Stratospheric geoengineering would come with benefits but also risks and concerns. More research is needed.

Benefits and Risks of Stratospheric Solar Radiation Management for Climate Intervention (Geoengineering)

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Climate intervention (geoengineering) is being considered as a response to global warming. I discuss the scheme that has been studied the most: creation of a permanent sulfuric acid cloud in the stratosphere to reflect sunlight, mimicking large volcanic eruptions. It is impossible to do today, as the technology remains to be invented, and I discuss the engineering challenges and costs. Even if it becomes possible, stratospheric geoengineering would come with benefits but also risks and concerns. Quantifying these benefits and risks requires more research.

Introduction

Global warming is a real threat to human and other life on Earth. The question is what to do about it. The answer, as explained, for example, in the recommendations of a US National Research Council report on climate intervention (NRC 2015), is mitigation (leaving fossil fuels in the ground), adaptation, and attempts to remove carbon dioxide from the atmosphere. However, despite decreasing costs for solar and wind power, current mitigation pledges are not expected to keep global warming under 2°C above preindustrial global average surface air temperatures (e.g., Robiou du Pont and Meinshausen 2018). Therefore, there have been suggestions to consider schemes to reflect sunlight to cool Earth.

Definition of Terms

Ideas for removing carbon dioxide from the atmosphere or reflecting sunlight to cool Earth used to be called geoengineering or climate engineering, but the favored term nowadays (e.g., AGU 2018; NRC 2015) is climate intervention. In this article, the word "geoengineering" appears as a legacy of previous nomenclature.

Solar radiation management proposals include use of stratospheric aerosols to block sunlight, mimicking volcanic eruptions.

The definition of climate intervention is "deliberate large-scale manipulation of the planetary environment to counteract anthropogenic climate change" (Shepherd et al. 2009, p. 1). It is conventionally separated into carbon dioxide removal (CDR) and solar radiation management (SRM, also called albedo modification), which have completely different technologies, benefits, risks, governance, and ethics. This paper deals with SRM, and mostly with proposals to use stratospheric aerosols to block sunlight, mimicking volcanic eruptions.

UN Framework Convention on Climate Change

The 1992 United Nations Framework Convention on Climate Change, signed and ratified by the United States, says,

> The ultimate objective of this Convention…is to achieve…stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent *dangerous anthropogenic interference* [DAI; emphasis added] with the climate system. Such a level should be achieved within a time frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened and to enable economic development to proceed in a sustainable manner.[1]

At the time, DAI did not have a specific definition. Enacting the Convention has been done by annual Conferences of the Parties (COPs). The third COP in Kyoto (1997) produced a protocol that was ineffective, as it required only developed (but not developing) countries to mitigate. It was not until COP15 in Copenhagen in 2009 that the world agreed to define DAI as global average surface air temperature greater than 2 K above preindustrial temperatures. At COP21 in Paris in 2015 various nations made voluntary pledges to reduce their emissions to try to prevent DAI, and an aspirational goal of keeping global warming under 1.5 K was also discussed.

A Combined Approach

Because the world is not moving rapidly to prevent DAI (e.g., Tollefson 2019) at either the 1.5 K or 2 K level, SRM—together with rapid conversion of the world's energy system and large-scale CDR, such as in the Representative Concentration Pathway 2.6 (van Vuuren et al. 2011)—is now being assessed as a possible additional response (e.g., MacMartin et al. 2018).

This paper discusses how SRM could be done technically, the research that needs to be done, the ethics and governance of such research, and potential benefits, concerns, and risks of SRM.

Geoengineering Methods and Costs

The technology for SRM does not yet exist (Smith and Wagner 2018). The two techniques that have been studied the most and seem the most practical involve either creating a sulfuric acid cloud in the stratosphere to simulate what large volcanic eruptions do occasionally, or brightening low clouds over the ocean (Robock et al. 2013). Brightening the surface (e.g., Oleson et al. 2010) is not considered to be effective on a global basis, and reflectors in space (e.g., Angel 2006) are unworkable and expensive. Much research is needed to tell whether it is possible to brighten marine clouds in a controlled way (NRC 2015), but stratospheric aerosol clouds do cool Earth after volcanic eruptions (Robock 2000), so I focus on that scheme here.

While balloons, artillery, and even towers have been suggested to get sulfur dioxide (SO_2, the precursor gas to sulfuric acid clouds created by volcanic eruptions) into the stratosphere (figure 1), the cheapest and most straightforward method would be with airplanes (Robock et al. 2009). However, it is not possible to retrofit current airplanes with the bigger engines or longer wings needed to do the job (Smith and Wagner 2018).

NAS, NAE, and IOM (1992) made the first quantitative estimates of the cost of putting gases or particles into the stratosphere to simulate volcanic eruptions; subse-

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[1] Available at https://unfccc.int/files/essential_background/background_publications_htmlpdf/application/pdf/conveng.pdf.

quent updates were rather rough estimates (McClellan et al. 2012; Robock et al. 2009). Now two teams have produced estimates that include the costs of developing new airplanes to inject particles (or their precursors) into the stratosphere (de Vries et al. 2020; Janssens et al. 2020; Smith and Wagner 2018). Such an aircraft could be operated remotely to save energy and weight by not having a pilot onboard (de Vries et al. 2020).

To estimate the cost, it is necessary to first decide how thick a cloud to create. Scenarios have been modeled to keep surface temperatures from changing until the end of the 21st century despite business-as-usual greenhouse gas emissions (Niemeier and Timmreck 2015; Tilmes et al. 2018), but those are model exercises and not meant to suggest an actual deployment.

Here, I choose a scenario where the climate still overshoots the preindustrial average by 1.5 or 2 K (e.g., Jones et al. 2018; Tilmes et al. 2016), and SRM would be applied for a limited time, as illustrated in John Shepherd's "napkin diagram" (Long and Shepherd 2014; figure 2). This scenario would require radiative forcing of about -2 W m^{-2} (Tilmes et al. 2016), which is also what would be required to offset half the climate change that would result from doubling atmospheric CO_2. Accounting for aerosol growth as SO_2 is continuously injected into an existing stratospheric cloud, the scenario would require about 12 teragrams (Tg; 1 Tg = 1 million tons) of sulfur (S) per year (Niemeier and Timmreck 2015).

If larger negative radiative forcing from stratospheric aerosols were required, the costs would go up nonlinearly, because additional SO_2 emissions would cause existing aerosol particles to grow larger, making them less effective at scattering per unit mass and likely to fall out of the stratosphere faster (Heckendorn et al. 2009). For example, a radiative forcing of -4 W m^{-2} would require 27 Tg S per year (Niemeier and Timmreck 2015).

Table 1 shows estimated costs based on four papers, scaling up from the cost of putting 1 Tg of material into the stratosphere per year. Volcanic stratospheric clouds are produced by injections of SO_2, so that might be the gas of choice, but some have suggested H_2SO_4 to reduce growth of aerosol particles (e.g., Pierce et al. 2010). However, it is not known if it is possible to produce sulfate droplets of the desired size distribution.

The price of the materials would probably not be a limiting factor, as sulfur is plentiful. Other substances have been suggested—such as calcium carbonate, aluminum oxide, or even diamonds (Keith et al. 2016), all of which might cause less ozone depletion—but there have been no studies of their practicality.

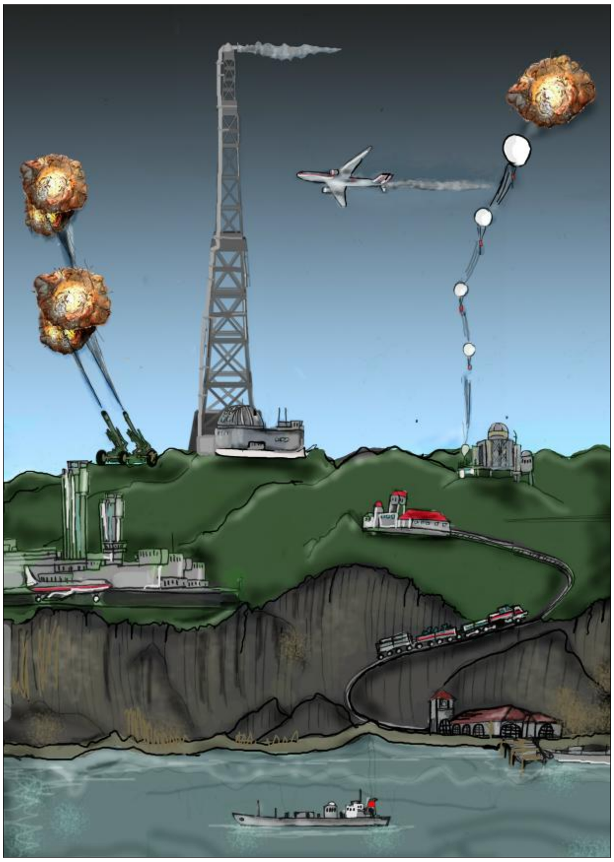

FIGURE 1 Proposed methods of stratospheric aerosol injection. Supplies would be delivered by ship and taken by train up the mountain. Then airplanes would fly them up, or they could be shot in artillery shells, sprayed from a tall tower, or delivered by balloons. A mountaintop location would require less energy for lofting to the stratosphere. Drawing by Brian West. Reprinted with permission from Robock et al. (2009).

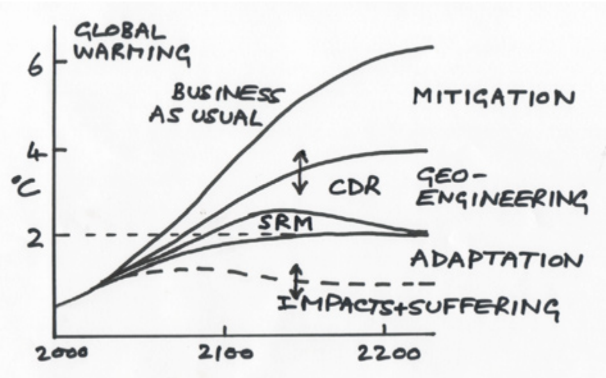

FIGURE 2 The "napkin diagram" originally drawn by John Shepherd on a napkin at the Asilomar International Conference on Climate Intervention Technologies in 2010. CDR = carbon dioxide removal; SRM = solar radiation management. Available at http://jgshepherd.com/wp-content/uploads/2011/01/Napkin-diagram.pdf and used by permission. Formally published as figure 87.1 in Long and Shepherd (2014).

TABLE 1 Annual cost in billions of US dollars to produce $-2\ \mathrm{W\ m^{-2}}$ using sulfur flown into the lower stratosphere, which would require 12 teragrams (Tg) of sulfur (S) per year (Tg S/yr; Niemeier and Timmreck 2016), based on four analyses. Smith and Wagner (2018) propose lofting liquid sulfur and burning it in the stratosphere to produce SO_2, but the other estimates include the costs of lofting SO_2 or H_2SO_4; SO_2 (64 g/mole) would require 24 Tg/yr, and H_2SO_4 (98 g/mole) would require 37 Tg/yr. The cost of construction of the airplanes is amortized over 20 years. Of the three H_2SO_4 options considered in de Vries et al. (2020), the cheapest is used here. Payload costs for SO_2 and H_2SO_4 are from de Vries et al. (2020).

	SO_2	H_2SO_4
Robock et al. (2009)	107	172
McClellan et al. (2012)	42	72
Smith and Wagner (2018)	17	69
de Vries et al. (2020)	34	54

To summarize, there is currently no way to do stratospheric climate intervention. However, designs of airplanes to loft sulfur into the stratosphere suggest that under a credible SRM scenario it would cost \$20–\$200 billion per year. Research and development to see if that is even practical remain to be done.

Research

Ethics and Governance

While the NAS concludes that "Albedo modification at scales sufficient to alter climate should not be deployed at this time," the authoring committee also recommended that "an albedo modification research program be developed and implemented that emphasizes multiple-benefit research that also furthers basic understanding of the climate system and its human dimensions" (NRC 2015, pp. 9, 10). This raises the question of whether such research is ethical (Robock 2012a).

Arguments for and against SRM Research

Although deployment of SRM may never be part of a portfolio to deal with global warming (Pierrehumbert 2019; Robock 2012b), a decision to deploy should be informed by knowledge of its potential benefits and risks. The National Academies of Sciences, Engineering, and Medicine (NASEM), as part of a major initiative on America's Climate Choices, have a committee working on such a research plan, to be published in 2020.[2]

Arguments against SRM research include a slippery slope to deployment or diversion of resources that could be better spent on something more valuable. Arguments in favor of such research include the need to know what would happen in order to avoid the risk of deployment in ignorance of potential consequences, the discovery of "showstoppers" that would reduce the likelihood of deployment, and the integral role of modeling research for climate intervention to improve climate models used for other purposes.

The National Research Council (NRC 2015), American Meteorological Society (AMS 2013), and American Geophysical Union (AGU 2018) all agree with previous strong recommendations for geoengineering research (e.g., Betz 2012; GAO 2011; Keith et al. 2010).

Indoor vs. Outdoor SRM Research

SRM research can be separated into indoor and outdoor (Robock 2012a). Indoor research consists of climate modeling of various SRM scenarios as well as analysis of analogs, such as volcanic eruptions, with climate models and study of observations. It may also involve technological development of nozzles or aircraft that could be used for deployment.

Outdoor research, which involves injecting salt particles into marine clouds or various substances into the stratosphere, requires governance, including review of potential environmental impacts, monitoring of the experiments, and sanctions if the researchers break the rules (e.g., Shepherd et al. 2009). The NASEM committee that is planning a research agenda is also looking at research governance approaches, and the Keutsch group at Harvard, which is planning an outdoor Stratospheric Controlled Perturbation Experiment (SCoPEx), has established an external advisory committee as a form of governance research.[3] But there are no national or international governance structures.

Perhaps outdoor research that involves the development of ships or planes designed for deployment, but

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[2] Information on the project for Developing a Research Agenda and Research Governance Approaches for Climate Intervention Strategies That Reflect Sunlight to Cool Earth is available at http://nas-sites.org/americasclimatechoices/new-study-reflecting-sunlight/.

[3] https://projects.iq.harvard.edu/keutschgroup/scopex-governance

does not involve spraying, can be done without governance to show how difficult and expensive it might be. Any spraying requires governance. Outdoor experiments that go beyond trying to build the equipment to brighten clouds or produce stratospheric aerosols need to be scientifically justified: What can be learned from them that cannot be learned from modeling and analogs?

Climate Modeling

Modeling is a major part of indoor research on climate change. Unlike other science, the system under study is the entire Earth, with no separate control and experimental versions. Any test of stratospheric SRM would have to be at full-scale implementation for decades to obtain statistically significant responses (because of the chaotic nature of the climate system, a large signal is needed to overcome the noise; Robock et al. 2010). Therefore, "laboratory research" relies on computer programs that simulate the behavior of the Earth system. They use the fastest computers in the world and have been tested by simulations of past climate and with weather forecasting.

Some experts argue that outdoor research is needed because they do not have confidence in imperfect computer models. But concerns about global warming are based on computer simulations of future climate changes in response to possible scenarios of human behavior and emissions of greenhouse gases and particles.

National and International Programs

The current international cooperative project on modeling of future climate is the Coupled Model Intercomparison Project Phase 6 (Eyring et al. 2016). It includes the Geoengineering Model Intercomparison Project (GeoMIP), in which 19 climate modeling groups have simulated how the climate would respond to reduced insolation, creation of a stratospheric aerosol cloud, or brightened marine clouds to reduce climate change from various global warming scenarios. GeoMIP (Kravitz et al. 2011) has produced more than 85 peer-reviewed publications, and results from experiments with the latest models (Kravitz et al. 2015) as well as those from previous experiments continue to be analyzed. Analysis has mostly focused on climate elements, but impacts also need to be studied, including those on agriculture and ecosystems (e.g., Trisos et al. 2018). There is no organized research program to support either the modeling or analysis of the experiments, but it is planned as part of the NASEM program.

Beyond the GeoMIP-specified research, new experiments, some labeled as GeoMIP Testbeds, are being conducted. These include the Stratospheric Aerosol Geoengineering Large Ensemble (GLENS) project (Tilmes et al. 2018). In addition, the Geoengineering Modeling Research Consortium (www.cgd.ucar.edu/projects/gmrc) has been initiated to coordinate testbed and other model simulations.

The Open Philanthropy Project funds the Developing Country Impacts Modelling Analysis for SRM (DECIMALS) project (www.srmgi.org/decimals-fund) to use local expertise to examine impacts in less developed countries. Eight DECIMALS teams are using output from GeoMIP and GLENS simulations to analyze impacts on agriculture, drought, dust storms, and the spread of cholera in Argentina, Bangladesh, Benin, Indonesia, Iran, Ivory Coast, Jamaica, and South Africa. Such work supports research capacity building and helps those who might be affected by SRM to have a voice in future research and implementation decisions.

What can be learned from outdoor experiments that cannot be learned from modeling and analogs?

In the United States there are many national centers (e.g., NCAR, the NOAA Geophysical Fluid Dynamics Laboratory, NASA Goddard Institute for Space Studies, NASA Goddard Space Flight Center, and the DOE with its new Earth system modeling efforts) with the resources to conduct relevant, needed research. In particular, NCAR has global climate modelers, land surface experts, cloud experts, and people working on impacts.

Business-as-usual research does not provide many resources for studying climate intervention (Necheles et al. 2018). Private funding is the largest source for global geoengineering research—$6 million in 2018; government funding fell from almost $6 million in 2014 to $2 million in 2018.

Deployment Scenarios

The impacts of any stratospheric SRM will depend on the amount of aerosols created and the timing and location of their deployment. So far only simple

FIGURE 3 Spectacular image of the June 22, 2019, eruption of Raikoke volcano in the Kuril Islands, from the International Space Station. Available online at https://earthobservatory.nasa.gov/images/145226/raikoke-erupts.

deployments have been studied, such as spraying aerosol precursors in the tropics (GeoMIP) or subtropics (GLENS) to produce globally averaged temperature targets or gradients. Many scenarios are extreme—such as balancing four times current CO_2 (GeoMIP G1) or business-as-usual greenhouse gas emissions until the end of the 21st century (GLENS; Niemeier and Timmreck 2015) to obtain a large signal in the climate response as compared to natural climate variability—and are not proposed as realistic.

Future research is planned with scenarios that might involve credible deployments, such as balancing overshoot scenarios to keep global warming at less than 1.5–2.0 K above preindustrial temperatures (e.g., Tilmes et al. 2016). In addition, research into the use of actual impacts on, for example, agricultural production, water availability, or human health as metrics, rather than global average temperatures, is in its infancy.

So far, sulfate aerosols, produced by either SO_2 gas injection or sulfate aerosol direct injection (e.g., Vattioni et al. 2019), have been the major type studied. Other types have been suggested, but study of them is just beginning (e.g., Keith et al. 2016). Given experience with sulfate aerosol clouds from volcanic eruptions and the availability of sulfur, the latter will probably remain the chemical of choice, but the engineering of sulfate aerosol particle production and the engineering, benefits, and risks of other chemicals deserve further study.

Analogues

The best analogue for stratospheric geoengineering is volcanic eruptions that inject sulfur into the stratosphere. Eruptions such as Eyjafjallajökull in 2010, which produced only tropospheric emissions, do not cause climate change as the aerosols have a lifetime of about a week rather than a year for the stratosphere. The last large eruption (defined as a stratospheric injection of 5 Tg SO_2) was that of Mount Pinatubo in the Philippines (17 Tg SO_2) in 1991, but there have been smaller ones since then, such as that of Nabro (1.3 Tg SO_2) in 2011 (Bourassa et al. 2012).

NASA (2018) has a plan to make observations following the next large volcanic eruption, using balloons immediately and airplanes later. A threshold of 1 Tg SO_2 would call for launching regular balloon flights, but the plan was not implemented after the June 2019 Raikoke eruption (figure 3), which emitted about 1.4 Tg SO_2 into the stratosphere (Simon Carn, Michigan Technological University, personal communication, June 24, 2019).

The NASA plan, once implemented, will allow observation of future eruptions not only to enhance understanding of the impacts of volcanic eruptions—the largest natural cause of climate change—but to observe how SO_2 converts into aerosols, how the aerosols grow and are transported, and how they affect ozone as well as UV and diffuse radiation at ground level. In the meantime, the same balloon instruments can monitor the background stratosphere to provide information about its composition and processes.

Summary

To produce $-2\ \mathrm{W\ m^{-2}}$ radiative forcing—enough to counter about half of the warming from doubling CO_2 or to keep global warming less than 2 K above the preindustrial level for an aggressive overshoot scenario—would cost \$20–\$200 billion per year based on current simplistic analyses. But research is needed into engineering to see if it is even possible, as the technology currently does not exist.

In addition, there are varying potential benefits, risks, and concerns associated with stratospheric solar radiation management (table 2). Recent scenarios that include more sulfur injection than originally considered and detailed analysis of the impacts (Eastham et al. 2018) suggest that the risk of additional acid rain and snow needs to be evaluated.

Table 2 is not meant to be used by just comparing the number of items on each side. Benefit number 1 is that if SRM could be implemented, it would reduce many of the impacts of global warming. The question is whether society would be willing to live with all the risks to get this benefit. Some of these risks appear to be difficult to

TABLE 2 Potential benefits, risks, and concerns of implementing stratospheric climate intervention, updated from Robock (2016).

Benefits	**Risks or Concerns**
1. Reduce surface air temperatures, which could reduce or reverse negative impacts of global warming, including floods, droughts, stronger storms, sea ice melting, and sea level rise 2. Increase plant productivity 3. Increase terrestrial CO_2 sink 4. Beautiful red and yellow sunsets 5. Unexpected benefits 6. Prospect of implementation could increase drive for mitigation	*Physical and biological climate system* 1. Drought in Africa and Asia 2. Perturb ecology with more diffuse radiation 3. Ozone depletion 4. Continued ocean acidification 5. Additional acid rain and snow 6. May not stop ice sheets from melting 7. Impacts on tropospheric chemistry 8. Rapid warming if stopped *Human impacts* 9. Less solar electricity generation 10. Degrade passive solar heating 11. Effects on airplanes flying in stratosphere 12. Effects on electrical properties of atmosphere 13. Affect satellite remote sensing 14. Degrade terrestrial optical astronomy 15. More sunburn 16. Environmental impacts of injection technology (e.g., local pollution, noise, CO_2 emissions) *Aesthetics* 17. Whiter skies 18. Make stargazing more difficult *Unknowns* 19. Human error during implementation 20. Unexpected consequences *Governance* 21. Cannot stop effects quickly 22. Commercial control 23. Whose hand on the thermostat? 24. Societal disruption, conflict between countries 25. Conflicts with current treaties 26. Moral hazard: the prospect of its effectiveness could reduce drive for mitigation *Ethics* 27. Military use of technology 28. Moral authority: do humans have the right to do this?

address (Robock 2012b). They include the difficulty of global agreement on how to set the planetary thermostat, lack of a system to determine those who would suffer and how to compensate them, rapid climate change if stratospheric injection is quickly terminated, and unexpected consequences.

Research shows that it may be possible to control regional climates (e.g., Tilmes et al. 2018), but does not show that temperature and precipitation can be controlled at the same time. As research progresses, with different scenarios, materials, and objectives, it will be interesting to reconsider table 2 in the future, add new issues that come up, remove items that have been addressed, and determine whether enough information is available to decide whether to implement SRM. If it is determined that SRM is still too risky, this will be important input to societal efforts to work much harder on mitigation.

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