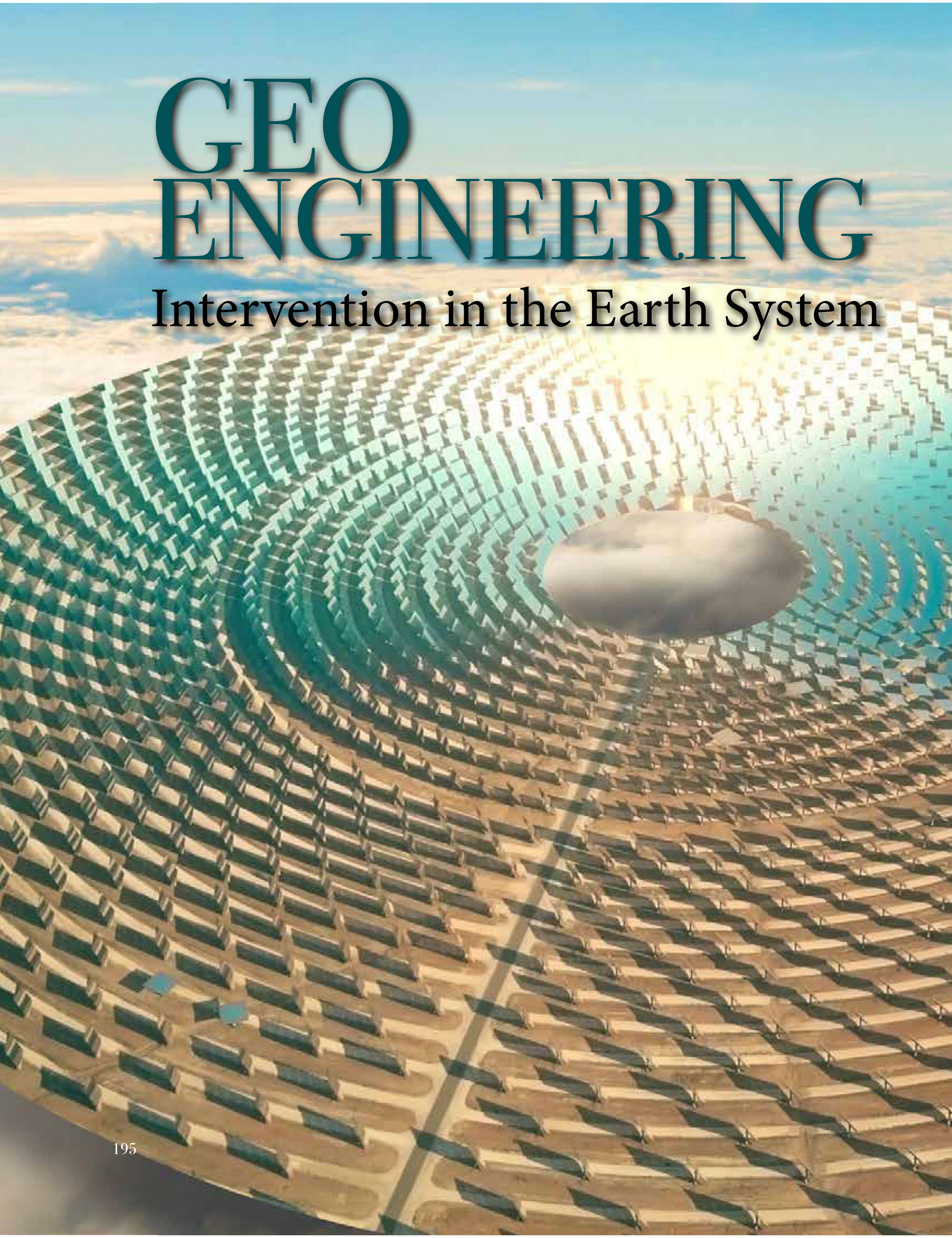
GEO ENGINEERING

Intervention in the Earth System



Op-ed

The Geopolitical Challenges of Geoengineering

and Geoengineering's Challenge to Geopolitics

Oliver Morton

In 2006 the atmospheric chemist Paul Crutzen, one of the world's most respected atmospheric scientists, published "A contribution to resolve a policy dilemma" in the journal *Climatic Change*.[1] The policy dilemma was this: the burden of respiratory disease associated with particulate emissions from coal-fired power stations was appallingly high, killing perhaps 500,000 people a year. Regulators planned to reduce this significantly by cleaning up power stations. As a result, anthropogenic sulphur emissions, then around 55m tonnes a year, would decline significantly over the coming decades.

As well as damaging people's lungs, though, the aerosol particles which sulphur emissions produce in the atmosphere also reflect sunlight back into space before it can warm the Earth's surface. The cooling due to such pollution, Crutzen estimated, was depressing the global temperature by up to one degree celsius, offsetting a significant fraction of the damage being done by anthropogenic greenhouse gas emissions. Remove those sulphur emissions, and the world would heat up more quickly than if you kept them in place. The policy dilemma: actions to reduce harm in the short term by curtailing respiratory disease would increase harm in the medium term by unleashing the full impact of greenhouse gas warming.

Crutzen suggested that the loss in cooling when sulphur emissions into the lower atmosphere were reduced could be made up for by releasing sulphur into the stratosphere. Because sulphate particles last much longer in the rainless, snowless stratosphere than in the weather-riled lower atmosphere, the amount of sulphur needed would be small compared to existing emissions: just a million tonnes or so a year, well within the technical capacity of a small fleet of aircraft.

Crutzen's paper paved the way for a growing interest in solar geoengineering: the use of technology to reduce the amount of sunlight that the earth absorbs. And in the years since its release, researchers have used computer models to produce hundreds of papers modeling solar geoengineering's climatic effects, technological implementation, adverse impacts, and compatability with notions of justice and democracy.

This climate model-based research shows that solar geoengineering could never simply cancel out anthropogenic temperature increases, let alone other climate change impacts. If carried out with stratospheric sulphur, for example, it would slow down the ozone layer's recovery from the damage caused by industry in the second half of the 20th century. It would also have a potentially profound effect on the hydrological cycle. A world in which all greenhouse warming after a certain date was offset by solar geoengineering would experience significantly less precipitation than one in which there was neither greenhouse warming nor geoengineered cooling.

However, all in all, the results of this research have increasingly come to suggest that in a world where greenhouse gas emissions peak some time between now and mid-century and then dwindle—which is to say, our current world—a solar geoengineering program that offset a signicant fraction of the resultant warming could greatly reduce overall harm. The benefits of that moderating effect would vary from region to region, but models suggest that there may well be levels and patterns of intervention where even the regions in which the benefits were found to be lowest and/or the harmful side effects highest would see little or no net harm. "Showstoppers" that cast doubt on the whole idea have, from the point of view of natural science, failed to appear.

A (Political) Science Experiment

It has thus become commonplace within the geoengineering research community to hold the opinion that the most substantial risks posed by solar geoengineering are not biogeophysical, but matters of international relations. These risks can be divided into systemic risks, which are geopolitical in the broad sense, in that they bear on international processes of decision-making, and scenario risks, which are geopolitical in the more specific sense of depending immediately on matters of territory and military capability.

The major systemic risk is the erosion of mitigation efforts. This does not depend on anyone actually doing solar geoengineering, just on people being willing to talk about and research the possibility. The insidious nature of the risk is illustrated by the role in recent climate negotiations of solar geoengineering's speculative sibling, carbon geoengineering—the active removal of carbon dioxide from the atmosphere.

It was by tacitly invoking carbon geoengineering that the Paris Agreement of 2015 was able to succeed where previous climate diplomacy had failed. Previous climate negotiations had been based, implicitly or explicitly, on the idea that the eventual level of global warming would depend on the total amount of long-lived greenhouse gas emitted into the atmosphere. A given temperature limit would imply a specific total amount of

emissions reductions required and the rate at which emissions should be cut. Major emitters, however, were not able, or willing, to promise cuts on the scale needed for the then widely accepted limit of a two degree temperature increase.

Paris squared this circle in two ways. The more obvious was that it set up a "ratcheting mechanism" whereby policies to cut emissions would get more and more ambitious over time. The second and subtler method was to open up the possibility of "negative emissions." The stable level of long-lived greenhouse gases that it imagined for the second half of the 21st centuy would not be brought about solely by an absence of anthropogenic emissions, but by the advent of technologies or policies that remove already-emitted carbon dioxide from the atmosphere. If positive and negative emissions are in balance, you have the world of "net-zero" emissions that the agreement talks about. If negative emissions come to predominate, you have a world of reducing greenhouse gas levels in which temperature will, after a certain degree of lag, actually come down. Invoking this sort of carbon geoengineering allows one to draw lines on graphs that connect today's modest emission cuts with stable and acceptable temperatures at the end of the century.

There are various plausible carbon-geoengineering technologies by means of which this might be done.[2] But at present they do not exist at any real scale, and efforts aimed at their creation and widespread acceptance are, on a global scale, nugatory. The Paris Agreement's squaring of modest emission-reduction pledges with ambitious future-temperature targets thus rests on what is in effect a fantasy (abeit one that could, in principle, be actualized). To make matters worse, the fantasy is fungible. Once you have allowed the idea of negative emissions into your thinking it is always possible, at the margin, to trade a little less emissions-reduction today for a little more negative emission tomorrow. Over time, there is nothing to stop a little from becoming a lot. The promise of geoengineering becomes a license for procrastination.

This is true regardless of whether that promise is made sincerely or cynically, or whether the geoengineering in question is carbon or solar. Indeed, the fact that both solar geoengineering and carbon geoengineering decouple climate outcomes from cumulative emissions is one of the reasons why I choose to see them as similar enough to carry the same name, despite the deep differences in the way they act and the effects they can produce. Treating either solar or carbon geoengineering as a medium-term possibility reduces the incentives for near-term emissions reduction.

This problem has been much discussed in the solar-geoengineering literature, often under the rubric of "moral hazard." The way in which the negative-emissions discussion has evolved before and after Paris strongly suggests that the risk is real: building the assumption of solar geoengineering into the policy framework really can be used to legitimize and valorize levels of effort not otherwise remotely sufficient to meet stated climate goals.

In demonstrating this, though, Paris may also have shown that the risk no longer matters. We already live in a world in which people do too little about climate change, in part because they are relying on notional future geoengineering to bail them out; it is just that the non-existent safety net is being provided by carbon geoengineering rather than solar geoengineering. It is not obvious that more serious discussion of solar geoengineering would further undermine current action on climate change.

Invidious Intervention?

Actual solar geoengineering, though, undoubtedly would. This is in part because the biogeophysical effects of solar geoengineering are strongly scenario dependent. Imagine a deployed solar-geo-engineering strategy aimed at limiting warming to two degrees while ensuring that no country or region faces unacceptable hydrological distress. The amount of cooling required will depend on the emissions pathway the world follows. If the act of starting the intervention changes the way nations act with respect to emissions, that pathway changes in turn—and thus so does the amount of solar geoengineering required. It is easy to imagine such a strategy soon finding itself in a world where its purported aim—capping temperatures but not causing hydrological distress—is no longer achievable. At this point the interests of nations in different regions, once plausibly aligned, diverge.

This is a special case of a general geopolitical problem: strategic stability. As solar geoengineering research quickened post-Crutzen, it was widely assumed that even if a strategy's net benefits were large, the workings of the climate system would ensure that they were sufficiently heterogeneous that some regions would end up worse off even if most others benefitted—in other words, that there would be winners and losers. Yet one of the most striking results to come out of solar geoengineering research has been the discovery that, in models, there seem to be strategies in which a moderate amount of solar geoengineering leaves no nation worse off than it is today.

There is a catch. A strategy in which no region loses will also be one in which some regions do less well than they would under some other strategy. Some nations will thus always have an interest in strategy change. This builds an asymmetric instability into the system that will tend to increase the amount of solar geoengineering beyond that originally seen as optimal.

Imagine a world in which a consortium of nations is injecting aerosols into the stratosphere in order to provide an optimized effect acceptable to all. Now imagine that one of those nations decides, in the light of how things play out on the ground, it wants less cooling. Unless it can convince all the other nations to agree, it is stuck; if it stops emitting aerosols unilaterally, the other nations can easily make up the deficit, keeping to the originally specified strategy. Reducing cooling (i.e., increasing warming) will always require consensus.

More cooling, though, does not. If Nation A wants more cooling, it merely needs to inject more aerosols. If the other nations reduce their contributions to try and keep things on an even keel, Nation A can decide to inject even more. If all the other nations stop injecting, Nation A can take on the whole task. This is what Marty Weitzmann and Gernot Wagner have called the "free driver" problem.[3] The amount of solar geoengineering carried out will be a function of the level of intervention preferred by the nation with the greatest desire for cooling and the willingness of other nations to impose a price for that cooling that the first nation finds unacceptable.

A New Geopolitical Phenomenon

Thus solar geoengineering depending on stratospheric aerosols offers a clear possibility of international conflict even among nations that, in principle, are all open to its deployment. This is because solar geoengineering is a global geophysical phenomenon subject to some level of national political influence—a class of phenomenon hard to embrace within current conceptions of geopolitics. The "geo" of geopolitics is, after all, fundamentally that of the geographer's map; a heterogeneous two-dimensional surface divided up among players whose interactions are encouraged or constrained by their relative sizes and positions. The "geo" of geoengineering is the geo of geophysics and biogeochemistry; an earth system in constant flux. This Earth system is in some ways deeply non-local; carbon dioxide emitted from any given source is like that from every other, for example. In other ways it is defiantly local; the climatic state, and direction of change, differ from place to place.

A geopolitics, and system of international relations, conceived on the basis of nations that hold territories, is a poor fit to the political demands of a unified planetary system defined by the flows of energy and material through unending climatic and biogeochemical cycles. Many of the problems that have dogged the development of climate diplomacy can be seen as direct or indirect consequences of that poor fit. But they are not necessarily perceived as such, because the concepts through which the problems are discussed—the natural climate, the economy—do not feel fundamentally new.

Solar geoengineering, on the other hand, is new: a global geophysical phenomenon subject to some level of national political influence that does not exist in any form today, but could tomorrow. It thus sheds a unique light on the degree to which a geopolitics that grew up in a world of great powers can be reconciled with an Earth system of planet-spanning flows, and on the challenges that such a reconciliation will entail. Solar geoengineering raises problems within geopolitics. It also brings into focus problems with the whole idea of geopolitics.

Endnotes

1 Crutzen, P. (2006, July 25). Albedo Enhancement by Stratospheric Sulfur Injections: A Contribution to Resolve a Policy Dilemma?. *Climatic Change*, 77(211). https://link.springer.com/article/10.1007/s10584-006-9101-y

2 Carbon Brief. (2016, November 4). *Explainer: 10 ways 'negative emissions' could slow climate change*. https://www.carbonbrief.org/explainer-10-ways-negative-emissions-could-slow-climate-change

3 Weitzman, ML. (2015, July 14). A Voting Architecture for the Governance of Free-Driver Externalities, with Application to Geoengineering. *Scandinavian Journal of Economics*, 117 (4): 1049-1068. https://scholar.harvard.edu/weitzman/publications/voting-architecture-governance-free-driver-externalities-application

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Without Attention, Geoengineering Could Upend Foreign Policy

Dhanasree Jayaram

In the summer of 2020, border tensions between India and China and the future of their bilateral relations came to dominate the news cycle in the subcontinent—or at least the space left over by the coronavirus pandemic. Although foreign policy experts are right to discuss the boundary dispute at the core of India-China tensions, they must not ignore the many other potential sources of tensions. One of the most significant is the probable implementation of large-scale geoengineering projects.

As emissions reductions prove elusive, major emitters are increasingly looking for other solutions to reduce global warming. Both China[1] and India[2] are exploring carbon dioxide removal or negative emission technologies. More controversially, they are also studying solar radiation management, a technological domain in which China is far ahead of India and the risk of bilateral disagreement is extremely high. The foreign policy community needs to incorporate climate change issues—especially geoengineering—into foreign policy.

Geoengineering's Potential to Heighten Tension

The emergence of ambitious geoengineering technologies could exacerbate tensions and even hostility between nations such as India and China. Without regulation, one country's efforts could affect other countries. While China has not yet shown signs of "unilaterally"[3] deploying geoengineering projects on the ground, the scale of its weather modification and other massive engineering projects, including mega-dam projects (such as the Three Gorges), suggests China is willing to deploy large-scale geoengineering schemes[4] to tackle the impacts of climate change and achieve its Paris targets.

Take, for example, China's large-scale weather modification project, *Tianhe*, or Sky River—a cloud seeding geoengineering project. The project has potential security implications for neighboring countries, including India, and other South and Southeast Asian countries.

Tianhe's climate geoengineering venture aims to manage drought-like conditions in the northern parts of the county that receive less rainfall and are seeing declining water levels in its rivers. With the project, China seeks to blast silver iodide particles[5] into the atmosphere using fuel-burning chambers in order to transfer more water from the Yangtze River basin to the Yellow River basin via water vapor that becomes rainfall.[6]

If past patterns repeat, conflicts may arise. India has accused China of creating floods in its northeast through suspicious dam-building activities.[7] The *Tianhe* project could further heighten concerns in the South and Southeast Asian regions, as the Tibetan Plateau is the source of major rivers such as the Indus, and Brahmaputra. Some Chinese scientists regard the project, led by researchers from Tsinghua University and Qinghai University, as technically "unfeasible," and scientifically "delusional."[8] But if it is to go through, it could unpredictably affect local and transboundary ecosystems[9], precipitation patterns, and even the long-term regional climate. These variables could raise the importance of information and data sharing (transparency) that is at times held hostage by geopolitical dynamics, as was the case during the 2017 Doklam military standoff between India and China, when owing to "technical" reasons, the latter did not share water flow data with the former.[10]

Just how solar geoengineering may affect regional climate and weather patterns is unclear, but the impacts are potentially significant. Climate change already seems to be affecting the Indian Summer Monsoon Rainfall (ISMR) that is the lifeline of all the South Asian economies. Studies have attributed a decline in the total rainfall and a concurrent rise in the magnitude and frequency of extreme rainfall events to climate change in many parts of India and other South Asian countries.[11] A few scientific studies have also pointed out that using techniques such as injection of stratospheric aerosols to cool the planet (the effect is comparable to that of a volcanic eruption) may reduce rainfall in India and China and may affect the ozone layer too, by thinning it.[12] The deployment of such initiatives in the region could therefore unleash far-reaching repercussions for ecological, livelihood, economic, social, and human security.

The Geopolitical Divide Between the Haves and Have-Nots

The consequences of a lack of safeguards on unregulated geoengineering could be disastrous, particularly for developing countries that do not possess enough resources to undertake research and development (R&D) in the field, deploy such schemes on a large-scale, or deal with their unintended outcomes. Geoengineering research,

especially solar geoengineering, both in terms of technological innovation and futuristic governance frameworks, continues to be dominated by the Global North (primarily North America and Western Europe).[13]

These dynamics could exacerbate the geopolitical divide between the haves and have-nots or winners and losers, an asymmetry in the international system that developing countries have long contested. Yet, scientists have spoken about the need to implement geoengineering not just to prevent a future climate emergency, but also to create "equity" in connection with the possibility of reducing surface temperature faster than mitigation, in a way that will be comparatively cheaper than adaptation, and as a moral obligation to save the global poor.[14]

The Military Factor

Wherever militaries are involved, we should proceed with caution. In some countries, the military may already be playing a role in developing these technologies.[15] If and when the technologies are deployed on a wide scale, militaries may be involved in various aspects of the process[16], including the protection of project sites, R&D, and potential militarization/weaponization (to have an upper hand in times of crises).

Tianhe, in fact, is being aided by the state-owned China Aerospace Science and Technology Corporation, a "major space and defense contractor," using "cutting-edge military rocket engine technology" and "satellite network."[17] The involvement of the militaries in an already geopolitically tense region without appropriate safeguards could lead to further opaqueness, mistrust, disagreements, and conflict over the use of such technologies.

Some argue that geoengineering governance research should be free of regulations that may politicize the debate, delay effective means of arresting the effects of climate change[18], and even lead to a potential moratorium on the use of these technologies. Others argue that there is not enough scientific evidence to prove the risks associated with geoengineering.[19] This is precisely why we cannot wait for perfect information to act, and we may have to adopt a cautious approach that looks to diplomatic efforts to deal with the effects of these technologies, if not impose a ban on them.

Designing Geoengineering Governance Frameworks

Concerned foreign policy and security stakeholders in the Global South will need to step up efforts to address the political, security, and governance-related implications of geoengineering schemes. The focus of geoengineering should shift from mere preoccupation with the global context to regional climate change, as the impacts of these technologies on a regional scale (including precipitation and hydrologic cycle) are still under-studied. In a region such as South Asia,

countries should cooperate. First, they should reach a common understanding on the role of climate geoengineering as a "plan B"[20] solution for tackling climate change, and help advance the discussion on and implementation of national regulatory frameworks (which are non-existent in most cases). Then they should design rules and norms that draw upon these frameworks and that can be used at the international level for developing a global governance, or regulatory, framework.

Accountability and transparency are the key to future global, regional, and national climate governance. Although most countries, including China, the United States, and India have ratified the Convention on the Prohibition of Military or Any Other Hostile Use of Environmental Modification Techniques (ENMOD), establishing "compliance" and liability[21] can be tricky in the event of perceived (or claimed) benign use of climate geoengineering, coupled with the existence of longstanding militarized border zones. According to ENMOD[22], states must "undertake not to engage in military or any other hostile use of environmental modification techniques having widespread, long-lasting or severe effects as the means of destruction, damage or injury to another State party." This is perhaps the most relevant legal framework that could cater to the security implications of climate geoengineering, albeit only in "hostile" scenarios. It is outdated and does not address "peaceful" modification techniques.[23]

In the present situation the uncertainties have multiplied, with the COVID-19 pandemic, geopolitical tensions, and climate change complicating existing challenges. With the pandemic, although there are never-ending calls for a "green recovery"[24]—"to build back better"—some speculate that many renewable energy projects are likely to be delayed.[25] In such a scenario, countries will be more ambitious about pushing ahead with geoengineering projects to achieve their climate objectives. Richer countries may set aside ethical concerns with regard to developing countries and pursue a technocratic solution to climate change. In this context, the need for better governance mechanisms and tools, and the role of foreign policy stakeholders, especially those who engage in climate diplomacy, will be paramount, including in regions such as South Asia.

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Endnotes

1 Wan, L. (2019, July 30). *Carbon capture and storage in China*. CRU. https://www.crugroup.com/knowledge-and-insights/insights/2019/carbon-capture-and-storage-in-china/?utm_medium=Press_release&utm_source=PR%20Newswire&utm_campaign=CRU%20Insight%20LW%20Jul%2019

2 Gupta, A., & Paul, A. (2019, February). Carbon capture and sequestration potential in India: A comprehensive review. *Energy Procedia*, 160, 848-855. https://doi.org/10.1016/j.egypro.2019.02.148

3 The National Academies. *Committee on Developing a Research Agenda and Research Governance Approaches for Climate Intervention Strategies that Reflect Sunlight to Cool Earth – International Briefing to U.S. NAS Study Committee*. Vimeo. https://vimeo.com/384026949

4 Bluemling, B., Kim, R.K., & Biermann, F. (2019, May 18). Seeding the clouds to reach the sky: Will China's weather modification practices support the legitimization of climate engineering? *Ambio, 49, 365-373*. https://link.springer.com/article/10.1007/s13280-019-01180-3

5 Dockrill, P. (2018, April 28). China's 'Sky River' Will Be The Biggest Artificial Rain Experiment Ever. *Science Alert*. https://www.sciencealert.com/how-china-s-sky-river-will-be-the-biggest-artificial-rain-experiment-ever-cloud-seeding

6 Zheng, J. (2016, May 14). Project aims to divert water through the sky. *China Daily*. https://www.chinadaily.com.cn/china/2016-09/14/content_26793165.htm

7 The Economic Times. (2016, October 5). *Why India is worried about China's dam projects on the Brahmaputra River*. https://economictimes.indiatimes.com/news/politics-and-nation/why-india-is-worried-about-chinas-dam-projects-on-the-brahmaputra-river/articleshow/54691589.cms?from=mdr

8 Xuan, T.J., & Wang, J. (2018, November 27). *Qinghai-Tibet Artificial Rainfall Project 'Delusional,' Experts Say*. Caixin Global. https://www.caixinglobal.com/2018-11-27/qinghai-tibet-artificial-rainfall-project-delusional-experts-say-101352671.html

9 Pike, L. (2018, December 19). China's Scientific Community Confronts 'Rogue Science.' *Science - The Wire*. https://science.thewire.in/external-affairs/world/chinas-scientific-community-confronts-rogue-science/

10 Jayaram, D. (2018, March 14). Mutual Mistrust should Give Way to Water Cooperation between India and China. *Climate Diplomacy*. https://www.climate-diplomacy.org/news/mutual-mistrust-should-give-way-water-cooperation-between-india-and-china-0

11 Roxy, M.K., Ghosh, S., Pathak, A., Athulya, R., Mujumdar, M., Murtugudde, R., Terray, P., & Rajeevan, M. (2017, October 3). A threefold rise in widespread extreme rain events over central India. *Nature Communications*, 8(708). https://www.nature.com/articles/s41467-017-00744-9

12 Robock, A., Oman, L., & Stenchikov, G.L. (2008, August 16). Regional climate responses to geoengineering with tropical and Arctic SO2 injections. *Journal of Geophysical Research*: Atmospheres, 113(D16). https://doi.org/10.1029/2008JD010050

13 Rahman, A.A., Artaxo, P., Asrat, A., & Parker, A. (2018, April 3). Developing countries must lead on solar geoengineering research. *Nature*. https://www.nature.com/articles/d41586-018-03917-8

14 Flegal, J.A., & Gupta, A. (2017, September 19). Evoking equity as a rationale for solar geoengineering research? Scrutinizing emerging expert visions of equity. *International Environmental Agreements: Politics, Law and Economics*, 18, 45-61. https://link.springer.com/article/10.1007/s10784-017-9377-6

15 Kintisch, E. (2009, March 14). *DARPA to Explore Geoengineering*. American Association for the Advancement of Science. https://www.sciencemag.org/news/2009/03/darpa-explore-geoengineering#

16 Muniruzzaman, A. (2018, January 11). *Climate Geo-engineering: Uncertainties and Implications*. RSIS Commentary. https://www.rsis.edu.sg/rsis-publication/rsis/co18005-climate-geo-engineering-uncertainties-and-implications/#.X0gMcshKhPZ

17 Chen, S. (2018, March 26). China needs more water. So it's building a rain-making network three times the size of Spain. *South China Morning Post*. https://www.scmp.com/news/china/society/article/2138866/china-needs-more-water-so-its-building-rain-making-network-three

18 Hamilton, C. (2010, September 13). The powerful coalition that wants to engineer the world's climate. *The Guardian*. https://www.theguardian.com/environment/2010/sep/13/geoengineering-coalition-world-climate

19 Frumhoff, P.C., & Stephens, J.C. (2018, April 2). Towards legitimacy of the solar geoengineering research enterprise. Philosophical transactions. *Series A, Mathematical, physical, and engineering sciences*, 376(2119). https://doi.org/10.1098/rsta.2016.0459

20 Hood, M. (2019, August 23). *Geoengineering: 'Plan B' for the planet*. Phys.org. https://phys.org/news/2019-08-geoengineering-planet.html

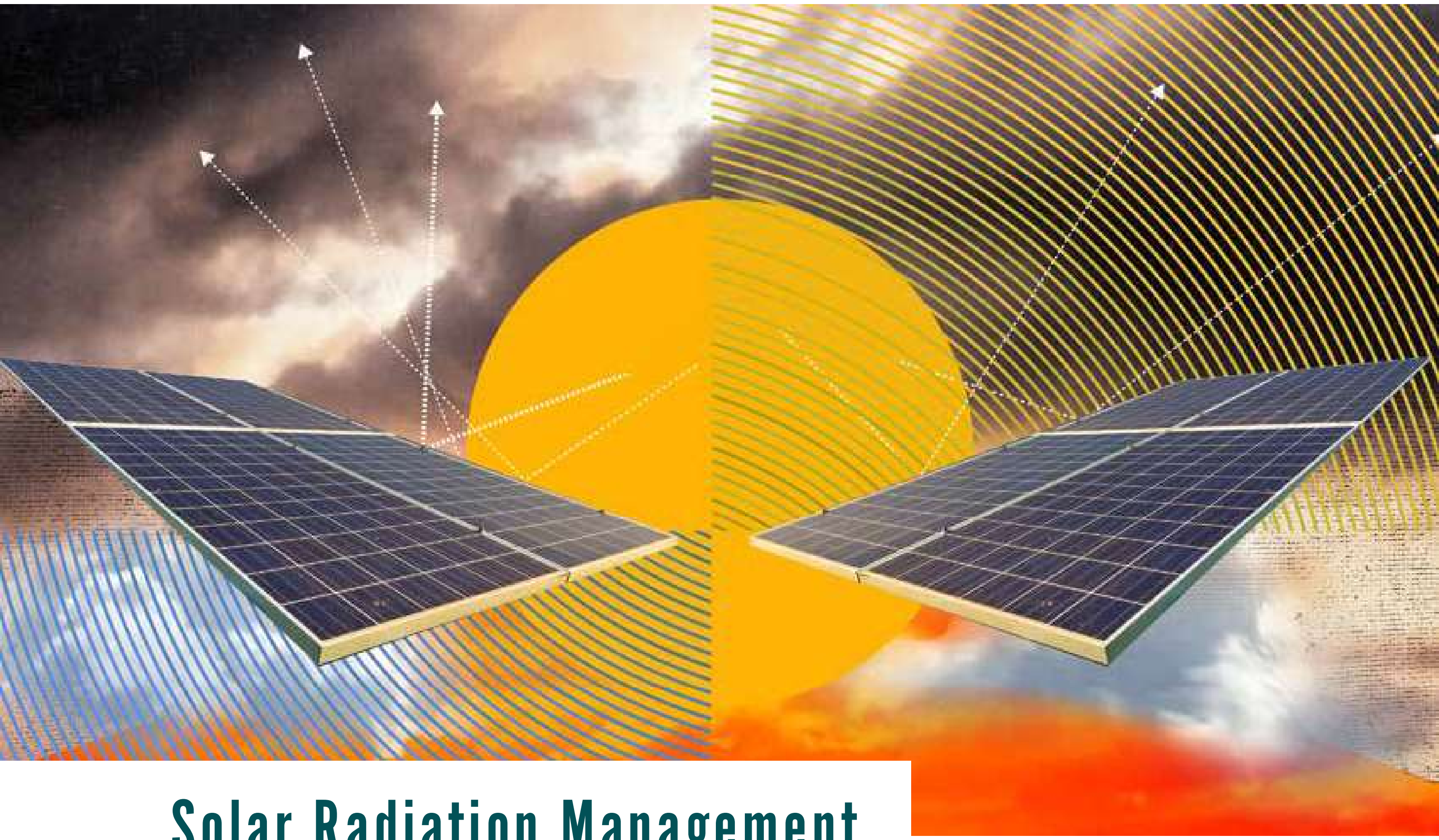
21 Smit, E. (2015, Spring). Geoengineering: Issues of Accountability in International Law. *Nevada Law Journal*, 15:1060-1089. https://scholars.law.unlv.edu/cgi/viewcontent.cgi?article=1604&context=nlj

22 United Nations Geneva. (2020). Convention on the Prohibition of Military or Any Other Hostile Use of Environmental Modification Techniques (ENMOD). Retrieved August 27, 2020 from https://www.unog.ch/enmod

23 Kolpak, G. (2020, April 7). *From ENMOD to geoengineering: the environment as a weapon of war*. Conflict and Environment Observatory. https://ceobs.org/from-enmod-to-geoengineering-the-environment-as-a-weapon-of-war/

24 Harrabin, R. (2020, May 6). Climate change: Could the coronavirus crisis spur a green recovery? *BBC*. https://www.bbc.com/news/science-environment-52488134

25 Mulchandani, P. (2020, May 8). COVID-19 Crisis: Economic Stimulus Packages and Environmental Sustainability. *Economic & Political Weekly* 55(19). https://www.epw.in/engage/article/covid-19-crisis-economic-stimulus-packages-and-environmental-sustainability?0=ip_login_no_cache%3Dc204c90b45ddb949092e94a8d22885a3



Solar Radiation Management

Simon Nicholson

Solar radiation management (SRM) is an idea born of desperation. It is also an idea that demands consideration as the global community grapples with an ongoing and accelerating climate crisis. This briefing note defines and describes SRM, discusses why SRM is under consideration by the scientific community, policy actors, and representatives of civil society, and looks at what effective governance of SRM requires. SRM raises big questions for the foreign policy community: Should SRM technologies be developed? Should they ever be used? Who decides based on what kinds of imperatives or criteria? Who would have control of operation and intended outcomes? This note makes the case that even though SRM approaches are still at the discussion stage, the building of a governance architecture around SRM should begin now.

SRM is a speculative form of climate change response. SRM schemes, should they ever be developed and used, would operate by reflecting some amount of incoming solar energy back into space before that energy can be trapped by the gases that produce the greenhouse effect. Think of SRM like a reflective shield, artificially providing regional or global cooling.

BOX 1:

The Language of Geoengineering, Carbon Removal, and Solar Radiation Management

The term **geoengineering** (or **climate engineering**) has long been used as a catch-all for any potential large-scale technological intervention in earth systems to tackle or address climate change. The term has, though, largely fallen out of favor. Instead, scientific and policy discussions tend now to distinguish more carefully between two distinct types of potential large-scale climate intervention:

1. **Carbon removal** (or **carbon dioxide removal** or **negative emissions technologies**) approaches could draw carbon dioxide from the atmosphere and direct the carbon dioxide to long-term storage or to beneficial use. Climate models now suggest large-scale carbon removal will be a necessary component of the global climate change response.[1] Biological pathways for carbon removal include the planting of trees[2], the managing of farmlands[3] for carbon uptake and storage, or, perhaps, depositing iron filings in the ocean[4] to promote blooms of carbon-inhaling phytoplankton. More speculative chemical and technological methods include direct air capture[5] (capturing carbon dioxide directly from the open air and then injecting it underground) and enhanced weathering[6] (speeding up the natural processes that turn atmospheric carbon into rock formations).

2. **Solar radiation management** (or **solar geoengineering** or **solar radiation modification** or **albedo modification**) could cool the planet by reflecting or refracting a small amount of incoming solar energy. Proposals include stratospheric aerosol injection, marine cloud brightening, or ground-level albedo enhancement. This briefing note focuses on the science and governance requirements of solar radiation management approaches.

Carbon removal and solar radiation management offer different and perhaps complementary ways to tackle climate change, in conjunction with reducing greenhouse gas emissions and adapting to a changing climate.

Setting aside for the moment potential negative or unintended consequences, increasing the reflectivity of planetary features at any altitude could achieve the cooling goal of SRM. At ground and sea level, SRM proposals have included using gigantic pumps to introduce microbubbles into reservoirs or other bodies of still water, the genetic engineering of crops to make leaves shinier, and the spreading of reflective films on the ocean's surface or on vulnerable ice flows. The two most-discussed proposals for SRM, outlined in the next section, are both options that would operate up in the atmosphere. Any of these options would increase what is known as the Earth's "albedo"—the reflectiveness of the planet—sending more solar radiation back into space before it can interact with greenhouse gases.[i]

FIGURE 1: Illustration of Sample Solar Radiation Management Proposals

Source: Graphic prepared by Isabelle Rodas for Nicholson, S. (2013). "The Promises and Perils of Geoengineering," in Erik Assadourian et al., Worldwatch Institute: State of the World 2013.

The emerging science and technology of SRM is complicated enough. SRM is not, though, just a technical enterprise. It's a big complex entanglement of technological and scientific ideas, promises, and understandings interacting with social forces and actions. Some see technological developments as a way to bypass messy political processes. That's not really the case. SRM is not a way to get around climate politics; SRM is *part* of climate and broader politics. Consideration of SRM will necessarily take place in the context of the rest of the global effort to understand and respond to climate change. With this in mind, the world will be better placed in 2040 and beyond to take action if investment in how to govern SRM is well underway in 2020. SRM has world-altering potential. Its governance needs to be early, anticipatory, and flexibly attentive to the range of different possibilities that lie just over the horizon.

Current SRM Proposals

Ground-level SRM options such as more reflective crops or white roofs on buildings could provide some localized cooling and, if implemented at a large enough scale across multiple locations, could even have a modest impact on global heating. Higher-leverage proposals that could more readily produce regional or global cooling would operate in the atmosphere. **Marine cloud brightening** would involve introducing saltwater particles from the

i The fact that increasing albedo or planetary brightness at any altitude would cool the planet has to do with the manner in which solar energy interacts with greenhouse gases in the atmosphere. Incoming solar radiation enters the Earth's atmosphere in short wavelengths. Some incoming shortwave radiation is reflected back into space by the cloud layer or particles in the atmosphere. Some makes it through to the Earth's surface, where it is absorbed and then re-radiated spaceward as longwave radiation. It is this outgoing longwave radiation that is trapped by greenhouse gases in the lower atmosphere, with increasing concentrations of greenhouse gases then leading to more planetary warming. Solar radiation management (SRM) has the potential to offset some human-induced warming by reflecting solar energy back into space before that energy becomes the longwave infrared radiation that can be captured by greenhouse gases.

ocean up into the cloud layer, with the hope that this would lead to the short-term appearance of new and whiter clouds. These artificial or newly whitened marine clouds would mimic the "ship tracks"[7] that appear above ocean-traveling ships. In Australia, marine cloud brightening is one of more than 40 proposals being looked at as part of an AU$150 million government-backed research enterprise aimed at reducing heat impacts on the Great Barrier Reef.[8] A trial in early 2020 used a modified turbine with hundreds of nozzles to spray salt crystals skyward as a proof of a potential particle delivery system.[9] Future tests are planned to test atmospheric and ocean surface impacts. A project based in Washington state has set out its own research plan and is seeking US$40-50 million over five years.[10]

A second proposal, stratospheric aerosol injection, would involve throwing reflective particles into the upper atmosphere. The particle might be sulfur dioxide, or, in some formulations, calcium carbonate or perhaps an engineered nanoparticle, with delivery most likely by a fleet of high-flying aircraft. This activity would replicate the cooling effect of a volcanic event. The eruption of Mount Pinatubo in the Philippines in 1991 produced a plume of gas containing some 20 million tons of sulfur dioxide, some of which was forced to high altitudes. The Earth's average temperature fell by around 0.5 degrees Celsius for the 18 months that the sulfur dioxide particles remained aloft.[ii] A team at Harvard University has begun early-stage investigations that could, in time, inform whether humans could replicate such a feat.[11]

One paper[12] has suggested that a program that would ramp up to a cooling impact of around 0.3 degrees Celsius could be achieved for about US$2.25 billion per year over an imagined 15 year lifespan.[iii] This kind of price tag makes stratospheric aerosol injection look a good bet in brute economic terms. Such cost estimates are scrambled, though, when one tries to take account of unintended or potential downside consequences. Working out whether any SRM proposal is a good idea is dependent not just on feasibility and direct cost estimates, but also on questions about whether and how any deployment can be governed, how costs and benefits are likely to be distributed, and what SRM development would mean for other needed efforts to respond to climate change.

Stratospheric aerosol injection would, if utilized, have a global cooling effect, though computer modeling suggests it would not impact all places in the same way. Optimistic forecasts[13] based on limited and carefully controlled deployment of stratospheric aerosols suggest that every region of the world would see some climate benefit, with some regions seeing more benefit than

ii This figure of 0.5 degrees Celsius is notable, given that the atmosphere has warmed a little more than 1 degree since the beginning of the Industrial Revolution and the goal of the Paris Agreement is to limit warming to no more than 2 degrees of warming above pre-industrial averages, aiming to limit warming to 1.5 degrees.

iii These cost estimates include aircraft development and production expenses spread across the fifteen-year life of the imagined program.

others. Other forecasts, however, suggest that this kind of SRM could upset rainfall patterns[14], amplify or change seasonal cycle[15], deplete stratospheric ozone[16], and potentially harm biodiversity.[17] Much would depend on the particular kind of aerosols deployed, what quantities are used, where they're deposited, and over what timeframe. Marine cloud brightening, by contrast, could have regional application[18] to slow Arctic sea ice melt or protect against coral bleaching. Small-scale ground level SRM efforts could be deployed entirely within one country, while atmospheric approaches would depend upon—or would spill over to—the atmospheric commons. This is all to say that while SRM approaches have in common that they would reflect solar radiation, there are some big and important differences in terms of what various SRM approaches entail and require in governance terms.

Why is Solar Radiation Management on the Table?

SRM could offer, by one well-known formulation, a "fast, cheap, and imperfect"[19] approach to slowing or offsetting temperature rise caused by greenhouse gas emissions. SRM is *fast* in the sense that deployment of an SRM approach would begin working immediately to reduce temperatures and it is *cheap* by the measure of anticipated direct costs.[iv] SRM is also imperfect, though, in that it does very little to address the underlying problem of the buildup of greenhouse gases in the atmosphere (or in the oceans, where atmospheric CO_2 is driving ocean acidification) and comes with a range of attendant risks.

Said differently, SRM is under consideration by scientists and policymakers because there is very little scientific doubt that using SRM approaches would cool particular regions or the planet. Climate change is about far more than temperature increase, however, and the cooling would come with a range of challenges and downside risks.

If SRM is to be used, it must be utilized alongside traditional emissions abatement (mitigation), adaptation to climate change effects, and, perhaps, carbon removal (see Box 1 and Figure 2). This is a key punchline when it comes to SRM: **SRM should only be considered a supplement to emissions abatement, never a substitute**. In the formulation in the left-hand portion of Figure 2[20], SRM is used in a "peak shaving" fashion, to remove the peak from a climate damage curve for a period of time. This could buy time for emissions abatement and then the removal of CO_2 from the atmosphere using large-scale carbon removal schemes (also a speculative notion) to stabilize and ultimately reduce atmospheric greenhouse gas concentrations. SRM in this scenario would be gradually ramped up through time and then gradually phased out, with the length of time and maximum scale of deployment depending on a range of different factors. In the right-hand portion of the figure, by contrast, SRM is used all by itself in an effort to keep climate impacts under control. In such a scenario SRM would need to be ramped up to keep pace with rising concentrations of greenhouse gases in the atmosphere, with the downside that higher concentrations of SRM entail more risk.

SRM has made it onto the international climate policy agenda, though it remains contentious. In 2019, a proposed resolution on "Geoengineering and its governance" was advanced for consideration at the 4th United Nations Environment Assembly (UNEA-4) in Nairobi. The proposal called

iv Note that this is an estimate of direct costs, and does not take account of potential indirect costs such as foreseeable or unforeseeable environmental disruption.

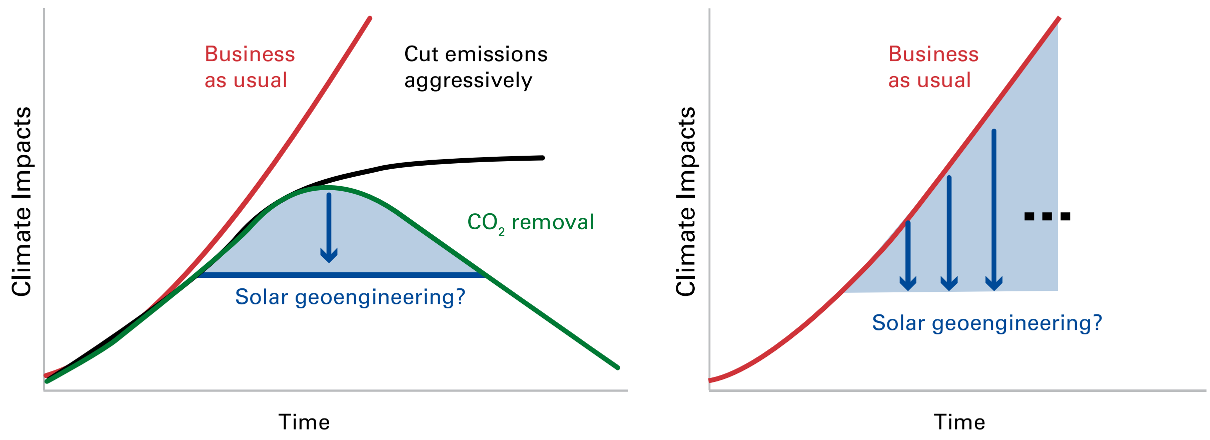


Figure 2: (Left) A limited role for SRM (solar geoengineering) as part of a broad portfolio of climate change response options; (Right) An unrealistic scenario shows SRM used alone, without emissions abatement or removal of carbon from the atmosphere, leads to more and more SRM needed each year for an indefinite period of time. From "Mission-driven research for stratospheric aerosol geoengineering," by D. MacMartin and B. Kravitz.[21] Copyright 2019 by Clearance Center, Inc. Reprinted with permission.

for a report or series of reports to be prepared by the United Nations Environment Programme (UNEP), assessing criteria to define SRM and carbon removal approaches, the state of existing science, and governance considerations. The proposal was ultimately withdrawn, in part because the U.S. delegation wanted to forestall any opportunity for international processes to impose restrictions on the kinds of research that might be pursued in the United States.[22] The formal governance of SRM will likely be back on the agenda at UNEA-5 and in other upcoming fora.

Governing Solar Radiation Management

What, then, does governing SRM require? Governing SRM means steering between the good that could come from developing and utilizing SRM options and the potential hazards and harms that SRM options present. Governance in a case like this one is not just about trying to protect against risks. Focusing just on the worst-case scenarios for SRM gone awry or terrible uses of SRM approaches by the worst imaginable actors leads one immediately to demands for a moratorium or strict restrictions on even SRM research efforts. An evaluation of SRM governance needs to start with comparing the potential risks and benefits of SRM approaches with the risks associated with climate change trajectories absent the availability of SRM. That is, could SRM provide a good and manageable way to offset some climate change risks? The truth is that we, collectively, don't yet know enough about SRM either in scientific or societal terms. We haven't yet sorted through whether SRM approaches could work, as models and early tests suggest they might; nor is it clear that people would accept SRM options and that governments and others could establish the rules and institutions needed to manage them. This means that, in addition to managing for risks and potential harms, effective governance of SRM is also about creating an appropriate enabling environment for critical, quality research; opening up space for the kinds of societal deliberations that need to be undertaken; and establishing transparency and information sharing mechanisms.

BOX 2:

Limited and Fragmented Formal Governance of SRM

At present, there is no single present or planned international regime that has taken up the governance of SRM. There exists, instead, a patchwork of relevant rules and a range of different proposals.

There have been, to date, three international environmental regimes that have given explicit attention to SRM. These are:

1. The Convention on Biological Diversity (CBD): The parties to the CBD adopted decisions in 2010 and 2012[23] motivated by concern about potential negative impacts on biodiversity from climate-related geoengineering activities. Some have argued that the CBD decisions represent a de facto moratorium[24] against SRM investigation or deployment. The decisions, though, are guidance rather than binding law, and they also explicitly call for and allow for various kinds of research activities attentive to and designed to help assess environmental risks associated with SRM.

2. The London Convention and London Protocol (LC/LP): The LC/LP establishes a regime covering the dumping of materials into the oceans. In 2010, parties to the LC/LP adopted a resolution on an "Assessment Framework for Scientific Research Involving Ocean Fertilization."[25] The assessment framework is designed to provide guidance on the monitoring of ocean iron fertilization experiments, which could remove carbon dioxide from the atmosphere. Ocean iron fertilization and SRM have often been brought together under the "geoengineering" umbrella, such that many read the LC/LP guidance as also applying to SRM approaches that involve putting materials into the oceans. In 2013, amendments were adopted designed to regulate marine geoengineering activities, where marine geoengineering was defined as "a deliberate intervention in the marine environment to manipulate natural processes, including to counteract anthropogenic climate change and/or its impacts, and that has the potential to result in deleterious effects, especially where those effects may be widespread, long-lasting or severe."[26] These amendments have not entered into force.

3. The Vienna Convention and Montreal Protocol: The parties to this regime to address human harms to the stratospheric ozone layer have taken some interest in SRM. This is because there is some concern that stratospheric aerosol injection, a type of SRM, could harm the ozone layer. Over recent meetings there has been a growing push to include consideration of SRM in an upcoming scientific assessment.[27] It is unclear at this juncture whether this scientific interest might lead to an interest in rulemaking.

In addition, there are a number of other environmental regimes that could have bearing on SRM based on existing treaty language or mandate. Among these regimes is the Convention on Long-range Transboundary Air Pollution (perhaps relevant in the case of the spread of sulfate aerosols or some other particle in the atmosphere), the UN Convention on the Law of the Sea (perhaps pertinent in the case of positive or negative marine impacts from SRM testing or deployment), and the Environmental Modification Treaty (ENMOD – perhaps relevant if some particular use of SRM were deemed or seen as hostile).[28]

A study published in 2020 by Susan Biniaz and Daniel Bodansky concluded that there is no obvious "one-stop shop" for SRM governance.[29] The international climate change regime, with the UN Framework Convention on Climate Change at its heart, is an obvious place to site formal governance of SRM, but the authors contend that the agenda for parties to that convention is already packed and contentious. Nor is there another obvious international forum with sufficient scope and mandate. Biniaz and Bodansky instead weigh a range of potential existing institutions or regimes that could pick up important *pieces* of the SRM governance agenda: the Intergovernmental Panel on Climate Change, World Meteorological Organization, or similar for scientific assessment, and the UN Security Council or G7/G20 or a regional forum for policy decisions. Others have endorsed this polycentric or multi-nodal governance notion.[30] SRM governance is needed. SRM governance does not, though, all need to be handled in one place, and for the foreseeable future fragmented governance of SRM is likely to remain the norm.

Right now, SRM is still an idea. There is some computer modeling and a handful of plans for early-stage scientific investigation into the efficacy of certain aspects of some SRM proposals, but there are no readily deployable SRM options. This means that in the near-term, governance of SRM means governance of SRM research. But even the mere mention of SRM research has garnered objections. Among the concerns (see also box 3 in *Governing Solar Radiation Management*[31]):

- SRM could be sold by fossil fuel interests and others as a kind of get-out-of-jail-free card;
- SRM might distract elites or society from the essential work of emissions abatement;
- SRM could experience a kind of technological lock-in or elite capture, where early stage research efforts would drive inexorably towards use even if it proved a bad idea; and,
- Even medium to large-scale testing of some forms of SRM would amount to messing with ecosystems, with very limited knowledge and ability to control and account for the impacts of such interventions.

Yet, quashing research denies us the opportunity to better understand a potentially beneficial tool and prevents informed decision-making—including baseline knowledge about potential risks—which is an especially important consideration should a group ever decide to rush to SRM deployment.

When it comes to potential deployment of SRM approaches, much depends on the particular kinds of SRM under consideration. A stratospheric aerosol injection program, for instance, would have global climatological impacts but could be launched by a single country or even a sub-state actor. This could not be a covert undertaking. Other countries would certainly notice if, say, China or Russia or the United States launched (in a deployment scenario) thousands of flights each year into the stratosphere, and satellite-based LIDAR could detect major engineered changes in planetary reflectivity. Still, the fact that one country could go it alone suggests the need for coordinated action, even if only to ward off the potential for rogue actions.

Another much-discussed challenge with a global stratospheric aerosol injection deployment is the so-called "termination shock" that could accompany a sudden cessation of activities. If a global SRM scheme were implemented while greenhouse gas concentrations continued to rise, then all that SRM would be doing is masking and suppressing potential warming. A sudden halt of the SRM scheme would result in a sudden, and potentially severe, pulse of warming. All of this suggests that SRM with global impacts would need to be managed effectively and without interruption for a potentially very long time.

A regional or local SRM approach, such as marine cloud brightening or the spreading of ocean films, has different implications. Such programs would infiltrate the global commons and have spillover impacts on neighboring states, but risks would likely be more geographically constrained than with global approaches.

A further consideration, of particular importance for foreign policy discussions, concerns security or securitization dimensions of SRM. While some have speculated that stratospheric aerosol injection might be weaponized, this is likely an overblown concern. More pressing is that costs and benefits of SRM deployment would be unevenly distributed. Even models that suggest that nearly everyone would benefit from SRM indicate that benefits would be spread unevenly. These kinds of equity concerns could have implications for vulnerability to climatic pressures, including pressure points for migration, and public acceptance of SRM developments.

Another security implication has to do with how SRM could shape public and elite understandings of climate change. Climate change is now a diffuse challenge, in the sense that every person on the planet contributes to climate change through their actions (recognizing that some contribute significantly more than others and focusing individuals as the producers of climate change lets corporations and flawed systems off the hook). SRM could potentially provide a touchpoint by which a particular actor is identified (correctly or not) as the source of climatological effects. Suppose that Pakistan were to experience a major flooding event the year after India announced field tests of an SRM approach.[32] Pakistan could blame India for the flooding *whether or not* a direct causal impact could be uncovered. In this way SRM would exacerbate and feed into existing interstate tensions. Some have gone so far as to suggest that SRM feeds a militarization of climate politics, intensifying a logic of surveillance and control, in ways that could undermine cooperative climate response efforts.[33]

Looking Ahead - Prospects for Solar Radiation Management and its Governance

Imagine the world in 2040. The ice sheets covering Greenland are sliding more rapidly into the ocean even as much of the world is experiencing massive fires. Climate-induced migration and global food system disruptions are increasing. Decision-makers and communities all over the world are finally aligned to do something about climate change. Climate change is acutely felt and the need to address it, urgent. Where does SRM fit in?

- **Scenario 1:** There has been limited research on SRM to this point, but things are getting so drastic that every tool needs to be used. *Fly the planes.*
- **Scenario 2:** Research has shown SRM to be good in certain respects but bad in others. Keep SRM local and avoid risks associated with global options. *Brighten the clouds.*
- **Scenario 3:** The world has taken a back-to-nature swing and there's widespread antipathy towards technological responses. *Shelve the plans.*
- **Scenario 4:** Jeff Bezos decides he's going to sidestep all the talk and get the SRM job done himself. *Anoint the savior.*

- **Scenario 5:** Governments have directed a multi-year coordinated research effort around stratospheric aerosol injection and have agreed upon rules to guide large-scale outdoor experimentation. *Proceed with caution.*

These scenarios begin just to hint at the array of possible futures into which SRM will fit and that consideration of SRM will help to create. Bottom line: though potential use of SRM is some way off in the future, SRM demands consideration now. How decision-makers answer the "where does SRM fit" question today will go a long way towards producing which of the paths outlined above, or others, we find ourselves on in 15-20 years.

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Endnotes

1 Morrow, D.R., Buck, H.J., Burns, W.C.G., Nicholson, S., & Turkaly, C. (2018). W*hy talk about carbon removal?* Washington, D.C.: Institute for Carbon Removal Law and Policy, American University. https://doi.org/10.17606/M6H66H

2 *Fact sheet: Forestation.* (2020, June 24). American University. https://www.american.edu/sis/centers/carbon-removal/fact-sheet-forestation.cfm

3 *Fact sheet: Soil carbon sequestration.* (2020, June 24). American University. https://www.american.edu/sis/centers/carbon-removal/fact-sheet-soil-carbon-sequestration.cfm

4 *Ocean iron fertilization.* (n.d.). Woods Hole Oceanographic Institution. https://www.whoi.edu/oceanus/special-series/ocean-iron-fertilization/

5 *Fact sheet: Direct air capture.* (2020, June 24). American University. https://www.american.edu/sis/centers/carbon-removal/fact-sheet-direct-air-capture.cfm

6 *Fact sheet: Enhanced mineralization.* (2020, June 24). American University. https://www.american.edu/sis/centers/carbon-removal/fact-sheet-enhanced-mineralization.cfm

7 *Ship tracks south of Alaska.* (n.d.). NASA Earth Observatory. https://earthobservatory.nasa.gov/images/37455/ship-tracks-south-of-alaska

8 *Marine Cloud Brightening for the Great Barrier Reef.* (n.d.). Marine Cloud Brightening for the Great Barrier Reef. https://www.savingthegreatbarrierreef.org/

9 Readfearn, G. (2020, April 16). Scientists trial cloud brightening equipment to shade and cool Great Barrier Reef. *The Guardian.* https://www.theguardian.com/environment/2020/apr/17/scientists-trial-cloud-brightening-equipment-to-shade-and-cool-great-barrier-reef

10 *Index - Marine Cloud.* (n.d.). The Marine Cloud Brightening Project. http://www.mcbproject.org/index.html

11 *SCoPEx Science.* (2014). Keutsch Research Group, Harvard University. https://projects.iq.harvard.edu/keutschgroup/scopex

12 Smith, W., & Wagner, G. (2018). Stratospheric aerosol injection tactics and costs in the first 15 years of deployment. *Environmental Research Letters*, 13(12), 124001. https://doi.org/10.1088/1748-9326/aae98d

13 Irvine, P., Emanuel, K., He, J., Horowitz, L. W., Vecchi, G., & Keith, D. (2019). Halving warming with idealized solar geoengineering moderates key climate hazards. *Nature Climate Change,* 9(4), 295–299. https://doi.org/10.1038/s41558-019-0398-8

14 Ferraro, A. J., Highwood, E. J., & Charlton-Perez, A. J. (2014). Weakened tropical circulation and reduced precipitation in response to geoengineering. *Environmental Research Letters*, 9(1), 014001. https://doi.org/10.1088/1748-9326/9/1/014001

15 Jiang, J., Cao, L., MacMartin, D. G., Simpson, I. R., Kravitz, B., Cheng, W., Visioni, D., Tilmes, S., Richter, J. H., & Mills, M. J. (2019). Stratospheric sulfate aerosol geoengineering could alter the high-latitude seasonal cycle. *Geophysical Research Letters*, 46(23), 14153–14163. https://doi.org/10.1029/2019gl085758

16 Tilmes, S., Muller, R., & Salawitch, R. (2008). The sensitivity of polar ozone depletion to proposed geoengineering schemes. *Science*, 320(5880), 1201–1204. https://doi.org/10.1126/science.1153966

17 Trisos, C. H., Amatulli, G., Gurevitch, J., Robock, A., Xia, L., & Zambri, B. (2018). Potentially dangerous consequences for biodiversity of solar geoengineering implementation and termination. *Nature Ecology & Evolution*, 2(3), 475–482. https://doi.org/10.1038/s41559-017-0431-0

18 Latham, J., Gadian, A., Fournier, J., Parkes, B., Wadhams, P., & Chen, J. (2014). Marine cloud brightening: regional applications. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, 372(2031), 20140053. https://doi.org/10.1098/rsta.2014.0053

19 Mahajan, A., Tingley, D., & Wagner, G. (2018). Fast, cheap, and imperfect? US public opinion about solar geoengineering. *Environmental Politics*, 28(3), 523–543. https://doi.org/10.1080/09644016.2018.1479101

20 MacMartin, D. G., & Kravitz, B. (2019). Mission-driven research for stratospheric aerosol geoengineering. *Proceedings of the National Academy of Sciences*, 116(4), 1089–1094. https://doi.org/10.1073/pnas.1811022116

21 MacMartin, D. G., & Kravitz, B. (2019). Mission-driven research for stratospheric aerosol geoengineering. *Proceedings of the National Academy of Sciences,* 116(4), 1089–1094. https://doi.org/10.1073/pnas.1811022116

22 Jinnah, S., & Nicholson, S. (2019). The hidden politics of climate engineering. *Nature Geoscience*, 12(11), 876–879. https://doi.org/10.1038/s41561-019-0483-7

23 Williamson, P., & Bodle, R. (2016). *Update on Climate Geoengineering in Relation to the Convention on Biological Diversity: Potential Impacts and Regulatory Framework*. Technical Series No.84. Secretariat of the Convention on Biological Diversity, Montreal, 158 pages. https://www.cbd.int/doc/publications/cbd-ts-84-en.pdf

24 *UN Convention still says "No" to manipulating the climate*. (2016, December 16). ETC Group. https://www.etcgroup.org/content/un-convention-still-says-no-manipulating-climate

25 International Maritime Organization, document LC 32/15 Annex 6, resolution LC-LP.2, *On the assessment framework for scientific research involving ocean fertilization* (2010, October 14), available from http://www.imo.org/en/OurWork/Environment/LCLP/EmergingIssues/geoengineering/Documents/OFassessmentResolution.pdf

26 International Maritime Organization 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* (2013, October 18), available from http://www.imo.org/en/KnowledgeCentre/IndexofIMOResolutions/London-Convention-London-Protocol-(LDC-LC-LP)/Documents/LP.4(8).pdf

27 Institute for Governance & Sustainable Development. (2018, November 12). *Montreal Protocol aims high in Quito to avoid 1°C of future warming.* Climate & Clean Air Coalition. https://ccacoalition.org/en/news/montreal-protocol-aims-high-quito-avoid-1%C2%BAc-future-warming

28 Reynolds, J. L. (2019). Solar geoengineering to reduce climate change: a review of governance proposals. *Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences,* 475(2229), 20190255. https://doi.org/10.1098/rspa.2019.0255

29 Biniaz, S. & Bodansky, D. (2020). S*olar climate intervention: Options for international assessment and decision-making.* Center for Climate and Energy Solutions & SilverLining. https://www.c2es.org/site/assets/uploads/2020/07/solar-climate-intervention-options-for-international-assessment-and-decision-making.pdf

30 Nicholson, S., Jinnah, S., & Gillespie, A. (2017). Solar radiation management: a proposal for immediate polycentric governance. *Climate Policy*, 18(3), 322–334. https://doi.org/10.1080/14693062.2017.1400944

31 Chhetri, N., Chong, D., Conca, K., Falk, R., Gillespie, A., Gupta, A., Jinnah, S., Kashwan, P., Lahsen, M., Light, A., McKinnon, C., Thiele, L.P., Valdivia, W., Wapner, P., Morrow, D., Turkaly C., & Nicholson, S. (2018). *Governing solar radiation management.* Washington, D.C.: Forum for Climate Engineering Assessment, American University. https://doi.org/10.17606/M6SM17

32 Rayner, S., Heyward, C., Kruger, T., Pidgeon, N., Redgwell, C., & Savulescu, J. (2013). The Oxford Principles. *Climatic Change*, 121(3), 499–512. https://doi.org/10.1007/s10584-012-0675-2

33 Surprise, K. (2020). Geopolitical ecology of solar geoengineering: from a "logic of multilateralism" to logics of militarization. *Journal of Political Ecology*, 27(1), 213–235. https://doi.org/10.2458/v27i1.23583

Governance is Essential to Manage the Risks of Solar Radiation Modification

Cynthia Scharf

Senior policymakers everywhere tend to react to the idea of new climate-altering technologies in a similar way: with a mix of curiosity, potential hope, and palpable anxiety.

It's a natural reaction, especially in these deeply challenging times.

For the past three years, my colleagues and I from the Carnegie Climate Governance Initiative (C2G)[1] have been meeting with senior interlocutors around the world, both in and out of government, and alerting them to the critical need for multilateral governance of powerful but risky new ideas to reduce the impacts of climate change.

These include proposals to remove billions of tonnes of CO_2 already in the atmosphere[2], and technologies to reflect back sunlight to lower the global temperature, known as solar radiation modification.[3]

All pose profound governance challenges, which need to be addressed. The latter, if deployed at a global scale, would affect every country on Earth.