Why Has Geoengineering Been Rejected?

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1 Introduction

Human activity unintentionally changes the Earth's climate. When we burn fossil fuels, we release carbon into the atmosphere that accumulated over hundreds of millions of years. These greenhouse gases are causing the temperature of the Earth to increase: The average temperature for 2021 was 0.85°C above the 1951-1980 norm.[1]

The effects of this climate change could be very bad, so many people are trying to replace our dependence on fossil fuels with alternative sources of energy. We could also try to intentionally cool the Earth's climate. This is the promise of geoengineering, "the deliberate large-scale manipulation of the planetary environment to counteract anthropogenic climate change."[2] The most promising form of geoengineering for reducing the global average temperature, or slowing its future increase, is stratospheric aerosol injection: spraying small droplets or particles in the upper atmosphere to reflect 1-2% of incoming sunlight.

This report looks at stratospheric aerosol injection in order to figure out why it is not being pursued by any of the actors who would most benefit from it.

We have been technologically capable of doing geoengineering for decades. Using large airplanes to fly the aerosols to an altitude of about 20 km at a scale large enough to stop or reverse global warming would cost about $1-10 billion per year. Individual large countries are currently spending tens of billions of dollars per year to reduce the global carbon emissions by a few percent. Other indirect global costs, due to reduced solar power production and possibly reduced crop growth, are maybe up to about $100 billion per year, although these would not be fully realized by the actor that implements it. My order of magnitude estimate of the net benefit of implementing geoengineering by 2050 is about $1-10 trillion per year for the world as a whole and about $10 billion per year for individual large countries. Compared to the risks of climate change and the costs people are willing to bear to prevent it, it is surprising that geoengineering is not being more seriously pursued.

The explanation seems to involve several parts. Geoengineering is not being implemented because not enough research has been done to trust a technological fix to an environmental problem. Research is not being done because a majority of climate scientists oppose it. When someone does get independent support for a geoengineering experiment, certain environmental groups advocate against it and get it stopped by a government or advisory group.

Geoengineering is something that I would call a 'resisted technological temptation.' AI Impacts, my employer, is collecting a list of resisted technological temptations.[3] We are interested in what has happened with other technological temptations to help us think about strategies for artificial intelligence safety research. I have also written a brief page connecting this report to the broader resisted technological temptations project.[4] I am not a climate scientist, but I have been to a couple of geophysical fluid dynamics conferences at APS DFD and Woods Hole Oceanographic Institution. The information in this report mostly comes from reading the scientific literature.[1]

[1] I began at the IPCC reports, but have looked far beyond there. For those of you who are not climate scientists, I should explain the role of the IPCC. The Intergovernmental Panel on Climate Change produces detailed reports every 6-7 years, which provide a systematic review of the entire field of climate science. Thousands of experts collaborate in the largest peer review process in science to produce a clear statement of the consensus of the field. Their most recent publication is the Sixth Assessment Report (AR6), which came out in 2021/2022. Also relevant here is the Special Report on Global Warming of 1.5°C (SR15), which came out in 2018. The IPCC reports are the source of scientific information for the United Nations Framework Convention on Climate Change and informed the Paris Climate Accords of 2015.

2 Volcanic Cooling

There is something that cools the planet naturally: extremely large volcanoes. If we understood how volcanoes cool the climate, we could find a good way to replicate it.

Large volcanoes emit sulfur-based gases that react to form aerosols of sulfuric acid droplets in the stratosphere.[2] These aerosols reflect some of the sunlight that would have instead been absorbed by the surface of the Earth, so the climate receives less heat from the sun and cools.

The classic example of volcanic cooling is the eruption of Tambora in Indonesia in 1815. Tambora was the largest known[3] volcanic eruption in the last thousand years, with a volcanic explosivity index of 7 (VEI-7). The following year was the "Year without a Summer," which saw widespread crop failures in China, Europe, and North America. Various records and proxies indicate that the northern hemisphere cooled by 0.6-2°C, while some local areas cooled by more than 3°C.[5] There were also significant changes to rainfall patterns.

Volcanoes with VEI-6 are more common (about two per century) and better understood. They tend to cool the climate by 0.2-0.4°C. The effect lasts for 1-3 years and only during the summer: winters are often unchanged and may even be warmer than usual.[6, 7, 8] The most recent and best studied VEI-6 eruption was Mount Pinatubo in the Philippines in 1991.[9]

3 Stratospheric Aerosol Injection

Instead of having a volcano create aerosols in the stratosphere, we can take the aerosols up there directly. This is called 'stratospheric aerosol injection.'

There are other forms of geoengineering. Marine cloud brightening also increases the Earth's albedo. Cirrus cloud thinning makes it easier for infrared light to leave Earth. Ocean fertilization, reforestation, and direct carbon capture are sometimes also included as geoengineering. I will be focusing specifically on stratospheric aerosol injection, both to limit the scope of this report and because it is the best example of a resisted technological temptation. Planting billions of trees is an effective mitigation strategy for climate change – and many people, organizations, and countries are implementing it.[10]

The best aerosol size is a few hundred nanometers because that size scatters the incoming light most effectively.[11] About 1-5 teragrams of sulfur per year would be needed to reflect 1-2% of the incoming light to reduce heating by 1-2 watts per square meter and cool the planet by 1-2°C.[12, 13]

Most of the research focuses on sulfates because we have relevant data from volcanic eruptions. Several other aerosol candidates have better optical properties, including alumina (Al_2O_3), silicon carbide (SiC), and diamond (C), while calcite ($CaCO_3$) also has better chemical properties. I compare the types of aerosols in Appendix A The alternatives to sulfates tend to be more expensive, but they do not change the order of magnitude cost estimates unless you decide to use diamond dust.

3.1 Injection Locations

The bottom of the stratosphere is the tropopause, which has a height of about 15 km in the tropics and about 8 km near the poles. In the stratosphere, air tends to flow up near the equator, north or south towards the poles, and then back down at higher latitudes.[4]

If you inject aerosols near the equator, they stay aloft for 1-3 years and spread out over all latitudes. If you inject aerosols near the poles, they stay aloft for only a few months and remain near the poles. Small scale experiments tend to be proposed near the poles, so the effects last for a shorter amount of time. For implementation, the most common suggestion seems to be injecting aerosols near the equator so they stay aloft for as long as possible. There have also been a few suggestions of injecting aerosols near the poles, only in the spring, for a more local effect.[14]

[2] The stratosphere is the layer of the atmosphere about 10-50 km above the surface.
[3] A mystery eruption in 1465, identified in distant ice cores, may have also been VEI-7.
[4] This is called Brewer-Dobson circulation.

Injection sites on both sides of the equator would be needed to avoid creating an asymmetry between the northern and southern hemispheres, which could shift global climate patterns north or south. Some studies assume four injection sites at 30°N, 15°N, 15°S, and 30°S.[15, 16] East-west circulation is rapid, so you do not need to have injection sites at different longitudes.

Most papers believe that the best injection altitude is about 20 km. This is important because which injection mechanism is possible depends on the altitude.

3.2 Injection Methods

Many different injection mechanisms have been investigated. It appears as though a newly designed aircraft is the best choice.

At an altitude of 15 km, several existing airplanes would work. Military refueling aircraft, in particular, can reach this altitude and have a large enough payload to be effective at hauling aerosols.

At an altitude of 20 km, these airplanes no longer work. There are some existing airplanes that do reach this altitude, but they can not carry enough weight. A newly designed airplane would be needed. It could be built using existing technology: some of the engines suggested have been in use since the 1980s. The fuselage of a large narrow passenger jet (e.g. Boeing 737-800) with twice as large wings and four engines instead of two would work. Some of the papers were written by a former executive of Boeing and Atlas who has experience designing airplanes.[15, 17]

Lighter-than-air airships might also be competitive because they have low fuel cost, but they have not been tested at these altitudes. Much less research has been done on airships than on airplanes in general, because they move at lower speeds, but speed is not a problem here.

At an altitude of 25 km, even newly designed aircraft would not work. More expensive mechanisms, like rocket gliders, would have to be used.

Balloons do not seem to be the most cost effective mechanism for lifting aerosols to any altitude.

Other ideas considered include various forms of guns (gas guns, railguns, and coil guns / MAGLEV), a 20 km hose tethered to a balloon, or building a 20 km tall tower.[18]

Several tables comparing the costs of different methods from different papers can be found in Appendix B.

Designing a new airplane to use for geoengineering would likely take 5-7 years and $1-3 billion.[15] The cost of using the airplane would likely be about $1-2 billion per megaton of aerosol delivered to the stratosphere. I stated an estimate earlier that 1-5 megatons of aerosol per year are needed to achieve 1-2°C of cooling, which implies that the cost of geoengineering would be $1-10 billion per year.

The cheapest way to do geoengineering involves dozens of airplanes making thousands of flights a year to high altitudes, ideally launching from multiple locations.

4 The Case Against Geoengineering

4.1 Challenges, Known and Unknown

I have been using both ‘climate change’ and ‘global warming’ in this report. I intend slightly different meanings with those two terms: ‘Global warming’ specifically refers to increases in the global average temperature, while ‘climate change’ refers to all of the human-caused changes to the climate.

Geoengineering would stop global warming, but it would not completely stop climate change. It would cool the Earth, reducing problems like Arctic sea ice loss and global sea level rise., It would not reduce direct effects of having more carbon dioxide in the atmosphere, like ocean acidification. Geoengineering would also influence the climate in other ways.

We can use our experience with past volcanic eruptions to determine many of the effects of adding sulfates to the stratosphere.[19]

The most direct effect is that aerosols would scatter about 1-2% of incoming sunlight. This is the goal. It also affects optical properties of the sky. The sky would be less blue and more white. Sunsets would be more red. Ground based astronomy would be less effective. The aerosols would interfere with some forms of remote sensing.

Sulfates in the stratosphere destroy ozone, allowing more harmful UV light to reach the surface. This problem is smaller or nonexistent for other aerosol types.

The less intense and more diffuse light would affect ecosystems and crop growth,[20] although the effects are not well understood and might even increase plant growth rates.[21] For a rough estimate of this cost, I will take the current total global value of crops, $4 trillion per year,[22] and assume that it is reduced by 2%, for a cost of about $80 billion per year. This is unlikely to be observable due to annual fluctuations in crop yields. The real sign of the effect might even point in the opposite direction. It seems likely that the various effects on crop yields from geoengineering will at least partially cancel each other out.[23]

The less intense sunlight would cause solar power to produce less electricity. Currently, the global electricity generation market is about $2 trillion per year,[24][5] and solar power accounts for about 4% of it,[25] for a market of $80 billion per year. If this were reduced by 2%, it would mean a cost of about $2 billion per year. Solar electricity is likely to grow more quickly than crop production between now and mid-century. If it expands by a factor of 10, then the reduction in solar power by geoengineering would cost about $20 billion per year.

I estimate that the indirect costs of geoengineering due to reduced crop yields and reduced solar power to be about $100 billion per year or less. This is more than the direct costs of geoengineering. These costs are globally dispersed and will mostly not accrue to the actor that implements geoengineering.

Rainfall patterns would also be affected. Since sunlight warms land more quickly than water, reducing the sunlight reduces the temperature difference between land and water. This could weaken the Asian and African monsoons, leading to less summer rain.[26, 27] A warmer stratosphere could also draw more water vapor to higher altitudes, altering rainfall patterns in unpredictable ways.

If geoengineering were adopted, then abruptly stopped, the Earth would warm very quickly. People and ecosystems would only have a couple of years to adapt to a new climate.[28]

There are also unknown unknowns to worry about. How would aerosols other than sulfates affect the climate differently? How is continual aerosol injection different from occasional volcanic eruptions?

The precedents of large volcanic eruptions makes it less likely for there to be major unknown unknowns. We know that they significantly altered the climate, and that the changes only lasted for a few years. They did not cross any tipping-points that led to irreversible changes to Earth's climate. We also do not know what would happen to the climate without geoengineering. There are unknown unknowns and possible tipping-points associated with a warming climate that geoengineering could help protect us against.[29] Without much larger greenhouse gas emissions reductions than we are currently seeing, this argument could be used symmetrically both for and against geoengineering.

4.2 Moral Hazard

A major concern for many people who are skeptical of geoengineering is the moral hazard:[6] If geoengineering is implemented, will people reduce or halt other efforts to mitigate climate change?[7]

To understand the moral hazard, we need to understand the extent to which geoengineering can be substituted for greenhouse gas emissions reductions. The hazard occurs when the perceived and actual substitutability differs.[31]

[5] Other estimates of the size of the global electricity market which range from $1-4 trillion per year.

[6] For example, Robock described this as "the oldest and most persistent argument against geoengineering."[30] This paper feels to me more like a rhetorical argument than a scientific investigation, but it is extensively cited in the literature.

[7] From an economics perspective, this is technically 'crowding out' instead of 'moral hazard,' but this is how the term is used for geoengineering.

What is the goal of climate change mitigation?

If the goal is simply to stop global warming, then geoengineering is almost a perfect substitution for emissions reductions. It can control the global temperature. Geoengineering might even be better because the climate responds to it more quickly.

If we have the broader goal of not changing the climate, then geoengineering is an imperfect substitute. Rainfall patterns will shift and the temperature will not be reduced by the same amount everywhere. Different regions would want different amounts of geoengineering. These differences get exasperated the more carbon dioxide there is in the atmosphere and the more aerosols there are in the stratosphere.[32]

A rational actor with a well defined goal might use geoengineering to reduce or slow down other mitigation efforts. This would work best with an overshoot scenario. An overshoot scenario would occur if we emit too much to stay within our climate goals, but subsequent efforts (perhaps carbon capture and storage) are able to return the atmosphere to close to how it was before. Geoengineering could be used to limit the harm done during the overshoot, without getting locked in to using geoengineering for the foreseeable future. A sample scenario with geoengineering used during the overshoot from the IPCC Special Report [13] is shown in Figure 1.

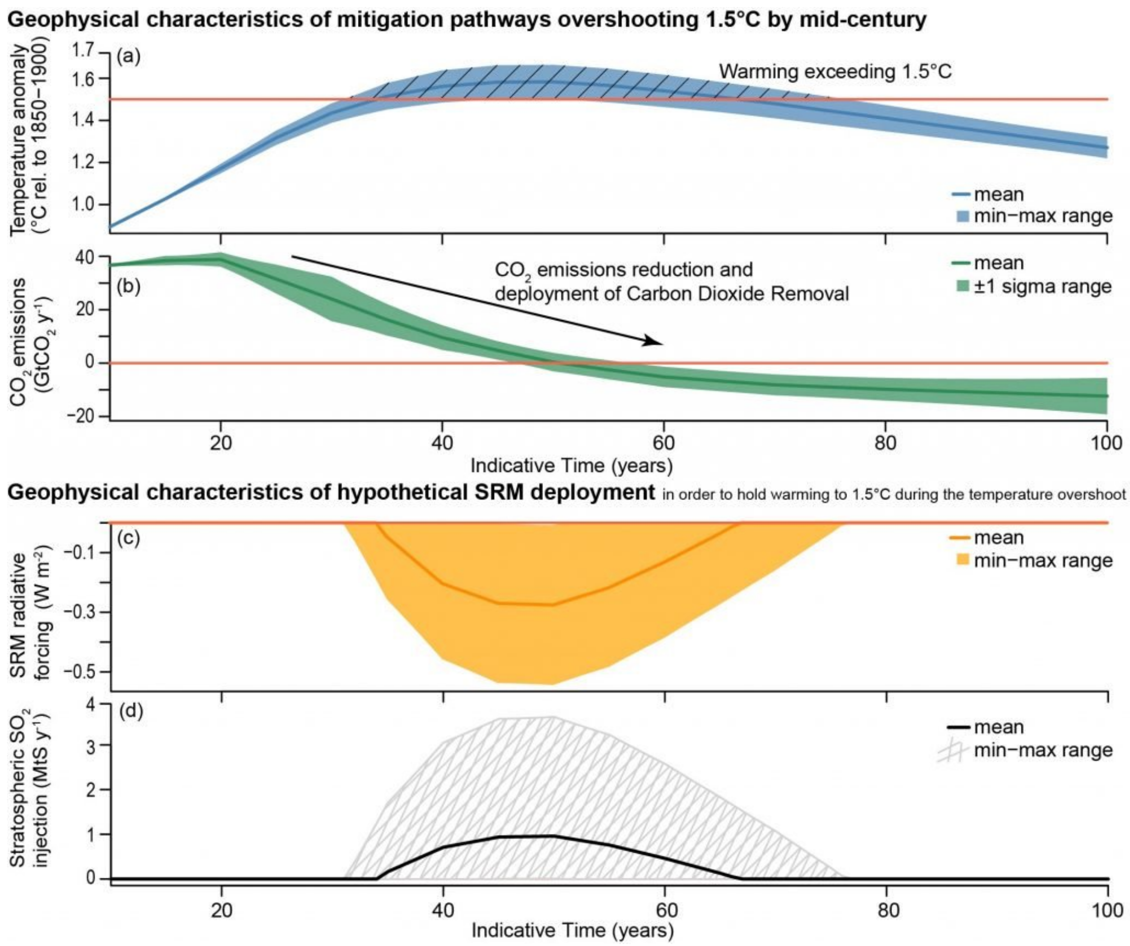

Figure 1: An overshoot scenario from p. 350 of the IPCC Special Report. A possible projection of CO_2 emissions and removal is shown in green. The resulting temperature is shown in blue. It exceeds 1.5°C of warming for a few decades, before falling again. To keep the climate from exceeding this threshold, the amount of incoming sunlight would have to be reduced, shown in yellow, which requires some stratospheric aerosol injection, shown in gray hashes.

The actual global response to climate change has not been that of a rational actor. The actual response to geoengineering is unlikely to be rational either, and is hard to predict. It could range from fossil fuel interests using geoengineering as an excuse to halt all other mitigation efforts to galvanizing people to take climate change more seriously.

The uncertainty about how geoengineering will affect people's other efforts against climate change is another reason to be cautious about geoengineering.

5 History

The idea of geoengineering has been around for almost as long as climatology has been a quantitative science. In 1974, one of the fathers of the field, Mikhail Budyko, proposed managing solar radiation with sulfate aerosols in the stratosphere if global warming ever became a problem.[33]

5.1 Taboo

For decades afterwards, very little was published about geoengineering. This changed in 2006, with a special section on the topic in the journal *Climate Change* led by Crutzen.[34] Six papers were published there, along with a paper in *Science* by Wigley a few months later.[35] Several of these papers described how they were breaking a taboo. Cicerone wrote: "I am aware that various individuals have opposed the publication of Crutzen's research, even after peer review and revisions, for various and sincere reasons that are not wholly scientific."[36] Lawrence described the situation as: "serious scientific research, such as discussed in the publications of Crutzen and Cicerone, is not at all condoned by the overall climate and atmospheric chemistry research communities."[37] Lawrence and Crutzen have also discussed the taboo, and their role in breaking it, more recently.[38]

Trends in the number of geoengineering papers provides additional evidence for the pre-2006 taboo, particularly for solar radiation management. Belter & Seidel examined publication trends for various geoengineering topic areas and found "an exceptionally large increase in the publication of articles on SRM from 2006 to 2009."[39] Oldham et al. focused on carbon dioxide removal (CDR) and solar radiation management (SRM) and found a similar pattern:[40] From 1990-2005, there were a total of 21 papers discussing solar radiation management, either alone or in a general paper. The year the taboo was broken, 2006, saw 13 papers, followed by 6 in 2007, 30 in 2008, and 55 in 2009. Linnér & Wibeck also look at similar trends, but start their analysis in 2006.[41] The figures for Belter & Seidel and Oldham et al. are shown in Figure 2.

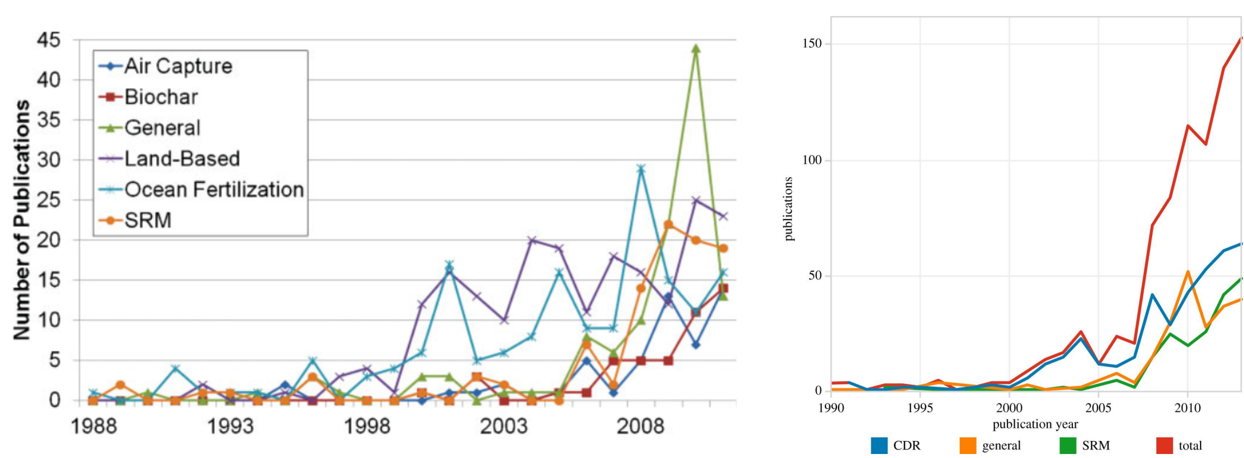

Figure 2: Trends in the number of geoengineering papers published, according to Belter & Seidel (left) and Oldham et al. (right). This report is interested in SRM and General, but not the other forms of geoengineering they considered. Note the low baseline and rapid rise after 2006 for the green and orange lines in both plots.

A similar pattern exists for policy discussion, although it is shifted by a few years. Huttunen et al. looked at 133 policy papers that mention geoengineering from 1997-2013.[42] They found a total of 10 documents from before 2009, and 20-35 documents per year from 2009 onwards.

Since 2006, some kinds of geoengineering research have been acceptable. Laboratory experiments can look at the effectiveness of different nozzles spraying aerosols and the chemical response of air from the stratosphere. Climate models simulate how the climate might respond. The IPCC supports the Geoengineering Model Intercomparison Project (GeoMIP), which suggests standardized numerical experiments for climate models to run and archives the results so they can be studied openly.[43] But there have been almost no outdoor experiments.

5.2 Attempted Outdoor Experiments

'Almost no' because there has been one outdoor solar radiation management experiment. In 2009, a Russian group injected aerosols into the atmosphere at a height of 2.5 km using helicopters.[44] They were able to measure the resulting attenuation of light. This study did not use a realistic injection method,[8] did not look at how the stratosphere would respond chemically or dynamically,[9] and it was not large enough to measure cooling. While this was a relevant outdoor experiment, it did not provide much information that would be useful to inform future experiments or possible implementation.

Several other stratospheric aerosol injection outdoor experiments have been proposed, but have not been performed. One marine cloud brightening experiment is ongoing.

In 2011, a group led by Matthew Watson of the University of Bristol made an attempt at an outdoor geoengineering experiment. SPICE (Stratospheric Particle Injection for Climate Engineering) wanted to attach a hose to a balloon 1 km in the air, pump 150 L of seawater up to the balloon, and spray it into the atmosphere. The height and scale are much too small to have a significant impact, but it was envisioned as a trial for a larger balloon with a 10 km long hose.[10] Certain environmental groups, including the ETC Group and Friends of the Earth, sent a letter criticizing the project to the UK's climate minister. The project was put on hold in September 2011 by an ethical advisory group because it "had not done enough to engage with environmental groups prior to announcing the test."[45] In May 2012, Watson told *Nature* that the experiment was canceled.[46] There were several reasons: "one factor in the cancellation was the lack of rules governing such geoengineering experiments. Although 'it is hard to imagine a more environmentally benign experiment,' in the absence of an agreed architecture, Watson said that the field trial would be 'somewhat premature.' " Another factor was that a collaborator had a patent related to the design of the experiment which he had not disclosed to the rest of the group. Popular articles focused on the conflict of interest,[47] but that seems to have just pushed the already troubled project over the edge. SPICE has done simulations and laboratory experiments, but no outdoor experiments.

More recently, a group at Harvard led by Frank Keutsch has attempted a different experiment. SCoPEx (Stratospheric Controlled Perturbation Experiment) has designed a 'gondola' to be carried by a balloon to an altitude of 20 km and spray calcium carbonate (calcite) powder.[48] They would measure plume dynamics, aerosol coagulation, and ozone-related chemistry at a scale too small to have climate effects. Their first experiment, planned for Kiruna, Sweden in 2021, would have tested the equipment, but not released any particles. Environmental and indigenous groups opposed the project. They wrote to the SCoPEx Advisory Committee, Swedish Space Corporation (who would have piloted the balloon), and Government of Sweden:

> Stratospheric Aerosol Injection research and technology development have implications for the whole world, and must not be advanced in the absence of full, global consensus on its acceptability.[49]

Harvard's Advisory Committee for SCoPEx indefinitely postponed the experiment to develop a more extensive and global societal review process.[50] The Saami Council and these environmental groups remain committed to opposing the project.[51]

[8] Helicopters cannot be used at the altitude needed.

[9] They did not look at how the plume of particles would flow and mix through the stratosphere.

[10] This is still probably too short to do geoengineering.

5.3 Marine Cloud Brightening

A different, more local form of geoengineering has had more success at pursuing experiments: marine cloud brightening. The idea is to spray sea water into the air, which provides additional nucleation sites for clouds, which makes the clouds more reflective.[11] Ship and aircraft exhaust similarly provide nucleation sites, at a smaller scale, and produce ship tracks and contrails. The "world's first field trial of marine cloud brightening" was performed in March 2020 over the Great Barrier Reef, and further experiments have been performed in subsequent years.[52] During heat waves, a significant fraction of the corals of the Great Barrier Reef can bleach and die.[53] Marine cloud brightening could be used during heat waves to shade and cool the corals and protect the reef.

What is different between this project and the projects involving stratospheric aerosols? One difference is scale: this was an experiment for a local intervention, not a global intervention. The Great Barrier Reef is not located in international waters, so Australia has clear jurisdiction. This did not prevent foreign environmentalists from objecting: "One could say that there should have been some level of consultation with the outside world," says Janos Pasztor from the Carnegie Climate Governance Institute.[52] The project did not face opposition from local indigenous groups because they made sure they had their support from the beginning. The existence of a particular salient goal also helped to build political support for the project. The Great Barrier Reef, one of the Seven Natural Wonders of the World,[54] faces a clear threat. The government of Australia has investigated 160 potential ways to protect the reef, 43 of which showed enough promise for further research.[55] One of these is geoengineering.[56] The desire to protect the Great Barrier Reef seems to have provided the political will for the Australian government to disregard the objections of these environmental groups.

6 Legal Status

The legal status of either deploying or prohibiting geoengineering is extremely unclear. "Currently, there is no targeted international law related to SRM [solar radiation management]."[57] Instead, there is a hodgepodge of treaties designed for other purposes which might be relevant to geoengineering. Some of the treaties seem to discourage or even ban geoengineering, while others seem to encourage or even require it.

In order to gain legal clarity, one of several things would have to happen: (1) A new treaty could be written which explicitly addresses geoengineering. This would only be binding for the countries which ratify the treaty. (2) An existing treaty about a related topic could clarify its position on geoengineering. This is potentially binding for the countries that have already ratified the treaty. (3) If someone did a geoengineering project, a different country could submit a case against the host country to the International Court of Justice (ICJ). The ICJ would then have the opportunity to clarify international law.

Legal scholars have written extensively about legal principles and frameworks that could be used to govern geoengineering. For example, in 2018, Harvard hosted a workshop to "advance understanding of how SG [solar geoengineering] deployment might be governed and help further the formation of some consensus on this set of issues."[58] Other legal scholars provide summaries of the relevant treaties that currently exist.[59, 60] One national government and several NGOs have also adopted frameworks for regulating geoengineering in hopes that they can establish norms.

6.1 Treaties

There are several treaties that might be relevant:

- The United Nations Framework Convention on Climate Change (UNFCCC) says that countries should mitigate the effects of climate change (in addition to stopping the causes), even if there is scientific uncertainty. The Paris Climate Accords set its main goal in terms of the global average temperature. The agreement could even be read to require geoengineering if no other methods are succeeding at this goal.

[11] This is called the Twomey effect.

- The Convention on Biological Diversity, Conference of the Parties Tenth Meeting (CBD-COP10) adopted some non-binding language encouraging countries to not do geoengineering that might affect biodiversity without an adequate scientific understanding.
- The Convention on Long-range Transboundary Air Pollution (CLRTAP), the Vienna Convention on the Protection of the Ozone Layer, and the United Nations Convention to Combat Desertification (UNCCD) might be relevant, but they have not commented on geoengineering directly.
- The Convention on the Prohibition of Military or Any Other Hostile Use of Environmental Modification Techniques (ENMOD) clearly bans the use of geoengineering as an act of war against another country, but is not applicable to peacetime uses.

More information about the treaties relevant to geoengineering can be found in Appendix C.

6.2 Customary Law

Treaties are not the only source of international law. If a particular practice has long been a custom in the interactions between countries, the International Court of Justice can recognize it as a requirement for countries in the future. One such law is relevant to geoengineering:

> It may now be considered a requirement under general international law to undertake an environmental impact assessment where there is a risk that the proposed industrial activity may have a significant adverse impact in a transboundary context ...[61]

Any country doing geoengineering, or allowing geoengineering to be done within its borders, would have to do an environmental impact assessment beforehand and continually monitor the results. What they decide to do with the information from the assessment and monitoring is not regulated under this customary law.

6.3 National Laws and NGOs

Individual countries could regulate geoengineering within their boundaries, but most have not chosen to do so. Exactly one country has adopted principles about geoengineering: the United Kingdom, in 2009. The Oxford Principles are:[62]

1. Geoengineering to be regulated as a public good.
2. Public participation in geoengineering decision-making.
3. Disclosure of geoengineering research and open publication of results.
4. Independent assessment of impacts.
5. Governance before deployment.

These principles also seem to have gained some traction as norms among geoengineering researchers.

The Asilomar Conference on Climate Intervention Technologies in March 2010 was modeled after a similar conference at the same location in 1975 which established norms for the field of recombinant DNA. They drew particularly from the Oxford Principles to establish their own recommended principles for geoengineering:[63]

1. Promoting collective benefit.
2. Establishing responsibility and liability.
3. Open and cooperative research.
4. Iterative evaluation and assessment.
5. Public involvement and consent.

Several NGOs have been established for geoengineering governance, including the Degrees Initiative[12] and the Carnegie Climate Governance Institute.[13] These institutions can influence norms and draft language that might be included in future treaties, but their statements carry no legal force.

[12] The Degrees Initiative, also called the Solar Radiation Management Governance Initiative, is a partnership between the Royal Society, the Academy of Sciences for the Developing World, and the Environmental Defense Fund.

[13] The Carnegie Climate Governance Institute is an initiative of the Carnegie Council for Ethics in International Affairs. We have already met them once as critics of Australia's marine cloud brightening experiments over the Great Barrier Reef.

6.4 Going Rouge

In the absence of a clear legal framework, individual actors could unilaterally pursue geoengineering. This was the situation for ocean iron fertilization in the 1990s and early 2000s.[64] Multiple experiments were conducted looking at how large of plankton blooms resulted from the fertilization and how much carbon was sequestered. Multiple companies sprang up to sell carbon offsets for ocean iron fertilization.

By 2008, it had become apparent that less carbon was sequestered than expected, so any fertilization project at a scale large enough to significantly affect Earth's carbon budget would also significantly disrupt ecosystems. The London Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter decided that "ocean fertilization activities other than legitimate scientific research should not be allowed."[65] Regulations on scientific research were adopted under the London Convention in 2010.

Nevertheless, rogue geoengineering continued. In 2012, Russ George, with the support of the indigenous Haida nation,[14] but not the rest of the world, fertilized 10,000 square kilometers of ocean off the western coast of Canada.[66] It did result in a large plankton bloom and an unusually large salmon catch, although the causal connection is disputed.[67] It also led to international outcry and several lawsuits. George was removed from his company and forced to pay legal costs.[68] Since then, no one has attempted to do ocean iron fertilization contrary to the London Convention.

No one has injected aerosols into the atmosphere in a similar manner, either taking advantage of the legal uncertainty or in violation of international law.

7 Costs and Benefits of Implementation

There are two main factors that limit who can do geoengineering: cost and geographic access.

A newly designed airplane could inject aerosols into the stratosphere at a cost of \$1-2 billion per megaton, as described in Section 3.2. There is additional uncertainty in how much aerosol is needed to cool the atmosphere by 1°C and in how much cooling we will want to do. The IPCC's Special Report from 2018 says that "There is high agreement that costs of SAI (not taking into account indirect and social costs, research and development costs and monitoring expenses) may be in the range of 1-10 billion USD yr^{-1} for injection of 1-5 MtS to achieve cooling of 1-2 W m^{-2}, suggesting that cost-effectiveness may be high if side-effects are low or neglected."[13] I will take \$1-10 billion per year as my order of magnitude estimate of the direct cost to do geoengineering.

I should also take into account the indirect costs of geoengineering. In Section 4, I estimated that geoengineering might reduce crop growth and solar electricity generation by 1-2%, and that this would cost about \$100 billion per year or less. These indirect costs are distributed across the globe.

I discussed geographic access in Section 3.1. The best injection sites are in the tropics on both sides of the equator. You could perform geoengineering from somewhere else, but the aerosols wouldn't stay in the stratosphere for as long and you could create an asymmetry between hemispheres that shifts global climate patterns north or south. Airplanes can also fly for thousands of kilometers before beginning to release their aerosols, although this would require more fuel and more planes.

Access to technology might also be a barrier for some actors. There is a limited number of aircraft manufacturers. They might not be willing to design and sell airplanes for geoengineering to an arbitrary customer. This is unlikely to be an issue for global organizations or large countries, which are currently capable of acquiring specialized aircraft.

I will now go through a list of potential actors to see whether implementing geoengineering is in their interest.

7.1 Global Organizations

It seems that most people who advocate for geoengineering would prefer it to be done by a broad coalition of countries.

[14] They stopped supporting the project after the international backlash.

The benefits of geoengineering are globally distributed. Stratospheric aerosols move rapidly around the globe, not respecting international borders. Having a broad coalition of countries means that the costs are shared among more of the people who receive the benefits.

Estimating the total global benefits of geoengineering is hard because it involves estimating the total global cost of climate change. The benefits of geoengineering are the avoided costs of global warming.

The most thorough estimates I have found of the costs of climate change are from the Swiss Re Institute. Swiss Re is an insurance company that specializes in insuring other insurance companies against large, highly correlated risks. They estimate that the costs of climate change will be 11%-14% of global GDP by mid-century for the likely range of temperature gains (2.0°C - 2.6°C). They also estimated a severe case (3.2°C), which would cost about 18% of global GDP, and the target of the Paris Climate Accords (well below 2°C), which would cost 'only' 4.2% of global GDP by mid-century. I estimate the current global GDP as $100 trillion[15] and the global GDP by mid-century to be about $200 trillion.[16] The Swiss Re's estimate for the cost of climate change by mid-century is $20-30 trillion per year. Even if the Paris target is achieved, the cost of climate change is estimated as $1 trillion per year by 2030 and $8 trillion per year by 2050.

The OECD published a report in 2018 titled *Financing Climate Futures*, which estimates that it would cost $6.9 trillion per year in infrastructure spending to meet the world's climate targets.[70] Since they seem to be advocating for this, I think it is reasonable to assume that they estimate the benefits of avoiding climate change to be greater than these costs.

The UN Environmental Programme - Copenhagen Climate Convention published a report in 2016 titled *Adaptation Finance Gap Report*, which estimates that the costs of adapting to climate change in developing countries are $140-300 billion per year by 2030 and $280-500 billion per year by 2050.[71] The total cost of climate change (not just financing needed for adaptation) for all countries will be larger than that. Below is a table summarizing these three organizations' estimates:

Organization	**Estimate of Cost by 2050**	**What is Estimated**
Swiss Re	$20-30 trillion/yr	Total cost of climate change, as a percent of GDP
OECD	$6.9 trillion/yr	Recommended infrastructure spending to meet climate targets
UNEP-CCC	$280-500 billion/yr	Cost of adapting to climate change in developing countries

There is clearly a large range of estimates of the costs of climate change. I expect that I could find more estimates if I looked farther, and that they would be similarly uncertain. I will take $1-20 trillion per year as a rough estimate of the global costs of climate change. Most of the costs of climate change seem to be mediated by the globally average temperature, which can be controlled using geoengineering. My order of magnitude estimate for the benefits of geoengineering will be $1-10 trillion per year.

The global benefits of geoengineering are 3 orders of magnitude greater than the direct costs and at least 1-2 orders of magnitude greater than the likely indirect costs.

Another reason to use a broad coalition of countries to implement geoengineering is to reduce international conflicts over it. Different countries might want different amounts of geoengineering, and so oppose unilateral actions. To avoid the potential conflict and to follow democratic principles, the coalition should involve as many countries as possible, including both developed nations with serious commitments to reducing their emissions and vulnerable developing nations.

There are several existing legal frameworks that geoengineering could be conducted under, including the UNFCCC and the CBD, or a new consortium of countries could be created to control geoengineering. There are some challenges to creating this international consortium:

> International governance of SAI faces the challenge that comprehensive institutional architectures designed too far in advance could prove either too restrictive or too permissive in light of subse-

[15] The global GDP for 2021 was $96.1 trillion.[69]

[16] This assumes a GDP growth rate of 2-3%, which has been the average growth rate of economies at the technological frontier. The global GDP growth rate over the last 50 years has been higher over the last 50 years, as some large developing countries experience catch-up growth. The average growth rate for the next 30 years is very uncertain, but this seems to be a conservative estimate.

quent political, institutional, geophysical and technological developments. Views on governance encompass a broad range, from aiming to restrict to wanting to enable research and potentially deployment; in between these poles, others suggest authors stress the operationalization of the precautionary approach: preventing deployment until specific criteria regarding scientific consensus, impact assessments and governance issues are met. Many scholars suggest that governance arrangements ought to co-evolve with respective SRM technologies, including that it stay at least one step ahead of research, development, demonstration, and – potentially – deployment.[57]

Creating large international coalitions is hard. Creating large international coalitions which involve as many people as possible in the decision making process is harder. This is especially true because there are a lot of people who strongly oppose geoengineering. It does not surprise me that an international institution to implement geoengineering has not yet been created.

7.2 Large Countries

In this section, I will show that large countries have the capacity to do geoengineering unilaterally.

Geographic access would be hard for some countries. Large countries which straddle the Equator, or control territories on both sides of the Equator, include the US, the UK, France, Brazil and Indonesia. Small groups of countries could also collaborate to get better geographic access and to share costs without having to solve a giant coordination problem.

Since the indirect costs of geoengineering are globally distributed, each individual country would incur only a small fraction of them. I will focus on the direct costs, because they do not scale down for smaller countries, cities, companies, or individuals.

Most large countries believe that climate change is imposing and will impose significant costs to them. We can estimate how large they think these costs are by looking at their current spending to reduce climate change and at cost estimates for what they have pledged to do. The cost estimates for pledges are less certain both because they are likely less rigorous than cost estimates for current policy and because we do not know if these countries will fulfill their pledged goals.

This is not a systematic survey for the cost of all climate policies for all countries larger than a certain size. I hope to show that there exist large countries for which geoengineering would be beneficial.

The United Kingdom passed the Climate Change Act in 2008, which plans to cut greenhouse gas emissions to 80% of 1990 levels by 2050.[72] The impact assessment for this bill estimates the present value of this reduction in greenhouse gas emissions to be £404 billion.[17] This corresponds to an average annual benefit of £18.3 billion per year, taking into account their time discounting rate. This is the benefit for the entire world from the UK reducing greenhouse gas emissions by 80%, but I want the benefits to Britain from stopping global warming for everyone. I can estimate this using the percent of emissions and the percent of global GDP that the UK accounts for.[18] The UK appears to have believed that 80% of the cost of climate change for them will be about £55 billion per year. This impact assessment also estimated that the average annual cost of their current climate change policies would be £14.7-18.3 billion per year. The direct costs of geoengineering are less than the costs of the UK's current climate change prevention efforts. The UK could also do geoengineering in addition to its current policies and still see a net benefit.

The United States estimated the Federal Budget Exposure to Climate Risk in 2021.[74] The White House estimated the financial risk due to climate change to the federal government from six specific things, disaster relief, flood insurance, crop insurance, healthcare expenditures, wildland fire suppression spending, and flood risk at Federal facilities, to be $5.4-17.3 billion per year by mid-century and $24.6-127.9 billion per year by late-century. This would be only part of the cost of climate change to the United States. In 2022, the

[17] Using a social cost of carbon in 2050 of £73.60 per ton. They also consider the possibility that this changes, and include some other benefits like improvements to air quality.

[18] Multiply the given annual benefit by (the ratio of the total carbon dioxide emitted globally to the carbon dioxide emitted by the UK) and by (the ratio of the UK's GDP to the global GDP) to get £55.1 billion per year. The numbers in the ratios are from 2008. This calculation assumes that the economic benefits from climate change are proportional to a country's GDP, which should be OK for an order of magnitude estimate.[73]

United States passed the Inflation Reduction Act, which will spend $370 billion on reducing greenhouse gas emissions over the next decade, or $37 billion per year.[75]

Germany has been pursuing an aggressive shift towards renewable energy, called the Energiewende.[76] In 2019, the Federal Court of Auditors estimated that Germany had spent €160 billion over the previous five years, or €32 billion per year, on the Energiewende. They seem to put at least this much value on not having climate change.

Emissions reduction goals can be even more extensive. China has pledged to be carbon neutral by 2060. The Boston Consulting Group estimates that this will cost a total of ¥100 trillion ($15 trillion), or $375 billion per year over 40 years.[77] The European Union's plan to be climate neutral by 2050 will cost €180 billion per year of additional capital, according to strategic consulting firm McKinsey & Company.[78][19] This is about five times Germany's spending on climate.[20] India's climate pledge of net zero greenhouse gas emissions by 2070 would cost an estimated $28 billion per year, according to CEEW, although India's current climate spending is more than an order of magnitude less.[79]

Individual countries' climate plans can cover the cost of geoengineering. A country would probably not want to completely replace their other climate change prevention efforts because geoengineering is not a perfect substitute for emissions reductions. But they could either spend additional money on climate, or potentially slow other efforts and use the money saved to do geoengineering. For example, the United Kingdom could add £5 billion per year on geoengineering to their current spending and still have lower costs than the benefits assessed for the Climate Change Act. If they instead kept the climate change budget the same and shifted money from existing plans to geoengineering, perhaps spending £5 billion per year on geoengineering and £10 billion per year on other policies, then it would delay them achieving their goal from 2050 to about 2070.[21] For countries which spend more on preventing climate change than the UK, the relative cost of adding geoengineering or the effect of shifting current spending to geoengineering would be smaller.

Why they don't do this is the mystery I am interested in.

7.3 Coastal Cities

Coastal cities have fewer resources than large countries, but also face more concentrated costs from climate change.

Rising sea levels can make flooding from storms much worse. Already, the worst storms can cause over $100 billion of damage to an individual city.[80] It seems plausible that a cost-benefit analysis might favor individual cities doing geoengineering.

In 2013, the OECD estimated future flood losses for major coastal cities in 2050. They forecasted the mean annual losses due to flooding for 136 cities if there is no change in sea level, if the sea level rises by 20cm, and if the sea level rises by 40cm.[81] If there were no adaptation in response to climate change, it would be in many cities' interest to do geoengineering unilaterally. If the sea level were to rise by 20cm, then there would be 51 cities that could pay $1 billion per year and 17 cities that could pay $10 billion per year for geoengineering with their savings from having fewer floods. If the sea level were to rise by 40cm, then there would be 71 cities that could pay $1 billion per year and 28 cities that could pay $10 billion per year for geoengineering with their savings from having fewer floods. A list of these cities can be found in this table.

Geoengineering is not the only option available to these cities. They could also construct larger levees and dikes[22] to keep back the floods. For an individual city, this seems to cost a similar amount or less than geoengineering. Even the most vulnerable cities rarely spend more than $1-2 billion per year building levees and dikes. After Hurricane Katrina, New Orleans spent $14.6 billion rebuilding its levee system from 2005-2018, or $1.1 billion per year.[82] In 2021, an additional $1.9 billion was approved to further strengthen the

[19] Most of the cost in the headline is from reallocating capital currently in carbon-intensive technologies. I have chosen to only state the additional capital outlays. If I had included everything, the cost estimate would be €800 billion per year higher.

[20] Germany accounts for about a fifth of the EU's GDP, so this is proportional.

[21] Assuming that spending the same amount of money over a longer time causes similar results.

[22] A levee holds back the water from a river, while a dike holds back the water from the sea. Since the most vulnerable cities are typically located in river deltas, both are needed.

levees from 2021-2028, and make them last another 50 years.[83] I expect that more money will be spent in that time period, but it will not be more than $1 billion per year. In 2014, Jakarta planned to spend $2.7 billion per year for 15 years building a new seawall and archipelago, but that project involved a lot more than just flood control and it was canceled in 2018 in favor of a much smaller seawall.[84, 85, 86, 87] The Dutch Ministry of Water, Public Works, and Transportation spends about $1.5 billion per year on flood defense and water management for the whole country.[88][23] New Orleans, the Netherlands, and Jakarta are all located in subsiding river deltas, which make them unusually vulnerable to rising sea levels. Most coastal cities would need to spend less than this.

Geoengineering also seems to be outside the Overton Window for most city governments. 'Could we cool the entire planet with our city's budget?' does not seem to me like the sort of question a mayor would take seriously. There is another option, building levees and dikes, which is within the Overton Window and has a similar or smaller cost. It is not surprising that cities take that option instead.

Cities also have problems with geographic access. Cities near the equator are better than cities far from the equator, and aircraft can fly thousands of kilometers from their launch site, but launching from a single location is not ideal.

7.4 Private Companies

The largest companies have revenue of hundreds of billions of dollars and profits of tens of billions of dollars per year.[89] This is enough to fund geoengineering. The question is whether they have the incentive to do it.

For most companies, it is unclear how they would make a profit from geoengineering. Retail or tech companies, for example, are affected by climate in mostly indirect ways, so it would be hard for them to see significant financial gain from the climate not being warmer. Banks and insurance companies might be more effective at concentrating the benefits into financial gains, but I do not know enough about these industries to know how that would work. There is one industry that I think could have a significant incentive to do geoengineering: oil and gas, because it could keep their markets from being reduced or eliminated by other climate policies.

I have not seen anyone who advocates for geoengineering who wants it to be implemented by the oil industry. This is the moral hazard people are worried about. It is still worth considering what their incentives are.

There are four private oil companies that definitely have the capacity to fund geoengineering: ExxonMobil ($23.1 billion in profit in 2021), Shell ($20.1 billion), TotalEnergies ($16.0 billion), and Chevron ($15.6 billion), and two that probably could: Marathon Petroleum ($9.7 billion) and British Petroleum ($7.6 billion).[90] There are also several state owned oil companies that could, but I will not consider them because they are not as independent of actors and are more closely tied to the decisions of a large country.

These companies might see their markets completely eliminated because of concerns over climate change. They could be willing to spend most of their current profit to prevent that from happening. We can look at other things that oil companies do to defend their market to see if they are willing to spend the amount of money required for geoengineering.

Some oil companies have spread climate change denial to discourage regulations on fossil fuels. The total amount spent here is too small to do geoengineering. It seems as though most accusations of oil companies' support for climate change denial involve tens of millions of dollars or less.[91] The total amount spent by fossil fuel companies lobbying the US government on climate change from 2000 to 2016 is $370 million.[92] This is much smaller than the $1-10 billion per year needed to do geoengineering.

Oil companies have spent more on clean energy than on climate denial, which is another way to continue to remain relevant as energy markets shift. Their reporting on clean energy investments is sporadic and their actual spending may be less than their pledged spending. The highest amount of capital expenditures in clean energy by one oil company in a year was $1.6 billion by BP in 2011. BP has pledged to spend $3-4

[23] This is from 2005. The Netherlands doesn't report its spending in the same way now, so it is harder to separate flood control from other infrastructure. The 2023 budget includes €13.0 billion for Infrastructure and Water Management.

billion per year on low carbon energy by 2025 and $5 billion per year on low carbon energy by 2030. Shell has pledged to spend $1-2 billion per year on renewables from 2018-2020 and $2-3 billion per year since 2020, but they only reported spending $0.9 billion in 2020. ExxonMobil and Chevron claim that their low carbon investments are increasing, but have not reported how much money they are spending.[93] Investments in renewable energy is not a perfect analogy for geoengineering because these companies probably hope that these investments will pay off, and are not just using them to defend their traditional market.

It seems to me that the cost of geoengineering is right at the limit of what oil companies are willing to spend to defend their market in response to climate change. It is plausible from them to do it, but not too surprising that they have not done it.

Oil companies might also have problems with geographic access. While they have operations all around the world, they do not rule over any territory. They would need the approval or at least the acquiescence of the country or countries they operate out of. This does increase the number of relevant actors beyond the large countries considered above, because a small country which would not be incentivized to do geoengineering on its own could be persuaded to allow an oil company to use its territory to do geoengineering.

Even in this case, the oil companies would be vulnerable to actions by other countries. Because they are global companies, they depend on market share in many countries. If large countries which do not approve of geoengineering decide to sanction the company that does it, they could destroy any gains that company receives. Angry consumers might also boycott a company seen as intentionally changing the climate.

It seems to me that geoengineering is at most a marginal benefit for large oil companies, and the risk of losing market share in countries that do not approve of it would be enough to keep them from doing it.

7.5 Individuals

The largest private fortune is about $200 billion. Several other individuals own wealth of over $100 billion.[94] Spending $1-10 billion per year on geoengineering would be a significant drain on their wealth. Geographic access is even harder for individuals than for cities or companies.

This does not mean that they could not do it. But it would be more like a large and controversial donation than an investment they are likely to make returns on. I am not surprised that no individual has tried to do geoengineering.[24]

8 Costs and Benefits of Research

We saw above that large countries have the capacity to do geoengineering, would gain a net benefit from it, and are not currently implementing geoengineering. Why?

One possibility is that they believe that geoengineering should be done by multinational institutions. This might partially explain the behavior of some large countries, but I do not think it is sufficient to completely explain the behavior of all of them. Large countries are willing to act unilaterally if they believe it is in their interest to do so.

Another possibility is that they do not believe that the costs of climate change are large enough to justify doing geoengineering now, even if they think that the costs of climate change will be larger in the future. If this were true, then we would expect them to be doing research so they are ready to implement geoengineering once they consider it more beneficial.

This is not what we are seeing. Almost no outdoor experiments for stratospheric aerosol injection have been done, as described in Section 5. This seems to be the most compelling argument for why large countries have not been implementing geoengineering: a technological solution to a major scientific problem should not be pursued without a full understanding of what the effects will be.

[24] Except maybe Elon Musk, because it just seems like the sort of thing he would do.

This only moves the problem up one level: Why hasn't more research been done? Scientists should be incentivized to investigate novel solutions to important problems. If they are not, it is worth understanding why.

8.1 IPCC's Opinion

The IPCC's Special Report from 2018 summarizes the current state of the field:[13]

> **Uncertainties surrounding solar radiation modification (SRM) measures constrain their potential deployment.** These uncertainties include: technological immaturity; limited physical understanding about their effectiveness to limit global warming; and a weak capacity to govern, legitimize, and scale such measures. Some recent model-based analysis suggests SRM would be effective but that it is too early to evaluate its feasibility. Even in the uncertain case that the most adverse side-effects of SRM can be avoided, public resistance, ethical concerns and potential impacts on sustainable development could render SRM economically, socially and institutionally undesirable (*low agreement, medium evidence*).

These uncertainties will not be resolved without outdoor experiments. The IPCC's list of recommendations for further research includes a section for "Carbon Dioxide Removal (CDR) and Solar Radiation Modification (SRM)," but all of the recommendations are for carbon dioxide removal.[95] The IPCC does not recommend geoengineering research.

8.2 Surveys

We can look at surveys to get some idea of the opinions of climate scientists, policy makers, and the public.

Most climate scientists do not support geoengineering. Among geoengineering papers, only 2% unreservedly advocated for it, while 28% say that it should be considered.[96] Dannenberg & Zitzelsberger's survey of scientists involved in the Fifth Assessment Report for the IPCC shows a similar level of support. Of the 214 scientists who responded (out of 900 contacted), 31% supported "including geoengineering in international climate negotiations," 31% supported "more investment in R&D on geoengineering technologies," and 52% supported "large-scale deployment of geoengineering in case of a climate emergency," for example, a sudden collapse of most of Greenland's ice sheet.[97] The IPCC's decision to not recommend geoengineering research seems consistent with the majority of climate scientists' beliefs.

Dannenberg & Zitzelsberger's survey also received 509 responses (out of 8763 contacted) from people involved in the negotiations that led to the Paris Climate Accords. This group was more evenly divided: 50% supported "including geoengineering in international climate negotiations," 64% supported "more investment in R&D on geoengineering technologies," and 68% supported "large-scale deployment of geoengineering in case of a climate emergency." An examination of 114 policy papers by Huttunen et al. shows a similar split: 41% are permissive to geoengineering (36% moderately & 8% strongly), 41% are opposed to geoengineering (29% moderately & 14% strongly), and 17% are undecided.[42] They also saw that 61% of these policy papers supported more governance and 58% supported more research.

Surveys of the general population show that most people are unfamiliar with geoengineering, so their responses vary widely based on how the questions are framed.[98]

It appears as though most climate scientists reject geoengineering experiments, and probably most of the climate scientists who accept experiments reject implementation. Climate policy makers are more favorable towards geoengineering, but their opinions are still very divided. Geoengineering is not a salient enough issue for the public to have formed consistent beliefs about it.

8.3 Funding Organizations

Geoengineering experiments need funding if they are going to occur. Most funding for climate science comes from government grants. It seems as though little of this money is available to geoengineering, especially outdoor experiments.

The total amount of funding for geoengineering increased from about $1 million in 2008 to about $8 million in 2018, according to a Harvard summary of geoengineering projects.[99] The earlier parts of this trend are dominated by publicly funded projects in the UK and Germany, including SPICE. This funding peaked in 2014. Starting in 2017, geoengineering funding became dominated by two projects in the US: SCoPEx and the Carnegie Climate Geoengineering Governance Initiative. Both of these projects are funded by private philanthropy.[25] About 3/4 of all geoengineering funding came from private sources in 2018.

Climate scientists who work on geoengineering sometimes talk about the lack of funding. Harvard's summary quoted one of them saying: "Nobody supports me for GeoMIP. I do all of that on nights and weekends." O'Neill described outdoor experiments: "Such work is rare, because field research with technologies designed to intentionally alter the climate are politically and environmentally fraught and do not tend to attract funding."[100] The lack of government funding also explains why geoengineering projects are increasingly turning to private philanthropy.

I have found it hard to know how grant agencies make their decisions from the outside, but I suspect that they tend to follow the recommendations by the IPCC. We do know that the IPCC reports are used to inform the climate policies of the US, the EU, and other countries.[101, 102] I suspect that the IPCC's lack of recommendation for geoengineering research limits the amount of public money grant agencies are willing to pay for it. Even if the IPCC reports are not directly involved, if the grant agencies follow the recommendations of the majority of climate scientists in their country, geoengineering research would not get funded. I do not think that it is unreasonable to suggest this amount of coordination: the pre-2006 taboo shows that some climate scientists have the willingness and some capability to limit geoengineering research.

8.4 Scientists Who Support Geoengineering

Suppose you are a climate scientist who would like to do geoengineering experiments. What incentives would you face?

The incentive structure of science is largely built around getting grants to fund your research, publishing papers about your research, and having other scientists cite your research. We have already seen that getting grants for geoengineering is hard and so many scientists turn to private philanthropy. Publishing papers and getting citations seems harder if you are working on something that most of your field does not approve of, but not impossible. The most cited geoengineering papers have hundreds of citations.[26] There seems to be an incentive here against trying to do geoengineering research, but not a particularly strong one.

If you do decide to try to do a geoengineering experiment and get funding for it, what happens next? We saw what happened Section 5. Certain environmental groups advocate against your work. The ETC Group[27] and Friends of the Earth[28] seem to be the most prominent here. They try to organize indigenous groups against you as well, if you have not preemptively persuaded them of the value of your experiments. Their effects, directed at a government or your institution's advisory committee, have a good chance of preventing your experiment from happening.

The combination of incentives from the scientific community, incentives from certain environmental groups, and the likelihood of your efforts ultimately being futile seem like enough to explain why almost no outdoor geoengineering experiments have been done.

[25] Including Open Philanthropy.

[26] Crutzen's taboo-breaking paper from 2006 has 1745 citations, according to Google Scholar, as of October 25, 2022. I have not seen any other geoengineering paper with more than a thousand citations.

[27] "ETC Group opposes geoengineering and other false solutions to climate change (e.g., proprietary, genetically-engineered 'climate-ready' crops) and supports peasant-led agroecological responses to the climate crisis." https://www.etcgroup.org/issues/climate-geoengineering.

[28] "We call for an International Non-Use Agreement on Solar Geoengineering." https://www.solargeoeng.org/endorsements/friends-of-the-earth-international/.

9 Summary of Anti-Geoengineering Efforts

No one is currently trying to implement geoengineering, even though it would be in some actors' interest to do so. Geoengineering could offset many of the effects of climate change and cost less than the current climate change prevention and mitigation efforts of some large countries. The cost-benefit analysis for a new global institution looks even better, because the costs for implementation are shared among more actors and the benefits are globally distributed. It is surprising that no one has done it, and worth understanding how that happened.

We can think of the efforts against geoengineering as operating on three levels: in published papers, in outdoor experiments, and in implementation. Each level precedes and precludes the later levels.

There was a taboo against publishing scientific papers about geoengineering prior to 2006. As long as this taboo held, very few people were even aware of geoengineering as a serious possibility. Once Crutzen broke this taboo in 2006, geoengineering became a legitimate object of scientific inquiry.[34]

The next level of the efforts against geoengineering is the current difficulty in doing outdoor experiments. There seems to me to be two main contributing factors: (1) Most climate scientists oppose geoengineering. They write the IPCC reports which do not recommend geoengineering experiments. Government funding agencies, which seem to use recommendations from the IPCC reports and local climate scientists, rarely fund geoengineering research. (2) When geoengineering experiments are proposed, certain environmental groups rally to oppose them. These environmental groups work with indigenous groups, when possible, to convince advisory committees and governments to not allow the research to proceed.

The third level is the question of whether or not to implement geoengineering. Several arguments against it have been put forward, including: (1) There is a 'moral hazard' that geoengineering might mean that we won't do anything else to prevent or mitigate climate change and we will become increasingly dependent on it. (2) Geoengineering requires global governance to keep it from causing conflicts between countries, and this governance structure has not been created yet. These do not seem to me to be a complete explanation for why no large country is pursuing geoengineering. Some large countries seem willing to not invest enough in preventing or mitigating climate change without the moral hazard of geoengineering. The difficulty of getting international agreement on a controversial topic makes it unsurprising that governance remains uncertain, but large countries are often willing to pursue their own interest when international law is uncertain. It seems to me that the most effective argument currently is: (3) Not enough geoengineering research has been done and we should not make a major decision like this without a good scientific understanding of what will happen. This argument allows the second level to block the third level.

So why hasn't geoengineering been done? Because we haven't done enough research to really know if it is a good idea. And why hasn't this research been done? Because enough climate scientists oppose it to keep it from getting enough support from government agencies and because certain environmental groups have been able to block experiments from happening.

A Aerosol Types

Volcanoes mostly release sulfur dioxide (SO_2), which reacts with water and oxygen in the stratosphere to form droplets of sulfuric acid (H_2SO_4). We could take the sulfur to the stratosphere as hydrogen sulfide (H_2S) or pure liquid sulfur, which are both lighter and would create similar droplets. Most of the research focuses on these sulfates because we have relevant data from volcanic eruptions, but there are two reasons why alternatives might be better.

Acids in the stratosphere destroy ozone. This occurs both with the chlorine and fluorine from chlorofluorocarbons and with sulfuric acid from large volcanic eruptions. Most of the solid aerosols are chemically inert in the stratosphere, so they do not impact the ozone layer as much, although they can provide nucleation sites for naturally occurring sulfuric acid. Calcite ($CaCO_3$) is a base, so it could neutralize existing acids in the stratosphere and strengthen the ozone layer.[103]

Aerosols are not perfect reflectors of light: they also absorb some of it. This warms the stratosphere, while cooling the surface. It is not well understood if having a warmer stratosphere would cause problems, but it seems better to not change the climate more than necessary. A warmer stratosphere would likely draw water vapor to higher altitudes, which might impact rainfall somehow.[104] Several solid aerosols reflect similar amounts of sunlight, while absorbing much less, including alumina (Al_2O_3), silicon carbide (SiC), and diamond (C).[105, 11] Alumina aerosols are present in space shuttle exhaust, so there is some data about their effects in the stratosphere. The chemical behavior of the other solid aerosols in the stratosphere is less well understood.

None of these aerosols would be in high enough concentrations to significantly affect the chemistry of the lower atmosphere or surface.[106]

B Comparing Injection Methods

Figure 3 shows tables from three papers which compare the costs of implementing stratospheric aerosol injection using different methods:

The top table is from Robock et al. [107] To compare with the other tables, divide the rightmost column by 10^9. This paper considers the fewest alternatives, and does not include a newly designed airplane. The cheapest option is the KC-135 Tanker, a military refueling aircraft, but it can only fly up to an altitude of 15 km, which is probably not high enough.

The middle table is from McClellan et al. [108] Read the rightmost column to compare. This paper proposes five new airplane designs and three new airship designs, depending on what altitude is needed for geoengineering. Getting to lower altitudes is (unsurprisingly) less expensive.

The bottom table is from Smith & Wagner. [15] SAIL (Stratospheric Aerosol Injection Launcher) is the new airplane design described in this paper. The units look different, but are equivalent to McClellan.

Both McClellin and Smith agree that a newly designed airplane could inject sulfates into the stratosphere at 20 km at a cost of about \$1-2 billion per megaton, if done at scale, including design costs. Using one of the solid aerosols, except diamond dust, would add about another \$1 billion per megaton.[17]

C Geoengineering Treaties

Multiple treaties are potentially relevant to the status of geoengineering in international law, but none give clear regulation for or against its peacetime use.

C.1 UNFCCC & Paris

The United Nations Framework Convention on Climate Change seems like the most obvious place to look for a discussion of geoengineering. The most recent treaty adopted under this framework is the Paris Climate Accords from 2015. Neither addresses geoengineering directly, but both have some potentially relevant language. Article 3.3 of the UNFCCC states:

> The Parties should take precautionary measures to anticipate, prevent or minimize the causes of climate change and mitigate its adverse effects. Where there are threats of serious or irreversible damage, lack of full scientific certainty should not be used as a reason for postponing such measures . . . [109]

This seems to encourage geoengineering, as a precautionary measure to mitigate the adverse effects of climate change, even if there is still scientific uncertainty. The Paris Climate Accords further establishes the goal of

> Holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels ... [110]

If other climate change prevention measures are failing to achieve this goal, this could be read as requiring geoengineering. The broad language of the UNFCCC and the goal stated in terms of a global average temperature make this the most pro-geoengineering treaty.

C.2 CBD-COP10

In contrast to the UNFCCC, the Convention on Biological Diversity has the clearest anti-geoengineering language. At the Tenth Meeting of the Conference of Parties, it "Invites Parties and other Governments, according to national circumstance and priorities, to consider the guidance below ..." to

> Ensure ... in the absence of science based, global, transparent and effective control and regulatory mechanisms for geo-engineering, and in accordance with the precautionary approach and Article 14 of the Convention, that no climate-related geo-engineering activities that may affect biodiversity take place, until there is an adequate scientific basis on which to justify such activities and appropriate consideration of the associated risks for the environment and biodiversity and associated social, economic and cultural impacts, with the exception of small scale scientific research studies that would be conducted in a controlled setting in accordance with Article 3 of the Convention, and only if they are justified by the need to gather specific scientific data and are subject to a thorough prior assessment of the potential impacts on the environment; [111]

This is the 23rd item in the list of things to consider. A footnote also provides a definition of geoengineering:

> Without prejudice to future deliberations on the definition of geo-engineering activities, understanding that any technologies that deliberately reduce solar insolation or increase carbon sequestration from the atmosphere on a large scale that may affect biodiversity (excluding carbon capture and storage from fossil fuels when it captures carbon dioxide before it is released into the atmosphere) should be considered as forms of geo-engineering which are relevant to the Convention on Biological Diversity until a more precise definition can be developed. ...

The language here is ambiguous in several ways.[112] The word "ensure" usually implies a legal obligation, but this is only a non-binding normative framework that the Parties are "invite[d] ... to consider." The various exceptions are not related to each other in obvious ways. "Small scale research studies" seem to have more restrictions because they are bound by Article 3, which is especially weird because "large scale" is part of the definition of geoengineering. The authors seem to recognize the incompleteness of this statement and repeatedly say that it only applies until a better legal framework is developed.

C.3 CLRTAP

The Convention on Long-range Transboundary Air Pollution exists to regulate

> the introduction by man, directly or indirectly, of substances or energy into the air resulting in deleterious effects of such a nature as to endanger human health, harm living resources and ecosystems and material property and impair or interfere with amenities and other legitimate uses of the environment ... [113]

when the sources of the pollution and damages caused by the pollution are in different countries. Sulfur emissions have been given quantified limits under this treaty, but the limits are designed for lower atmosphere emissions and are much higher than what would be used for geoengineering. Other potential aerosols are not regulated, and might not have "deleterious effects." This treaty has only been ratified by 51 countries, which are mostly in North America and Europe.

C.4 Vienna Convention

The Vienna Convention "establishes an obligation to take appropriate measures to protect human health and the environment against adverse effects resulting or likely to result from human activities which modify or are likely to modify the ozone layer."[114] Stratospheric sulfur emissions are not currently regulated under the Vienna Convention, but they could be because they can destroy ozone. Other aerosols which do not affect ozone are not affected by this treaty.

C.5 UNCCD

Geoengineering might affect rainfall patterns. The details of this are not currently understood, but a sufficiently large amount of geoengineering might weaken the Asian and African monsoons. If this were to happen, then the UN Convention to Combat Desertification in Those Countries Experiencing Severe Drought and/or Desertification, particularly in Africa would become relevant.

C.6 ENMOD

The ENMOD Convention originated during the Vietnam War after the US used cloud seeding to increase rainfall along the Ho Chi Minh trail and disrupt the operations of the Viet Cong.[29] It contains the least ambiguous language of any treaty pertaining to geoengineering:

> Each State Party to this Convention undertakes 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 any other State Party. ... The term "environmental modification techniques" refers to any technique for changing - through the deliberate manipulation of natural processes - the dynamics, composition or structure of the earth, including its biota, lithosphere, hydrosphere and atmosphere, or of outer space. [115]

This clearly bans using geoengineering as a hostile act against another country. It does not impact peaceful uses of geoengineering. International law which applies to military conflicts is clearly distinct from peacetime international law, so this treaty could not be expanded to cover geoengineering in other circumstances.

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Table 2. Costs for Different Methods of Injecting 1 Tg of a Sulfur Gas Per Year Into the Stratosphere[a]

Method	Payload (tons)	Ceiling (km)	Number of Units	Purchase Price (2008 Dollars)	Annual Cost
F-15C Eagle	8	20	167 with 3 flights/day	$6,613,000,000	$4,175,000,000[b]
KC-135 Tanker	91	15	15 with 3 flights/day	$784,000,000	$375,000,000
KC-10 Extender	160	13	9 with 3 flights/day	$1,050,000,000	$225,000,000[b]
Naval Rifles	0.5		8,000 shots per day	included in annual cost	$30,000,000,000
Stratospheric Balloons	4		37,000 per day	included in annual cost	$21,000,000,000–$30,000,000,000

[a]Airplane data from Air Combat Command (2008), Air Mobility Command (2008a, 2008b). See text for sources of data for airplanes. Costs in last two lines from *COSEPUP* [1992]. Conversion from 1992 and 1998 dollars to 2008 dollars (latest data available) using the Consumer Price Index (http://www.measuringworth.com/uscompare/).

[b]If operation costs were the same per plane as for the KC-135.

Table 2. Summary of all systems examined. 1 Mt yr^{-1}, all costs in FY10 dollars.

System type	Altitude (kft)	Altitude (km)	RDT&E and acquisition costs ($B)	Recurring cost per kg (less RDT&E, acquisition costs)	Yearly total cost including depreciation and interest ($B)
Boeing 747 Class	45	13.7	$0.8	$1.00	$1.1
Modified Gulfstream Class	60	18.3	$3.2	$2.15	$2.9
New design airplane	40	12.2	$2.0	$0.30	$0.6
New design airplane	60	18.3	$2.1	$0.35	$0.7
New design airplane	70	21.3	$5.6	$0.56	$1.5
New design airplane	80	24.4	$7.8	$0.60	$1.9
New design airplane	100	30.5	$11	$0.75	$2.6
Gun (Mark 7 16″)	91	27.7	$0.34	$137	$137
Gun (Modernized Mark 7)	91	27.7	$0.55	$18.90	$19
Hybrid airship	66	20.0	$4.0	$0.35	$1
Hybrid airship	82	25.0	$5.9	$0.40	$1.4
Hybrid airship	98	30.0	$7.5	$0.80	$2
Rocket	100	30.5	$2300	$263	$390
Floating slurry pipe	70	21.3	$24	$0.25	$4
Floating gas pipe	70	21.3	$59	$0.63	$10

Table 2. Cost and capabilities comparison of lofting technologies.

Platform	Cost ('000 $/t)	SAIL multiple	Source
Mission capable			
SAIL[a]	1.4	1×	
McClellan New High Altitude Aircraft	1.5[b]	~1×	McClellan *et al* (2010, 2012)
Delft SAGA[c]	4.0	~3×	Delft Report[c]
McClellan Modernized Gun	19	~14×	McClellan *et al* (2010, 2012)
Balloons	~40	~28×	Near Space[d]
NASA WB57	43	~30×	NASA[d]
NASA ER2	50	~35×	NASA[d]
NASA Global Hawk	70	~50×	NASA[d]
SpaceX Falcon Heavy Rocket	71[e]	~50×	Chang (2018)
Gun Mark 7 16'	137	~100×	McClellan *et al* (2010, 2012)
Vector Rocket	1180[e]	~850×	Chang (2018)
Virgin Orbit Rocket	2000[e]	~1400×	Virgin Orbit[d]
Mission incapable			
Existing Commercial Aircraft	Not capable of reaching ~20 km[f]		
Modified Commercial Aircraft	Not capable of reaching ~20 km[g]		
Existing Military Transporters[h]	Not capable of reaching ~20 km[g]		
Military Fighters	Not capable of sustained flight at ~20 km[g]		
Tethered Hose	Not sufficiently mature technology[g]		
Aerostats/Airships	Not sufficiently mature technology[g]		

[a] See section 4 for cost derivations.

[b] Assumes a program deploying ~1 Mt yr^{-1}.

[c] TU Delft student report developing SAGA, the Stratospheric Aerosol Geoengineering Aircraft (Design Synthesis Exercise Group 2 2016).

[d] Personal communications with individuals at respective entities.

[e] Reduced by 95% to account for 20 km target altitude relative to 200 km for Earth orbit; Chang (2018)'s estimates for Vector Rocket confirmed by Vector Launch.

[f] McClellan *et al* (2010, 2012) and authors' analysis (see text).

[g] Authors' analysis (see text), including, for military fighters, personal communication with Boeing, Lockheed Martin, and Northrup Grumman.

[h] Including existing military tankers.

Figure 3: Comparisons of possible stratospheric aerosol injection methods.