" *Geophysical Research Letters*, vol. 42, no. 20 (2015), p. 8775; these authors do not find CCT to be an effective cooling technique. See also B. Gasparini et al., "To What Extent Can Cirrus Cloud Seeding Counteract Global Warming?" *Environmental Research Letters*, vol. 15, no. 5 (2020), 054002; these researchers found that different models produced differing results.

[52] Storelvmo and Herger 2014; see also D. J. Cziczo et al., "Clarifying the Dominant Sources and Mechanisms of Cirrus Cloud Formation," *Science*, vol. 340, no. 6138 (2013), p. 1320 (hereinafter Cziczo 2013); B. Gasparini and Ulrike Lohmann, "Why Cirrus Cloud Seeding Cannot Substantially Cool the Planet," *Journal of Geophysical Research: Atmospheres*, vol. 121, no. 9 (2016), p. 4877 (hereinafter Gasparini and Lohmann 2016); J. E. Kristjánsson et al., "The Hydrological Cycle Response to Cirrus Cloud Thinning," *Geophysical Research Letters*, vol. 42, no. 24 (2015), p. 10,807 (hereinafter Kristjánsson 2015).

[53] Gasparini and Lohmann 2016; see also Storelvmo and Herger 2014; J. E. Penner et al., "Can Cirrus Cloud Seeding Be Used for Geoengineering?" *Geophysical Research Letters*, vol. 42, no. 20 (2015), p. 8775; B. Gasparini et al., "To What Extent Can Cirrus Cloud Seeding Counteract Global Warming?" *Environmental Research Letters*, vol. 15, no. 5 (2020), 054002.

[54] Henry Fountain and Christopher Flavelle, "Test Flight for Sunlight-Blocking Research Is Canceled," *New York Times*, April 2, 2021, https://www.nytimes.com/2021/04/02/climate/solar-geoengineering-block-sunlight.html.

[55] Alejandro de la Garza, "A Controversial Technology Is Creating an Unprecedented Rift Among Climate Scientists," *Time*, March 17, 2023, https://time.com/6264143/geoengineering-climate-scientists-divided/.

commitment not to use government funds for the development of SG.[56] The group is concerned that the potential adverse impacts of SG are not well understood, that the perception of SG's availability may reduce the policy commitment to emission reductions, and that global governance systems, both institutional and informal, are inherently incapable of providing equitable control of SG.

Another group of scientists and scholars calling for "balance in research and assessment of solar radiation modification" takes the position that the risk of adverse impacts from climate change is so great that a well-regulated program of research should be considered to provide SG as an option if necessary.[57] In an open letter published online in 2023, the group cites the possibilities that climate mitigation efforts such as emissions reductions and CO_2 removal may prove inadequate, by themselves, in averting catastrophic adverse climate impacts. They state that research on SG is necessary to make informed decisions about SG, including a decision not to implement SG if research findings indicate that it is too risky. The group advocates the formation of a governance framework based on a set of ethical principles before any possibility of implementation of SG.

Federal Law and SG

A number of statutes may be relevant to SG, although Congress has not considered or passed any law with the exclusive purpose of covering SG activities. For example, the Weather Modification Reporting Act of 1972 (15 U.S.C. §§330 et seq.) has a reporting requirement for activities "Modifying the solar radiation exchange of the Earth or clouds, through the release of gases, dusts, liquids or aerosols into the atmosphere."[58] Also, if sulfate aerosols used in SAI are found to have a damaging effect on stratospheric ozone, their use in SG might be regulated under Title VI of the Clean Air Act Amendments of 1990 (42 U.S.C. §7401).

International Agreements and SG

To date, no multilateral treaty is in force or has been proposed with the exclusive intent of addressing the full spectrum of possible geoengineering activities, including SG. However, principles of customary international law and existing international agreements may be relevant to SG research or deployment projects. Customary international law refers to the general and consistent practices by countries that are followed from a sense of legal obligation.[59] Under customary international law, countries have a duty not to cause significant transboundary harm.[60]

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[56] Solar Geoengineering Non-Use Agreement, "Open Letter," https://www.solargeoeng.org/non-use-agreement/open-letter/.

[57] Claudia Wieners et al., "Solar Radiation Modification Is Risky, but So Is Rejecting It: A Call for Balanced Research," https://www.call-for-balance.com/letter.

[58] C.F.R. 908.3(a)(3).

[59] Restatement (Third) of Foreign Relations Law §102, (1987).

[60] Ibid. at §601(1) (stating that a nation is generally obligated to take "such measures as may be necessary, to the extent practicable under the circumstances, to ensure that activities within its jurisdiction or control ... are conducted so as not to cause significant injury to the environment of another state.") Countries are also obligated under international law to take necessary measures to the extent practicable to prevent, reduce, and control pollution that is causing or threatening to cause significant injury to the marine environment. Ibid. at §603(2).

Because SG carries with it the likelihood of transboundary effects, this duty could be relevant to SG research and/or deployment projects.[61]

The international agreements on climate change encourage their parties to implement national policies and mitigation actions to reduce their greenhouse gas emissions.[62] As SG does not directly affect atmospheric GHG concentrations, only those aspects that address climate change mitigation more broadly are likely to be relevant to SG.[63] In addition, the Convention on Biological Diversity (CBD), in a decision adopted on December 2016 at the 14th Congress of Parties to the Convention, noted the need for geoengineering research.[64] MCB specifically may fall under the marine geoengineering provisions of the London Protocol, as MCB carries the risk of deleterious effects.[65] Aspects of other international agreements may subsequently be found to be relevant to SG.

Congressional Action and Considerations

The 117th Congress appropriated funds for FY2022 for activities related to SG in the Consolidated Appropriations Act of 2022.[66] These included the preparation of a report by the Office of Science and Technology Policy (OSTP) in conjunction with the National Oceanic and Atmospheric Administration (NOAA) and the National Science Foundation (NSF):

> NOAA is directed to support OSTP, in coordination with DOE and the National Science Foundation (NSF), to provide a five-year plan, not later than 180 days after enactment of this Act, with a scientific assessment of solar and other rapid climate interventions in the context of near-term climate risks and hazards. The report shall include: (1) the definition of goals in relevant areas of scientific research; (2) capabilities required to model, analyze, observe, and monitor atmospheric composition; (3) climate impacts and the Earth's radiation budget; and (4) the coordination of Federal research and investments to deliver this assessment to manage near-term climate risk and research in climate intervention.[67]

Further, under this legislation OSTP, working with NOAA, the National Aeronautics and Space Administration (NASA), and the Department of Energy (DOE), is tasked to form an interagency

[61] CRS Report R41371, *Geoengineering: Governance and Technology Policy*, by Kelsi Bracmort and Richard K. Lattanzio.

[62] United Nations Framework Convention on Climate Change, May 9, 1992, 1771 U.N.T.S. 107; S. Treaty Doc No. 102-38, htttps://unfccc.int/resource/docs/convkp/conveng.pdf. See also Paris Agreement to the United Nations Framework Convention on Climate Change, December 12, 2015, T.I.A.S. No. 16-1104, https://unfccc.int/sites/default/files/english_paris_agreement.pdf; CRS Report R44609, *Climate Change: Frequently Asked Questions About the 2015 Paris Agreement*, by Jane A. Leggett and Richard K. Lattanzio.

[63] Jesse L. Reynolds, "Solar Geoengineering to Reduce Climate Change: A Review of Governance Proposals," *Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences*, vol. 475, no. 2229 (2019), 20190255 (hereinafter Reynolds 2019).

[64] "[T]hat more transdisciplinary research and sharing of knowledge among appropriate institutions is needed in order to better understand the impacts of climate related geoengineering on biodiversity and ecosystem functions and services, socio economic, cultural and ethical issues and regulatory options"; see Conference of the Parties to the Convention on Biological Diversity, December 4-17, 2016, Decision XIII/14, https://www.cbd.int/doc/decisions/cop-13/cop-13-dec-14-en.pdf.

[65] London Protocol, "Annex 4 Resolution LP.4(8) On the Amendment to the London Protocol to Regulate the Placement of Matter for Ocean Fertilization and Other Marine Geoengineering Activities," adopted October 18, 2013.

[66] U.S. Congress, House Committee on Appropriations, *Consolidated Appropriations Act, 2022 (H.R. 2471; P.L. 117-103): Provisions Applying to All Divisions of the Consolidated Appropriations Act*, committee print, 117th Cong.

[67] U.S. Congress, House Committee on Appropriations, *Consolidated Appropriations Act, 2022* (*H.R. 2471*; *P.L. 117-103*)*: Provisions Applying to All Divisions of the Consolidated Appropriations Act*, committee print, 117th Cong.

working group to manage SG risk and research and to develop a governance framework for publicly funded SG research.[68]

OSTP put out a public call for input on the five-year plan limited to comments regarding research on the plan's climate intervention components. The comment period ended on September 9, 2022.[69] As of May 2023, OSTP has not published the report on solar geoengineering specified in the statute.[70] The USGCRP operates under OSTP and provides a list of climate-related interagency working groups. As of May 2023, the interagency working group tasked to coordinate SG research and create an SG research governance framework does not appear on the list of interagency working groups.[71]

As described above, a number of U.S. statutes may be relevant to SG, and Congress may review and amend the existing statutes such that they refer specifically to SG. Research and implementation of SG, including unilateral action by countries or nonstate actors, could have transboundary global effects that could affect international relations. Congress may consider these potential effects in determining SG policy.[72]

Congressional actions regarding deploying SG would likely need to assess the trade-off in choosing between the potential benefits provided by SG—atmospheric cooling to offset GHG-driven global warming—against the risks associated with SG described above. Congress also may consider how the potential need to deploy SG might evolve if global GHG emissions increase or decrease in the future: a rise may increase focus on SG as a means to offset global warming associated with more GHGs in the atmosphere, whereas a decrease in GHG concentrations may reduce the potential need for SG.

There are uncertainties regarding SG with respect to the underlying science, the technological implementation, the effects on the Earth's climate, and the mechanisms for the governance of SG research and development, indicating that SG is currently not a technology that is likely to be ready for development and implementation in the near or medium term.[73]

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[68] U.S. Congress, House Committee on Appropriations, *Consolidated Appropriations Act, 2022 (H.R. 2471; P.L. 117-103): Provisions Applying to All Divisions of the Consolidated Appropriations Act*, committee print, 117th Cong.

[69] The White House, "Request for Input to a Five-Year Plan for Research on Climate Intervention," https://www.whitehouse.gov/ostp/legal/.

[70] P.L. 117-103 became law on March 15, 2022, specifying that the five-year plan was to be provided within 180 days of after enactment—that is, on or before September 11, 2022.

[71] U.S. Global Change Research Program, "Interagency Groups," https://www.globalchange.gov/about/iwgs.

[72] Reynolds 2019; see also Arunabha Ghosh, "Environmental Institutions, International Research Programmes, and Lessons for Geoengineering Research," in *Geoengineering Our Climate?* (New York: Routledge, 2018), pp. 199-213, https://doi.org/10.4324/9780203485262-37.

[73] NASEM 2021; see also M. Diamond et al., "To Assess Marine Cloud Brightening's Technical Feasibility, We Need to Know What to Study—and When to Stop," *Proceedings of the National Academy of Sciences*, vol. 119, no. 4 (2022), e2118379119; see also United Nations Environment Program, *One Atmosphere: An Independent Expert Review on Solar Radiation Modification Research and Deployment*, February 28, 2023.

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