Stratospheric Aerosol Geoengineering

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ABSTRACT

In response to global warming, one suggested geoengineering response involves creating a cloud of particles in the stratosphere to reflect some sunlight and cool Earth. While volcanic eruptions show that stratospheric aerosols cool the planet, the volcano analog also warns against geoengineering because of responses such as ozone depletion, regional hydrologic responses, whitening of the skies, reduction of solar power, and impacts of diffuse radiation. No technology to conduct geoengineering now exists, but using airplanes or tethered balloons to put sulfur gases into the stratosphere may be feasible. Nevertheless, it may be very difficult to create stratospheric sulfate particles with a desirable size distribution.

The Geoengineering Model Intercomparison Project, conducting climate model experiments with standard stratospheric aerosol injection scenarios, has found that insolation reduction could keep the global average temperature constant, but global average precipitation would reduce, particularly in summer monsoon regions around the world. Temperature changes would also not be uniform; the tropics would cool, but high latitudes would warm, with continuing, but reduced sea ice and ice sheet melting. Temperature extremes would still increase, but not as much as without geoengineering. If geoengineering were halted all at once, there would be rapid temperature and precipitation increases at 5–10 times the rates from gradual global warming. The prospect of geoengineering working may reduce the current drive toward reducing greenhouse gas emissions, and there are concerns about commercial or military control. Because geoengineering cannot

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safely address climate change, global efforts to reduce greenhouse gas emissions and to adapt are crucial to address anthropogenic global warming.

1 Introduction

On September 27, 2013, the Intergovernmental Panel on Climate Change (IPCC) Working Group I released the *Summary for Policymakers of the Fifth Assessment Report*, which stated that ''It is *extremely likely* that human influence has been the dominant cause of the observed warming since the mid-20th century.'' ''Extremely likely'' is defined as with a greater than 95% probability of occurrence, using the expert judgment of the IPCC scientists. Furthermore, they outlined the projected global warming, sea level rise, changes in precipitation patterns, increase in tropical storms, and other responses to future anthropogenic pollution with a greater degree of certainty than before.

The United Nations Framework Convention on Climate Change (UNFCCC) was established in 1992. Signed by 194 countries and ratified by 189, including the United States, it came into force in 1994. It says in part, ''The ultimate objective of this Convention ... is to achieve ... stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system.'' ''Dangerous anthropogenic interference'' was not defined when the UNFCCC was signed, but following the Conference of the Parties in Copenhagen in 2009, the countries of the world agreed that global warming of 2 K above pre-industrial levels should be considered dangerous.

In light of the failure of society to take any concerted actions to deal with global warming in spite of the UNFCCC agreement, two prominent atmospheric scientists published papers in 2006 suggesting that society consider geoengineering solutions to global warming.[1,2] Although this was not a new idea,[3,4] this suggestion generated much interest in the press and in the scientific community, and there has been an increasing amount of work on the topic since then.

The term ''geoengineering'' has come to refer to both carbon dioxide removal and solar radiation management (SRM),[5,6] and these two different approaches to climate control have very different scientific, ethical and governance issues. This chapter will only deal with solar radiation management, and will focus on the suggestion of producing stratospheric clouds to reflect sunlight in the same way large volcanic eruptions do. Stratospheric aerosols, sunshades in space (see Chapter 8), and marine cloud brightening (see Chapter 6) are the only schemes that seem to have the potential to produce effective and inexpensive large cooling of the planet,[6] but each of them has serious issues, and no such technology currently exists for any of these proposed schemes. Unless otherwise noted, this chapter will use the term ''geoengineering'' to refer to SRM with stratospheric aerosols.

Clearly, the solution to the global warming problem is mitigation (reduction of emissions of gases and particles that cause global warming, primarily CO_2). Society will also need to adapt to impacts that are already occurring. Whether geoengineering should ever be used will require an analysis of its benefits and risks, as compared to the risks of not implementing it. While research so far has pointed out both benefits and risks from geoengineering, and that it is not a solution to the global warming problem, at some time in the future, despite mitigation and adaptation measures, society may be tempted to try to control the climate to avoid dangerous impacts. Much more research on geoengineering is needed so that society will be able to make informed decisions about the fate of Earth, the only planet in the universe known to sustain life.

This chapter will first discuss how it might be possible to create a permanent cloud in the stratosphere. Next it will survey climate model simulations that inform us of some of the benefits and risks of stratospheric geoengineering. Since full implementation of geoengineering to test these theoretical calculations might be dangerous, lessons from volcanic eruptions, the closest natural analog to stratospheric geoengineering, are used to inform the model results. The next section discusses the ethical and governance aspects of both geoengineering research and potential geoengineering implementation. Finally, the potential benefits and risks of stratospheric geoengineering are summarized.

2 How to Create a Stratospheric Cloud

2.1 *Why the Stratosphere?*

Every so often, large volcanic eruptions inject massive amounts of sulfur dioxide (SO_2) gas into the stratosphere, the layer of the atmosphere from about 12 km up to 50 km, which resides above the troposphere where we live. The SO_2 is oxidized in the atmosphere to sulfuric acid which has a low enough vapor pressure to form a cloud of droplets. Only volcanic eruptions that are strong enough to get sulfur into the stratosphere have an important impact on climate. They do this by scattering some of the incoming sunlight back to space, thus cooling the surface.[7]

A stratospheric volcanic cloud lasts for a couple years if the eruption is in the Tropics, but for several months if the eruption is at high latitudes. The stratosphere has little vertical motion and no precipitation, so the main removal mechanism is gravitational settling until the particles fall into the troposphere. Initial growth of the particles by coagulation depends on their concentration, and the larger particles fall faster and are removed more rapidly. At the same time, stratospheric circulation moves the particles poleward. The main location for the removal of sulfate from the stratosphere to the troposphere is in the jetstream region in the middle latitudes.[8] The troposphere has vertical motion, mixing, and rain, which can wash particles out of the atmosphere in about a week. The removal of particles from the stratosphere typically is an exponential process. The e-folding time is about one year, which means that a year after the formation of volcanic sulfate particles from tropical injection, the concentration is about 1/3 of the original amount, and after another year, the concentration is about 1/3 of that. For geoengineering, injection would have to be repeated frequently to maintain a stratospheric cloud.

The main suggestion of how to create a stratospheric cloud to reflect sunlight has been to emulate volcanic eruptions.[1–6] Materials other than sulfur have been suggested, for example soot, but soot would be terribly damaging to stratospheric ozone because it would absorb sunlight, heating the stratosphere, and enhancing ozone destruction reactions.[9] This would produce large enhancements of dangerous ultraviolet (UV) flux to the surface. Other substances may be developed in the future, such as minerals or engineered particles,[10] but current work has focused on sulfuric acid.

While sulfuric acid in high concentrations can be dangerous, and acid rain in the troposphere is mainly sulfuric and nitric acid, the amount of annual sulfur emissions to the stratosphere that have been proposed, 5–10 Tg ($Tg = 10^{12}$ g), is much less than the annual volcanic SO_2 emissions into the troposphere,[11] about 13 Tg, plus the annual human emission of SO_2 as a byproduct of burning fossil fuels, about 100 Tg. Nevertheless, sulfur emissions at the level proposed for stratospheric geoengineering would still produce additional impacts on human health and ecosystems.

Since the sulfuric acid clouds created in the stratosphere immediately start to fall out, geoengineering would require continuous replenishment of the sulfur. We know from observations and climate model simulations of volcanic eruptions like the Mt. Pinatubo eruption in the Philippines in 1991, the largest of the 20th Century, that sulfuric acid clouds gradually move from the Tropics poleward covering the entire globe. Therefore, to achieve the longest lifetime for an artificial geoengineering cloud, it would be optimal to start it out in the Tropics. The boundary between the troposphere and the stratosphere, called the tropopause, however, has a maximum altitude in the Tropics, about 18 km. So to conduct stratospheric geoengineering, the task would be to inject sulfur about 20 km into the atmosphere every year in the Tropics. The amount would depend on the size of the effect desired (where to set the planetary thermostat), an unresolved issue.

2.2 Means of Stratospheric Injection

How would it be possible to get several Tg of S into the tropical stratosphere every year? If it were lofted as H_2S gas, with a molecular weight of 34 g per mole S, it would take a little more than half the mass of lofting the S as SO_2 gas, with a molecular weight of 64 g per mole S. The H_2S would probably quickly oxidize to SO_2 and then convert to H_2SO_4. One issue is that H_2S is rather nasty stuff, and even SO_2 can be dangerous, but assuming that industrial procedures could be created to get either gas into a delivery system, what would be the cheapest one?

The first quantitative estimates of the cost for stratospheric geoengineering considered naval guns, hydrogen and hot air balloons, and airplanes for delivering aluminum oxide particles, reflective stratospheric balloons, or soot to the stratosphere,[12] but all options considered were quite expensive. More recent analyses showed that either existing military airplanes or specially designed ones, perhaps pilotless, could deliver 1 Tg S to the tropical lower stratosphere for a few billion US dollars per year.[13,14] While some with experience in scientific aviation question these estimates, it seems that cost would not be a limiting factor if the world was determined to do geoengineering. Towers or tethered balloons have also been suggested,[15] and tethered balloons would be cheaper than airplanes. Figure 1 illustrates some of the suggested options.

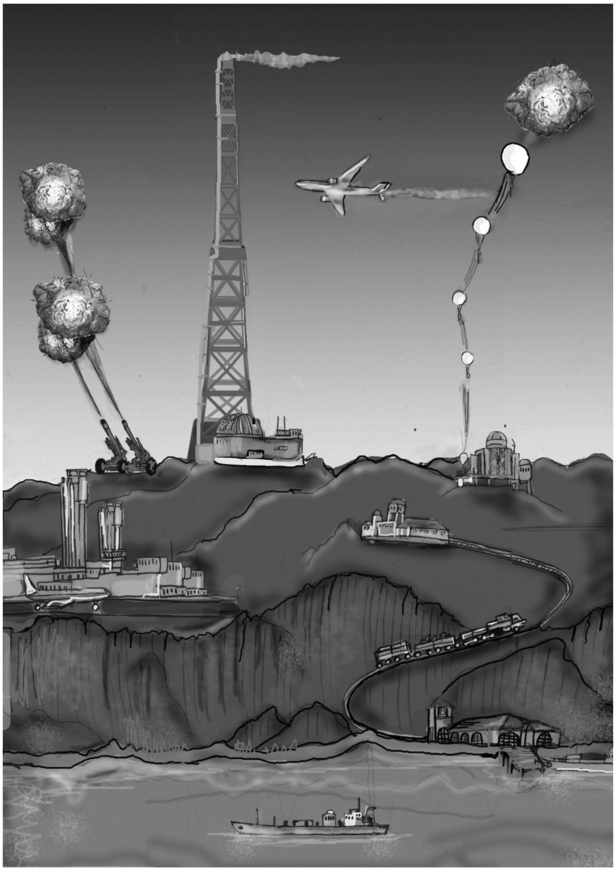

Figure 1 Proposed methods of stratospheric aerosol injection, including: airplanes, artillery, balloons and a tower. A mountain top location would require less energy for lofting to stratosphere.
(Drawing by Brian West, Figure 1 from ref. 13).

2.3 Creating an Effective Sulfuric Acid Cloud

An ideal particle would be effective at scattering sunlight, would not affect stratospheric chemistry, and would be safe when it fell out of the stratosphere.[10] As volcanic eruptions provide us with natural examples, sulfate particles are the most studied candidates. A one-time stratospheric injection of SO_2 from a volcanic eruption results in sulfate aerosols with an effective radius of about 0.5 μm, which would be very effective at back-scattering a portion of the incoming sunlight, cooling the surface. Climate model simulations of the impacts of geoengineering (see section 3) assume that the aerosol cloud that would be produced would have properties similar to these volcanic clouds, such as observed after the 1991 Pinatubo eruption. However, if SO_2 were continuously injected into the lower stratosphere, theory says that rather than producing more small particles, much of the SO_2 would be incorporated into existing particles, making them larger.[16] The result is that, per unit mass, the S would be much less effective at scattering sunlight and cooling the surface, and to achieve the same optical depth or reduction in incoming sunlight, as much as 10 times or more mass of S would be needed, if it were possible at all.

This self-limiting feature of stratospheric sulfate aerosols has prompted suggestions of injecting sulfuric acid directly rather than SO_2 to prevent the particle growth,[17,18] but only by widely spreading out the injection of either SO_2 or sulfuric acid would this growth be limited.[19] A system to inject S throughout broad latitude bands has not been developed, and it is not clear that even this would work once there was an existing sulfate cloud, so there is doubt about claims that this would be cheap and easy, since the technology to do stratospheric geoengineering does not currently exist.

The size of aerosol particles not only affects their lifetimes and effectiveness at reflecting sunlight, but it also affects their chemical interactions that destroy ozone. Ozone in the stratosphere absorbs UV radiation from the Sun, protecting life at the surface. Anthropogenic chlorine in the stratosphere, a result of chlorofluorocarbon use in the troposphere (which is now severely limited by the Montreal Protocol and subsequent treaties), is typically found as chlorine nitrate and hydrochloric acid. However, when polar stratospheric clouds form every spring over Antarctica, heterogeneous reactions on the surface of cloud droplets liberate chlorine gas from the reaction between chlorine nitrate and hydrochloric acid, and it catalytically destroys ozone, producing the annual Ozone Hole. Ozone depletion by the same mechanism occurs at the North Pole, but because stratospheric winds are more variable, the vortex does not get as cold, and ozone depletion is more episodic and not as large. As the chlorine concentration in the stratosphere gradually declines, the Ozone Hole is expected to stop forming in 2050 or 2060. The presence of an anthropogenic aerosol cloud as the result of geoengineering, however, would allow ozone depletion to go on even without polar stratospheric clouds. Calculations show that the Ozone Hole would persist for two or three decades more in the presence of geoengineering, and would even start forming in the Northern Hemisphere in cold winters.[20] This effect has been observed after large volcanic eruptions.[21]

3 Climate Impacts of Stratospheric Geoengineering

Although we can learn much from observations of the climatic response to large volcanic eruptions, they are rare and an imperfect analog: volcanic eruptions inject a large amount of SO_2 once; ash is sometimes associated with the sulfate; volcanic eruptions are rare and we have imperfect observations of past ones; and the injection is into a pristine stratosphere and not one with an existing cloud. Therefore some of the processes associated with the continuous creation of a sulfate cloud cannot be studied by observations of volcanic eruptions. The preferred tool for investigating the effects of geoengineering on climate is the climate model. If a climate model has been evaluated by simulations of past volcanic eruptions for which we do have observations and simulations of other causes of climate change, we gain confidence in its ability to simulate similar situations.

3.1 Climate Models

General circulation models (GCMs) of the atmosphere and ocean are the workhorse of the climate community for studying how the climate responds to a large number of natural and anthropogenic forcings (factors that change the amount of energy being received by the climate system). A typical GCM divides the atmosphere and ocean each up into a number of grid boxes and layers, with a typical horizontal spacing of 100 km in the atmosphere and 50 km in the ocean, with 25–90 layers in the atmosphere and 30–40 layers in the ocean. A GCM is started with a particular state of the atmosphere and ocean, and then moves forward in time calculating all the variables of the climate, including wind, ocean current, temperature, clouds, precipitation, sea ice, and amount of sunlight. Modern GCMs also include models of vegetation and the carbon cycle, with interactions on Earth's surface with soil moisture and plants.

GCMs are the same as computer models that are used every day to forecast the weather. However, because they are run for long periods of time, they also explicitly calculate changes in slow-varying components of the climate system, such as ocean currents and heat content, soil moisture, and sea ice, which are typically kept fixed for weather forecasts. Since the atmosphere is a chaotic system, preventing skillful weather forecasts beyond about two weeks, GCMs simulate possible weather states, but not the evolution of weather that did happen in the past or will happen in the future. For that reason, it is typical to use ensembles of GCM simulations, each started with a different arbitrary state of the weather, and to then calculate statistics of the ensemble to study how the climate will change. However, because the real world only evolves along one particular path, climate models are not expected to simulate the exact future state of the climate, only probability distributions and envelopes of climate states that the real world will be expected to inhabit.

3.2 Scenarios of Geoengineering

As with studies of global warming, specific scenarios of geoengineering implementation are needed to conduct studies of the climate impacts. Stratospheric geoengineering has been implemented in GCM studies mainly in two different ways. One is to simply reduce insolation (the solar radiation that reaches the Earth's surface), which is easily implemented in a climate model by reducing the solar constant, or reducing insolation in certain regions. Another scenario is to more realistically simulate the emission of SO_2 gas in the lower stratosphere, and allow models that include these processes to convert the SO_2 to sulfate aerosols, transport the aerosols through the climate system, interacting with sunlight and heat radiation from the Earth along the way, and then remove the aerosols from the system. When aerosols interact with radiation, they alter atmospheric circulation, which then can affect the lifetime and deposition fate of the sulfur.

The specific global warming scenario that stratospheric geoengineering is attempting to address will have a big impact on the resulting climate response. The specific goal of geoengineering will also affect the response. This touches on the larger scale question of, ''Whose hand will be on the planetary thermostat?'' That is, what is the goal of geoengineering? Is it to keep the global average temperature constant at the value at the time of geoengineering implementation? Is it to only allow warming up to the predetermined level of dangerous anthropogenic interference, say 2 K above pre-industrial temperatures? Is it to just slow global warming and compensate for only part of future warming? Or is it to cool the planet back to a level colder than current conditions, since the planet is already too warm, and sea ice melting, sea level rise, and the potential for Arctic methane releases are already dangerous at the current climate?

The impacts of geoengineering also depend on how GCM results are evaluated. Once the goal of geoengineering is decided, how are the resulting climate changes to be judged? As compared to the climate at the time of implementation? As compared to the climate that would have resulted at some time in the future if no geoengineering had been used? As compared to pre-industrial climate?

Early geoengineering GCM experiments each made different choices for each of these factors, and therefore it was not possible to compare the results to see if they were robust with respect to each other, as each was doing different experiments. For example, some tried to just cool the Arctic, and some the entire planet. Some tried to balance a doubling of CO_2 and others compensate for gradually increasing greenhouse gases. To address this issue, the Geoengineering Model Intercomparison Project (GeoMIP) was implemented.[22] GeoMIP developed four scenarios of stratospheric geoengineering, and asked all the GCM modeling groups in the world to conduct the same experiments and share their results so that others could analyze them and compare the effectiveness and risks of geoengineering with respect to a number of different metrics.

The GeoMIP scenarios are shown in Table 1 and Figure 2. These built on experiments already conducted by modeling groups to examine the climate system response to increases of CO_2.[23] G1 and G2 were the easiest to implement, involving adjusting the amount of incoming sunlight to balance the heating caused by an instantaneous quadrupling of CO_2 or a gradual increase of CO_2 of 1% year^{-1}. Twelve modeling groups from around the world participated in the first round of experiments. G3 and G4 were more ''realistic,'' involving a ''business-as-usual'' scenario of increasing greenhouse gases by modeling the injection of SO_2 into the tropical lower stratosphere to create a global sulfate cloud to either balance the anthropogenic heating or to immediately overwhelm that heating (say in the event of a planetary emergency) and injecting 5 Tg of SO_2 per year. G1 and G2 start from an artificial equilibrium climate, while G3 and G4 start from a more realistic warming climate. This means that for G3 and G4, preventing further radiative forcing would not be enough to stop the planet from warming, since there would be a built-in energy imbalance at the start.

Table 1 A summary of the four GeoMIP experiments. The different experimental designs are shown in Figure 2. RCP4.5 (representative concentration pathway resulting in 4.5 W m^{-2} radiative forcing) is a ''business-as-usual'' scenario used to force climate models in recent standardized experiments.[23] (Table 1 from ref. 22).

G1	Instantaneously quadruple the CO_2 concentration (as measured from pre-industrial levels) while simultaneously reducing the solar constant to counteract this forcing.
G2	In combination with a 1% increase in CO_2 concentration per year, gradually reduce the solar constant to balance the changing radiative forcing.
G3	In combination with RCP4.5 forcing, starting in 2020, gradual ramp-up the amount of SO_2 or sulfate aerosol injected, with the purpose of keeping global average temperature nearly constant. Injection will be done at one point on the Equator or uniformly globally. The actual amount of injection per year will need to be fine tuned to each model.
G4	In combination with RCP4.5 forcing, starting in 2020, daily injections of a constant amount of SO_2 at a rate of 5 Tg SO_2 year^{-1} at one point on the Equator through the lower stratosphere (approximately 16–25 km in altitude) or the particular model's equivalent. These injections would continue at the same rate through the lifetime of the simulation.

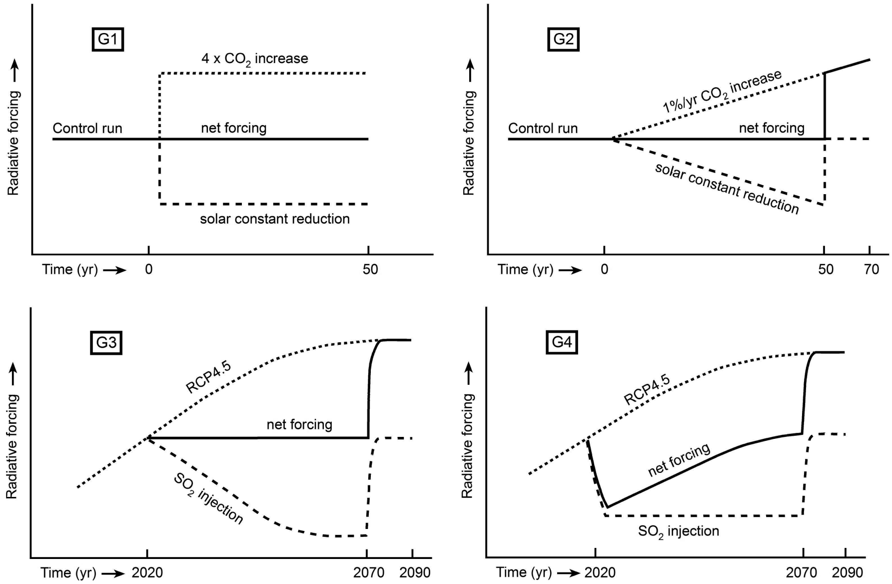

Figure 2 The four GeoMIP experiments, described in Table 1. G1: The experiment is started from a control run. The instantaneous quadrupling of CO_2 concentration from pre-industrial levels is balanced by a reduction in the solar constant until year 50. G2: The experiment is started from a control run. The positive radiative forcing of an increase in CO_2 concentration of 1% year^{-1} is balanced by a decrease in the solar constant until year 50. G3: The experiment approximately balances the positive radiative forcing from the RCP4.5 scenario by an injection of SO_2 or sulfate aerosols into the tropical lower stratosphere. G4: This experiment is based on the RCP4.5 scenario, where immediate negative radiative forcing is produced by an injection of SO_2 into the tropical lower stratosphere at a rate of 5 Tg year^{-1}. (Figures 1–4 from ref. 22).

3.3 Global and Regional Temperature Impacts

While a wide range of potential geoengineering implementations might be considered, the GeoMIP experiments allow the best opportunity to systematically study the climate system response. Since in general the climate system responds linearly to changes in the amount of energy being added or taken away, other scenarios of geoengineering can be scaled by the GeoMIP results for a first order understanding of the climate system response.

Figure 3 shows the global response in 11 different climate models for the G2 experiment.[24] A 1% year^{-1} CO_2 increase (approximately what we have observed in the past several decades) would produce a global warming of about 1 K in 50 years. With varying levels of success, climate models are able to completely stop this warming by reducing sunlight. However, when geoengineering is halted at year 50, the result is rapid global warming, at a rate as much as 10 times the rate we will experience with no geoengineering. It is often the rate of change of climate that is more disruptive than the

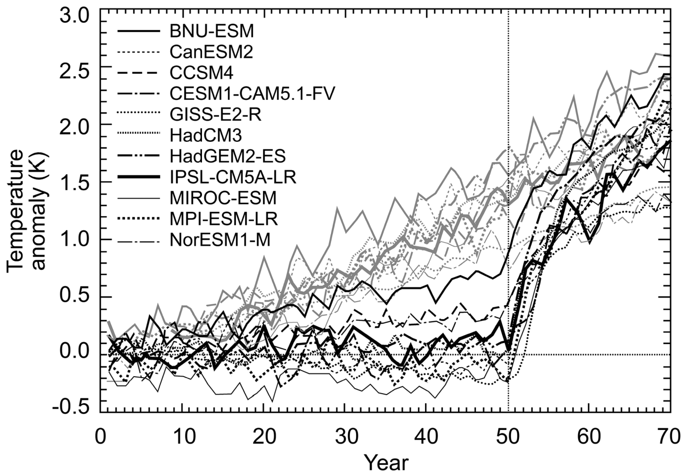

Figure 3 Evolution of annual mean anomaly of global mean near-surface air temperature (K) in the G2 simulations (black lines) with respect to the long-term mean from each model's control simulation. Time series from corresponding 1% CO_2 year^{-1} increase simulations are also shown (gray lines). The termination of geoengineering in the G2 simulations is indicated by the dashed vertical line.
(Figure 1 from ref. 24; see this reference for climate model abbreviations and details).

actual climate, as it is difficult in some cases to quickly adapt, say for infrastructure built under the assumption of no, or gradual, change. And if geoengineering were ever actually implemented, there would be no way to predict when society might lose the will or means to continue the geoengineering, producing this termination effect. While it would be logical to slowly ramp down geoengineering if there were a reason to stop it, it is easy to imagine a devastating drought or flood somewhere in the world that is blamed on geoengineers, with a demand that geoengineering be halted at once.

Even if it were possible to control the global temperature with a global reduction of sunlight, say from tropical sulfur injections, the G1 experiment teaches us that the temperature changes would not be uniform.[25] Figure 4 shows that if the warming from CO_2 were balanced by insolation reduction, keeping the global average temperature from changing, temperatures would fall in the Tropics and continue to go up in the Arctic. The regional details are not well known, however, as indicated by the stippling in the figure. The simple explanation for the variation with latitude is that while the warming from CO_2 is a little bit larger in the Tropics than the poles (because the downward heat radiation from the excess CO_2 is a function of temperature and it is warmer in the Tropics), the warming is still fairly well distributed around the world. However, there is much more sunlight to reflect in the Tropics than at the poles, and the change in energy by blocking sunlight is

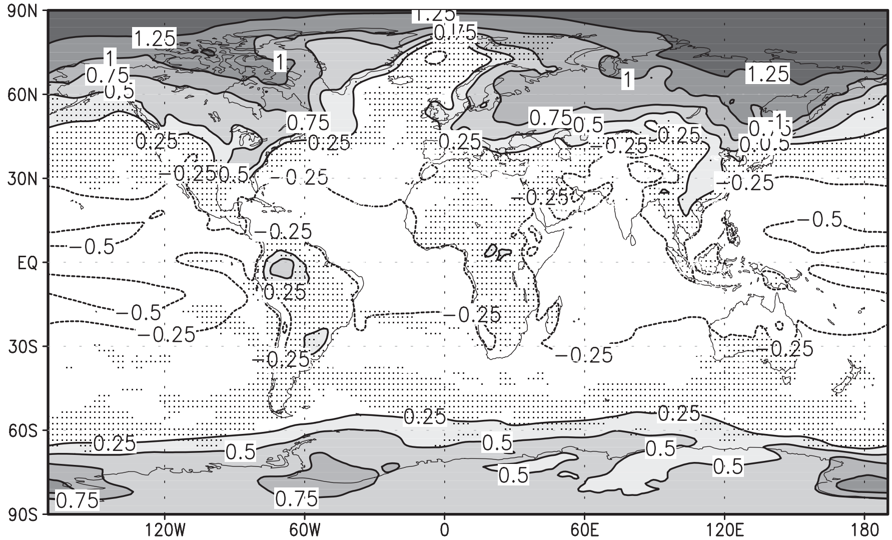

Figure 4 All-model ensemble annual average surface air temperature differences (K) for G1 minus the control run, averaged over years 11–50 of the simulation. Stippling indicates where fewer than 75% of the models (9 out of 12) agree on the sign of the difference.
(Figure 2 from ref. 25).

much more asymmetric. This means that if global geoengineering were to be used to try to stop sea level rise, there would have to be global cooling to not only keep the ice sheets at the poles (Greenland and Antarctica) from melting, but also to reverse the built-in sea level rise already happening from energy in the oceans from the warming that has already taken place in the recent past.[26]

3.4 Global and Regional Precipitation and Monsoon Impacts

Temperature is important, as warming directly affects sea level through melting land-based glaciers and ice sheets and expanding the ocean water; reduced seasonal snowpack threatens water supplies; and crops are sensitive to temperature changes. Precipitation changes from global warming are a more direct threat, however, to agriculture and water supplies. One of the aims of geoengineering might be to reverse changes in precipitation patterns being caused by global warming, particularly the expansion of areas of drought. However, volcanic eruptions are known to increase drought in certain monsoon regions.[27] In addition, global warming is producing more precipitation extremes, with the strongest thunderstorms and hurricanes getting stronger, producing more flooding. It turns out that temperature and precipitation changes cannot be controlled independently.

Figure 5 shows global average precipitation changes from the G2 experiment. At the same time that global average temperature is being kept

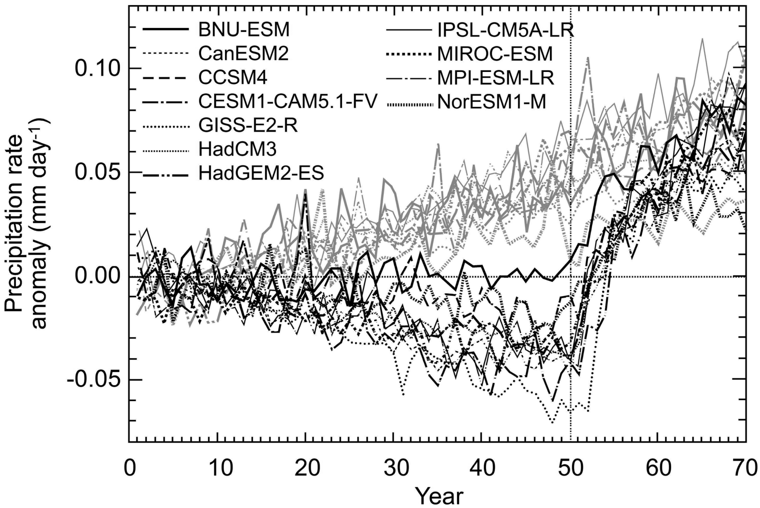

Figure 5 As in Figure 3 but for the anomaly in global mean precipitation rate (mm day^{-1}).
(Figure 2 from ref. 24; see this reference for climate model abbreviations and details).

constant by balancing increased CO_2 by insolation reduction (see Figure 3), global average precipitation would decrease. This result reproduces previous results and is well-understood.[28] Increases of greenhouse gases, particularly CO_2, absorb longwave heat radiation throughout the troposphere, decreasing the lapse rate of temperature and making the atmosphere more stable, reducing precipitation. At the same time they warm the surface, producing more evapotranspiration and making the hydrological cycle stronger, increasing precipitation. The evapotranspiration effect wins out over time, but there is a delay in the increase in precipitation in response to increases in CO_2, and this can be seen by comparing the gray lines in Figures 3 and 5. While the temperature effect is seen immediately, it takes 10–20 years for the precipitation increases to emerge from the initial values. Insolation reduction only affects the evaporation rate changes from CO_2, but does not affect the lapse rate part, so it only partially compensates for precipitation changes in a combined high CO_2, low sunlight environment, and global precipitation therefore goes down.

As impacts are felt locally, the spatial pattern of precipitation changes is important. The monsoon regions of the world (see Figure 6) are regions where the difference between summer average and winter average precipitation exceeds 180 mm and the local summer monsoon precipitation produces at least 35% of the total annual rainfall.[29] They are important for agriculture, particularly in Asia and Africa. In the G1 experiment,[30] summer land precipitation went up in six of the seven monsoon regions because of CO_2 increases in the base case, but in six of the seven regions, G1 caused a reduction of summer land precipitation. (see Figure 7).

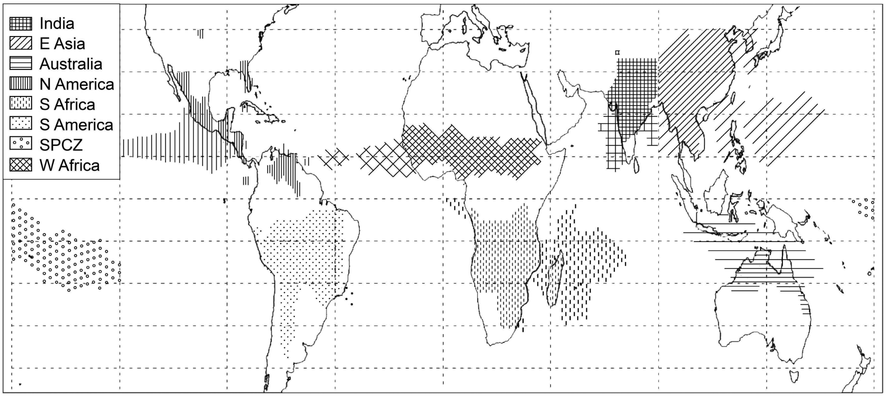

Figure 6 Monsoonal regions (shaded) over land (more dense shading) and ocean (less dense shading), derived from the *Global Precipitation Climatology Project (GPCP) dataset*,[58] covering the years 1979 to 2010, and using criteria described in ref. 29. The North and South American monsoon are defined here as the American monsoon north and south of the equator, respectively.
(Figure 6 from ref. 30).

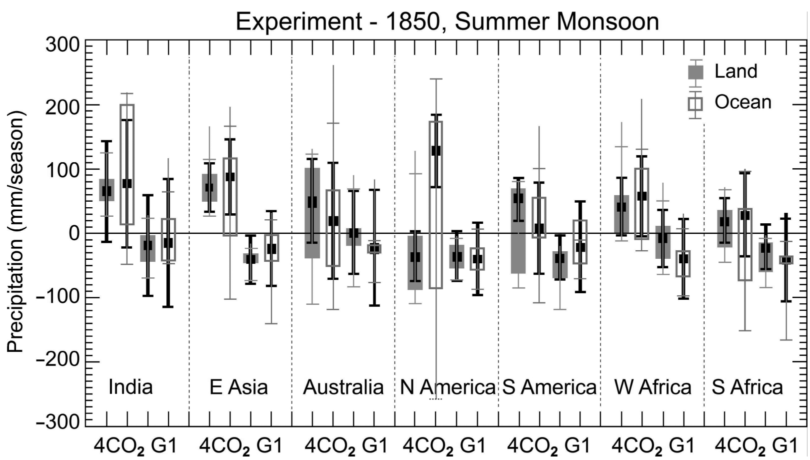

Figure 7 Summer monsoon change of precipitation for 4×CO_2 and G1 with regard to 1850 (control) conditions. Results are for land (grey – 1st and 3rd column for each region) and ocean (white – 2nd and 4th column for each region) and for different regions (see Figure 6). The multi-model range is illustrated by a vertical line, the 25th and 75th percentile of multi-model results are given as a box, and the 5th and 95th percentile are horizontal bars. In addition, the multi-model median is shown as solid symbols and the inter-annual variability of each experiment, represented by the median standard deviation of seasonal averages for each model, is show as error bars pointing off the median of the multi-model results. The two left whisker plots for each region are the 4×CO_2 statistics, and the two rightmost whiskers plots are for G1.
(Figure 14 from ref. 30).

Whether this reduction of summer monsoons would have a large impact on agriculture would depend on how evapotranspiration changed, how much CO_2 fertilization (increased photosynthesis and plant growth as CO_2 concentration rises) would compensate for the negative impacts of geoengineering,[31,32] and how humans would adapt to the changing climate. In G1, evapotranspiration reductions partially compensated for precipitation reductions over most of the land areas.[25,30] Net primary productivity (a measure of natural and managed biological productivity) changes from geoengineering are not well known, as there is a large variation in model responses depending on how the models considered the effects of CO_2 fertilization.[24,25] Much more work is needed on the biological response to stratospheric geoengineering, including modeling the effects on specific species from the range of changes that would result, before we can have a definitive answer.

3.5 Impacts of Enhanced Diffuse Radiation

Among the many potential risks associated with stratospheric geoengineering,[33] is the impact of more diffuse and less direct radiation on the surface of Earth. Much of the light impinging on a stratospheric aerosol cloud would be forward scattered, producing enhanced diffuse radiation, which means that the sky will appear whiter due to the perpetual thin cloud there.[34] In addition to no more blue skies, with its as yet unquantified psychological impact on everyone on Earth, this redistribution of direct radiation to diffuse would have impacts on solar generation of electricity and on the biosphere.

While photovoltaic solar panels are currently the most ubiquitous way that electricity is generated with sunlight, those that focus the direct solar beam with mirrors and boil water or other fluids to drive turbines are more efficient at using solar power. After large volcanic eruptions, observations at Mauna Loa, Hawaii, have shown a large decrease in this direct radiation, for example by 34% after the 1982 El Chichón eruption, which put about 7 Tg of SO_2 into the stratosphere.[7] After the 1991 Mt. Pinatubo eruption, during the summer of 1992 in California when the effects of the eruption were the strongest, solar generators using direct solar radiation produced 34% less electricity than during the period with a clean stratosphere.[35] While the correspondence of these numbers is fortuitous, they point out that one unintended consequence of geoengineering would be a reduction of electricity generation from one of the key sources needed to mitigate the emission of CO_2.

In general, plants grow more when subject to more diffuse light.[13] Stomata on leaves can stay open longer when the leaves are not as hot, as this reduces the loss of water when they are open to obtain CO_2 for photosynthesis. In addition, diffuse light can penetrate the canopy, also increasing photosynthesis. The result is that the CO_2 sink at the surface would increase with geoengineering. In fact, a reduction of the rate of CO_2 increase has been observed in the Mauna Loa CO_2 record for about a year after each of the large volcanic eruptions since the record was started: Agung in 1963, El Chichón in 1982, and Pinatubo in 1991. A calculation of net primary productivity after the Pinatubo eruption, accounting for the effects of changes of temperature and precipitation and isolating the diffuse radiation effect, found a 1 Pg C increase in the CO_2 sink in 1992 (ref. 36), more than 10% of the current annual anthropogenic carbon input to the atmosphere. While an increased carbon sink would be a benefit of stratospheric geoengineering, the effect would be felt differentially between different plant species, and whether it would help or hurt the natural ecosystem, or whether it would preferentially favor weeds rather than agricultural crops, has not been studied in detail yet.

4 Ethics and Governance of Stratospheric Geoengineering

The audacious idea of actually controlling Earth's climate brings up a number of ethical and governance issues. The fundamental question is that of where to set the planet's thermostat. Who would decide how to carry out geoengineering? What values would be used to decide? For whose benefit would this decision be made? For those controlling the geoengineering? For the entire planet, however defined? For the benefit of those most at risk? For only humans, or taking into account the rest of the natural biosphere? These decisions are in the realms of politics and power, and are different from testable scientific hypotheses, but scientific evaluations of the benefits, risks, and uncertainties of various proposals should, in an ideal world, inform decisions about implementation of geoengineering. The discussion in this section separates the issues of research and deployment, and speculates about international governance.

4.1 Ethics and Governance of Research

There have been many recent recommendations that geoengineering research be enhanced, including from the UK Royal Society,[5] the American Meteorological Society,[37] the American Geophysical Union,[38] the U. S. Government Accountability Office,[39] and prominent scientists.[40,41] But is such research ethical?[42] Does it lead to a slippery slope toward geoengineering deployment? Does it take resources away from other more useful pursuits? Is it yet another way for developed countries to continue to dominate the world to benefit themselves? Does the knowledge that this research is ongoing present a "moral hazard,"[43] and reduce whatever political drive there is toward mitigation, since it will be seen as an easier solution to global warming? Does indoor geoengineering research (in a laboratory or a computer, with no emissions to the environment) have different ethical issues from outdoor research (in which sulfur is emitted into the stratosphere to test potential technology and its impacts)? Are weapons being developed in the guise of understanding the science of geoengineering, which was a strong motivation for past research on weather and climate modification?[44] Or would it be unethical not to investigate a technology that may prevent widespread dangerous impacts on climate associated with global warming? Would it be unethical not to be able to provide policymakers in the near future with detailed information about the benefits and risks of various geoengineering proposals so that they can make informed decisions about implementation? Would it be unethical not to develop the technology to carry out geoengineering, both so that the costs and efficacy can be determined (maybe it will prove impossible or much too expensive or dangerous), and to have the designs available so that it could be rapidly implemented if needed?

Answers to these questions are summarized here, based on a longer article.[42] Additional concerns about geoengineering research include the fact that the existence of the technology might enable hasty, politically-driven decisions to be deployed. And as a recent report says,[45] ''SRM research could constitute a cheap fix to a problem created by developed countries, while further transferring environmental risk to the poorest countries and the most vulnerable people.'' The same report also discusses hubris, ''Artificial interference in the climate system may be seen as hubristic: 'playing God' or 'messing with nature,' which is considered to be ethically and morally unacceptable. While some argue that human beings have been interfering with the global climate on a large scale for centuries, SRM involves *deliberate* interference with natural systems on a planetary scale, rather than an inadvertent side effect. This could be an important ethical distinction.''[45]

If the research itself were dangerous, directly harming the environment, this would bring up ethical concerns. Is it ethical to create additional pollution just for the purpose of scientific experiments? There have been no such outdoor experiments in the stratosphere. To test whether there were a climate response or whether existing sulfuric acid cloud droplets would grow in response to additional emissions would require very large emissions, essentially implementation of geoengineering,[46] and would therefore be unethical. But what about flights to spray a little SO_2 or other S species and then observe how particles grow or the response of ozone? Although no such governance now exists, any such outdoor experiments need to be evaluated by an organization, like a United Nations commission, independent from the researchers, that evaluates an environmental impact statement from the researchers and determines that the environmental impact would be negligible, as is done now for emissions from the surface. There would also need to be enforcement of the limits of the original experiment, so that it would not be possible to emit a little more, or over a larger area or for a longer time than in the initial plans, should the experimenters be tempted to expand the experiment in light of inconclusive results.

To make decisions about ethics requires a declaration of values, unlike in the physical sciences, where nature follows well-accepted laws, such as conservation of energy. The above conclusions are based on the following principles: (1) curiosity-driven indoor research cannot and should not be regulated, if it is not dangerous; (2) emissions to the atmosphere, even for scientific purposes, should be prohibited if they are dangerous; and (3) the idea of geoengineering is not a secret, and whatever results from it will need to be governed the same way as all other dangerous human inventions, such as ozone depleting substances and nuclear weapons.

The conclusions are therefore, "in light of continuing global warming and dangerous impacts on humanity, indoor geoengineering research is ethical and is needed to provide information to policymakers and society so that we can make informed decisions in the future to deal with climate change. This research needs to be not just on the technical aspects, such as climate change and impacts on agriculture and water resources, but also on historical precedents, governance, and equity issues. Outdoor geoengineering research, however, is not ethical unless subject to governance that protects society from potential environmental dangers…Perhaps, in the future the benefits of geoengineering will outweigh the risks, considering the risks of doing nothing. Only with geoengineering research will we be able to make those judgments."[42]

4.2 *Ethics and Governance of Deployment*

Suppose that technology is developed to produce an effective stratospheric aerosol cloud using sulfur or more exotic materials, and that estimated annual direct costs are in the order of US $10 000 000 000. Considering that this is less than $\frac{1}{4}$ of the annual *profits* of one of the leading purveyors of products that emit greenhouse gases, ExxonMobil, it would be very tempting to implement – global warming problem solved! But what about the risks? Would the prevention of more severe weather, crop losses, and sea level rise be worth the negative impacts geoengineering would have in some regions? Would it be OK to allow continued ocean acidification, and its impact on ocean life? Could we be sure that there would be no sudden termination of geoengineering, with its associated rapid climate change?

How would the world make this decision?[47] How would it be possible to determine that we have reached a point where there is a planetary emergency? By what criteria, and an emergency for whom? Even if we could have an accurate idea of the losers of such a decision, how well would society compensate them for the disruption to their livelihoods and communities? The past record of such relief is not good – just think of what happens when "development" destroys old neighborhoods or people are moved when a dam is built. And given the natural variability of weather and climate, how would it even be possible to attribute negative events to the geoengineering? What if a country or region had either severe flooding or severe drought for a couple years in a row during the summer monsoon? Although it would not be possible to definitively point the finger at geoengineering, certainly such claims would be made, and there would be demands not only for compensation, but also for a halt to geoengineering.

In medical procedures, the principle of "informed consent" applies. How could society get informed consent from the entire planet? Would all governments of the world have to agree? What if they agree to control the climate, but some want the temperature to be a certain value and others a different one? Would this result in international conflict? Or what if a big multinational geoengineering corporation is running things? They would have an interest in continuing the work no matter what, and would argue that we cannot stop because it will kill jobs. The over-built militaries of the world, particularly in the United States, are a lesson in how dangerous technologies perpetuate themselves. Weapons continue to be built because of lobbying by special interests. Nuclear weapons are the most dangerous example.[48,49]

There have been a number of papers addressing the ethical and governance issues associated with geoengineering,[50–53] and they discuss the above issues and others. One such attempt to do this is the Oxford Principles.[54] They are "geoengineering to be regulated as a public good," "public participation in geoengineering decision-making," "disclosure of geoengineering research and open publication of results," "independent assessment of impacts," and "governance before deployment." While these are only a proposal with no enforcement, there is no evidence that legitimate geoengineering researchers are not attempting to follow them. One of the more interesting papers imagines various scenarios of future developments that result in different decisions about deployment, with different consequences.[55] Given the uncertainty that will remain even after more research is completed, the dangers of human mistakes either in the construction or operation of the technology, and the possibilities of surprises, will society stake the fate of our planet on geoengineering technology?

5 Benefits and Risks of Stratospheric Geoengineering

Stratospheric geoengineering has the potential to reduce some or all of the warming produced by anthropogenic greenhouse gas emissions, which would then lessen or eliminate the dangerous impacts of global warming, including floods, droughts, stronger rainfall events, stronger hurricanes, sea ice melting, land-based ice sheet melting, and sea level rise. But would these benefits reduce more risk from global warming than would be created by the implementation of geoengineering? That is, would implementation of geoengineering lower overall risk to Earth or add to the level of risk? And will research ever be able to answer this question definitively enough for rational policy decisions? Or will some of the less quantifiable risks, such as the threat of conflict due to disagreement on how to control the planet or unknown unknowns, prevent any agreement on governance?[47]

In addition to the risks and benefits discussed above, other risks and benefits have been suggested but have not been quantified.[33,56] These include: the conflict of geoengineering with the *United Nations Convention on the Prohibition of Military or any Other Hostile Use of Environmental Modification Techniques*; the potential of the sulfuric acid to damage airplanes flying in the stratosphere; an increase in sunburn, as people would be less likely to protect themselves from diffuse radiation; the effect of changing UV on tropospheric chemistry; and unexpected benefits that would accompany unexpected consequences. Table 2 summarizes the risks and benefits from stratospheric geoengineering.

Table 2 Benefits and risks of stratospheric geoengineering. The effects that are observed after volcanic eruptions are indicated by an asterisk (*).[56] (Updated from ref. 57).

Benefits	*Risks*
1. Reduce surface air temperatures*, which could reduce or reverse negative impacts of global warming, including floods, droughts, stronger storms, sea ice melting*, land-based ice sheet melting, and sea level rise*	1. Drought in Africa and Asia*
2. Increase plant productivity*	2. Perturb ecology with more diffuse radiation*
3. Increase terrestrial CO_2 sink*	3. Ozone depletion, with more UV at surface*
4. Beautiful red and yellow sunsets*	4. Whiter skies*
5. Unexpected benefits	5. Less solar energy generation*
	6. Degrade passive solar heating
	7. Environmental impact of implementation
	8. Rapid warming if stopped*
	9. Cannot stop effects quickly
	10. Human error
	11. Unexpected consequences
	12. Commercial control
	13. Military use of technology
	14. Conflicts with current treaties
	15. Whose hand on the thermostat?
	16. Degrade terrestrial optical astronomy*
	17. Affect stargazing*
	18. Affect satellite remote sensing*
	19. Societal disruption, conflict between countries
	20. Effects on airplanes flying in stratosphere*
	21. Effects on electrical properties of atmosphere
	22. More sunburn (from diffuse radiation)
	23. Continued ocean acidification
	24. Impacts on tropospheric chemistry
	25. Moral hazard – the prospect of it working would reduce drive for mitigation
	26. Moral authority – do we have the right to do this?

In the real world, decisions are made without full knowledge, and sometimes under pressure from extraordinary events. In my opinion, much more research in stratospheric geoengineering, transparently and published openly, is needed so that the potential benefits and risks that can be quantified will be known to aid in future policy decisions.

Even at this late date, a global push to rapid decarbonization, by imposing a carbon tax, will stimulate renewable energy, and allow solar, wind, and newly developed energy sources to allow civilization to prosper without using the atmosphere as a sewer for CO_2. Adaptation will reduce some of the negative impacts of global warming. Geoengineering does not now appear to be a panacea, and research in geoengineering should be in addition to strong efforts toward mitigation, and not a substitute. In fact, geoengineering may soon prove to be so unattractive that research results will strengthen the push toward mitigation.

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References

1. P. Crutzen, *Climatic Change*, 2006, **77**, 211.
2. T. M. L. Wigley, *Science*, 2006, **314**, 452.
3. M. I. Budyko, *Climate and Life,* Academic Press, New York, NY, 1974.
4. R. E. Dickinson, *Clim. Change*, 1996, **33**, 279.
5. J. Shepherd *et al.*, *Geoengineering the Climate: Science, Governance and Uncertainty,* Royal Society Policy document 10/09, Royal Society, London, UK, 2009.
6. T. M. Lenton and N. E. Vaughan, *Atmos. Chem. Phys.*, 2009, **9**, 5539.
7. A. Robock, *Rev. Geophys.*, 2000, **38**, 191.
8. B. Kravitz, A. Robock, L. Oman, G. Stenchikov and A. B. Marquardt, *J. Geophys. Res.*, 2009, **114**, D14109, doi: 10.1029/2009JD011918.
9. B. Kravitz, A. Robock, D. T. Shindell and M. A. Miller, *J. Geophys. Res.*, 2012, **117**, D09203, doi: 10.1029/2011JD017341.
10. F. D. Pope, P. Braesicke, R. G. Grainger, M. Kalberer, I. M. Watson, P. J. Davidson and R. A. Cox, *Nature Clim. Change*, 2012, **2**, 713, doi: 10.1038/nclimate1528.
11. H.-F. Graf, J. Feichter and B. Langmann, *J. Geophys. Res.*, 1997, **102**(D9), 10,727, doi: 10.1029/96JD03265.
12. Committee on Science Engineering and Public Policy, Appendix Q, in *Policy Implications of Greenhouse Warming: Mitigation, Adaptation, and the Science Base,* Natl. Acad. Press, Washington, DC, 1992, 433.
13. A. Robock, A. B. Marquardt, B. Kravitz and G. Stenchikov, *Geophys. Res. Lett.*, 2009, **36**, L19703, doi: 10.1029/2009GL039209.
14. J. McClellan, J. Sisco, B. Suarez and G. Keogh, *Geoengineering Cost Analysis,* Aurora Flight Sciences Corp, Cambridge, MA., 2010, AR10-182.
15. P. Davidson, C. Burgoyne, H. Hunt and M. Causier, *Phil. Trans. R. Soc. London, Ser. A*, 2012, **370**, 4263, doi: 10.1098/rsta.2011.0639.
16. P. Heckendorn, D. Weisenstein, S. Fueglistaler, B. P. Luo, E. Rozanov, M. Schraner, L. W. Thomason and T. Peter, *Environ. Res. Lett.*, 2009, **4**, 045108, doi: 10.1088/1748-9326/4/4/045108.

17. J. P. Pinto, R. P. Turco and O. B. Toon, *J. Geophys. Res.*, 1989, **94**(D8), 11,165, doi: 10.1029/JD094iD08p11165.
18. J. R. Pierce, D. K. Weisenstein, P. Heckendorn, T. Peter and D. W. Keith, *Geophys. Res. Lett.*, 2010, **37**, L18805, doi: 10.1029/2010GL043975.
19. J. M. English, O. B. Toon and M. J. Mills, *Atmos. Chem. Phys.*, 2012, **12**, 4775, doi: 10.5194/acp-12-4775-2012.
20. S. Tilmes, R. Müller and R. Salawitch, *Science*, 2008, **320**, 1201 doi: 10.1126/science.1153966.
21. S. Solomon, *Rev. Geophys.*, 1999, **37**, 275.
22. B. Kravitz, A. Robock, O. Boucher, H. Schmidt, K. Taylor, G. Stenchikov and M. Schulz, *Atmos. Sci. Lett.*, 2011, **12**, 162, doi: 10.1002/asl.316.
23. K. E. Taylor, R. J. Stouffer and G. A. Meehl, *Bull. Am. Meterol. Soc.*, 2012, **93**, 485, doi: 10.1175/BAMS-D-11-00094.1.
24. A. Jones, J. M. Haywood, K. Alterskjær, O. Boucher, J. N. S. Cole, C. L. Curry, P. J. Irvine, D. Ji, B. Kravitz, J. E. Kristjánsson, J. C. Moore, U. Niemeier, A. Robock, H. Schmidt, B. Singh, S. Tilmes, S. Watanabe and J.-H. Yoon, *J. Geophys. Res. Atmos.*, 2013, **118**, 9743, doi: 10.1002/jgrd.50762.
25. B. Kravitz, K. Caldeira, O. Boucher, A. Robock, P. J. Rasch, K. Alterskjær, D. Bou Karam, J. N. S. Cole, C. L. Curry, J. M. Haywood, P. J. Irvine, D. Ji, A. Jones, J. E. Kristjánsson, D. J. Lunt, J. Moore, U. Niemeier, H. Schmidt, M. Schulz, B. Singh, S. Tilmes, S. Watanabe, S. Yang and J.-H. Yoon, *J. Geophys. Res. Atmos.*, 2013, **118**, 8320, doi: 10.1002/jgrd.50646.
26. J. Moore, S. Jevrejeva and A. Grinsted, *Proc. Nat. Acad. Sci. U. S. A.*, 2010, **107**(36), 15699, doi: 10.1073/pnas.1008153107.
27. J. M. Haywood, A. Jones, N. Bellouin and D. Stephenson, *Nature Clim. Change*, 2013, **3**, 660, doi: 10.1038/nclimate1857.
28. G. Bala, P. B. Duffy and K. E. Taylor, *Proc. Nat. Acad. Sci. U. S. A.*, 2008, **105**, 7664, doi: 10.1073/pnas.0711648105.
29. B. Wang and Q. Ding, *Geophys. Res. Lett.*, 2006, **33**(6), L06711, doi: 10.1029/2005GL025347.
30. S. Tilmes, J. Fasullo, J.-F. Lamarque, D. R. Marsh, M. Mills, K. Alterskjær, H. Muri, J. E. Kristjánsson, O. Boucher, M. Schulz, J. N. S. Cole, C. L. Curry, A. Jones, J. Haywood, P. J. Irvine, D. Ji, J. C. Moore, D. B. Karam, B. Kravitz, P. J. Rasch, B. Singh, J.-H. Yoon, U. Niemeier, H. Schmidt, A. Robock, S. Yang and S. Watanabe, *J. Geophys. Res. Atmos.*, 2013, **118**, 11,036, doi: 10.1002/jgrd.50868.
31. J. Pongratz, D. B. Lobell, L. Cao and K. Caldeira, *Nature Clim. Change*, 2012, **2**(2), 101, doi: 10.1038/nclimate1373.
32. L. Xia, A. Robock, J. N. S. Cole, D. Ji, J. C. Moore, A. Jones, B. Kravitz, H. Muri, U. Niemeier, B. Singh, S. Tilmes and S. Watanabe, *J. Geophys. Res. Atmos*., submitted.
33. A. Robock, *Bull. Atomic Sci.*, 2008, **64**(2), 14, doi: 10.2968/064002006.
34. B. Kravitz, D. G. MacMartin and K. Caldeira, *Geophys. Res. Lett.*, 2012, **39**, L11801, doi: 10.1029/2012GL051652.

35. D. M. Murphy, *Environ. Sci. Technol.*, 2009, **43**(8), 2784, doi: 10.1021/es802206b.
36. L. M. Mercado, N. Bellouin, S. Sitch, O. Boucher, C. Huntingford, M. Wild and P. M. Cox, *Nature*, 2009, **458**, 1014, doi: 10.1038/nature07949.
37. American Meteorological Society, *Geoengineering the Climate System*, AMS Policy Statement, American Meteorological Society, Boston, MA, 2013; www.ametsoc.org/policy/2013geoengineeringclimate_amsstatement.pdf (accessed 15th January 2014).
38. American Geophysical Union, *Geoengineering the Climate System*, AGU Position Statement, American Geophysical Union, Washington, DC, 2009; www.agu.org/sci_pol/positions/geoengineering.shtml (accessed 15th January 2014).
39. Government Accountability Office, *Climate Engineering: Technical Status, Future Directions, and Potential Responses*, Government Accountability Office, Washington, DC, Report GAO-11-71, p. 135; www.gao.gov/new.items/d1171.pdf (accessed 15th January 2014).
40. D. W. Keith, E. Parson and M. G. Morgan, *Nature*, 2010, **463**, 426, doi: 10.1038/463426a.
41. G. Betz, *Clim. Change*, 2012, **111**, 473, doi: 10.1007/s10584-011-0207-5.
42. A. Robock, *Peace Security*, 2012, **4**, 226.
43. A. Lin, *Ecol. Law Q.*, in press.
44. J. R. Fleming, *Fixing the Sky: The Checkered History of Weather and Climate Control,* Columbia University Press, New York, 2010.
45. Solar Radiation Management Governance Initiative, *Solar Radiation Management: The Governance of Rsearch,* Royal Society, London, UK, 2011.
46. A. Robock, M. Bunzl, B. Kravitz and G. Stenchikov, *Science*, 2010, **327**, 530, doi: 10.1126/science.1186237.
47. A. Robock, *Ethics, Policy Environ.*, **15**, 202.
48. A. Robock and O. B. Toon, *Sci. Am.*, 2010, **302**, 74.
49. A. Robock and O. B. Toon, *Bull. Atomic Sci.*, 2012, **68**(5), 66, doi: 10.1177/0096340212459127.
50. S. M. Gardiner, in *Climate Ethics: Essential Readings*, ed. S. M. Gardiner, S. Caney, D. Jamieson and H. Shue, Oxford University Press, New York, NY, USA, 2010, p. 284.
51. T. Svoboda, K. Keller, M. Goes and N. Tuana, *Public Affairs Q.*, 2011, **25**(3), 157.
52. C. J. Preston, *Engineering the Climate: The Ethics of Solar Radiation Management,* Lexington Books, 2012.
53. Special issue on Geoengineering Research and its Limitations, ed. R. Wood, S. Gardiner and L. Hartzell-Nichols, *Clim. Change, 2013.*
54. S. Rayner, C. Heyward, T. Kruger, N. Pidgeon, C. Redgwell and J. Savulescu, *Clim. Change*, 2013, **121**, 499, doi: 10.1007/s10584-012-0675-2.
55. B. Banerjee, G. Collins, S. Low and J. J. Blackstock, *Scenario Planning for Solar Radiation Management,* Yale Climate and Energy Institute, New Haven, CT, USA, 2013.

56. A. Robock, D. G. MacMartin, R. Duren and M. W. Christensen, *Clim. Change*, 2013, **121**, 445, doi: 10.1007/s10584-013-0777-5.
57. A. Robock, *Clim. Change*, 2011, **105**, 383, doi: 10.1007/s10584-010-0017-1.
58. R. F. Adler, G. J. Huffman, A. Chang, R. Ferraro, P. Xie, J. Janowiak, B. Rudolf, U. Schneider, S. Curtis, D. Bolvin, A. Gruber, J. Susskind, P. Arkin and E. Nelkin, *J. Hydrometrol.*, 2003, **4**, 1147.