THE BENEFITS, RISKS, AND COSTS OF STRATOSPHERIC GEOENGINEERING

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Submitted for publication in *Geophysical Research Letters*

May, 2009

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Abstract

Injecting sulfate aerosol precursors into the stratosphere has been suggested as a means of geoengineering to cool the planet and reduce global warming. The decision to implement such a scheme would require a comparison of its benefits, dangers, and costs to those of other responses to global warming, including doing nothing. Here we evaluate those factors for stratospheric geoengineering with sulfate aerosols. Using existing U.S. military fighter and tanker planes, the annual costs of injecting aerosol precursors into the lower stratosphere would be several billion dollars. Using artillery or balloons to loft the gas would be much more expensive. We do not have enough information to evaluate more exotic techniques, such as pumping the gas up through a hose attached to a tower or balloon system. Anthropogenic stratospheric aerosol injection would cool the planet, stop the melting of sea ice and land-based glaciers, slow sea level rise, and increase the terrestrial carbon sink, but produce regional drought, ozone depletion, less sunlight for solar power, and make skies less blue. Furthermore it would hamper Earth-based optical astronomy, do nothing to stop ocean acidification, and present many ethical and moral issues. Further work is needed to quantify many of these factors to allow informed decision-making.

1. Introduction

Global warming will continue for decades due to anthropogenic emissions of greenhouse gases and aerosols [*IPCC*, 2007a], with many negative consequences for society [*IPCC*, 2007b]. Although currently impossible, as there are no means of injecting aerosols or their precursors into the stratosphere, the possibility of geoengineering the climate is now being discussed in addition to the conventional potential responses of mitigation (reducing emissions) and adaptation [*IPCC*, 2007c]. While originally suggested by *Budyko* [1974, 1977], *Dickinson* [1996], and many others (see *Robock et al.* [2008] for a comprehensive list), *Crutzen* [2006] and *Wigley* [2006] rekindled interest in stratospheric geoengineering using sulfate aerosols. This proposal for “solar radiation management,” to reduce insolation with an anthropogenic stratospheric aerosol cloud in the same manner as episodic explosive volcanic eruptions, will be called “geoengineering” here, recognizing that others have a more inclusive definition of geoengineering that can include tropospheric cloud modification, carbon capture and sequestration, and other proposed techniques.

The decision to implement geoengineering will require a comparison of its benefits, dangers, and costs to those of other responses to global warming. Here we present a brief review of these factors for geoengineering. It should be noted that in the three years since *Crutzen* [2006] and *Wigley* [2006] suggested that, in light of no progress toward mitigation, geoengineering may be necessary to reduce the most severe impacts of global warming, there has still been no global progress on mitigation. In fact, Mauna Loa data show that the rate of CO_2 increase in the atmosphere is actually rising. However, the change of U.S. administration in 2009 has completely changed the U.S. policy on global warming. In the past eight years, the U.S. has stood in the way of international progress on this issue, but now President Obama is planning to lead a global effort toward a mitigation agreement in Copenhagen in December 2009. If geoengineering is seen as a potential low-cost and easy "solution" to the problem, the public backing toward a mitigation agreement, which will require some short-term dislocations, may be eroded. This paper, therefore, is intended to serve as useful information for that process.

Robock [2008a] presented 20 reasons why geoengineering may be a bad idea. Those reasons are updated here. However, there would also be benefits of geoengineering, against which the risks must be weighed. So first we discuss those benefits, then the risks, and finally the costs. As the closest natural analog, examples from the effects of volcanic eruptions are used to illustrate the benefits and costs.

2. Benefits

The benefits of stratospheric geoengineering are listed in Table 1. Both observations of the response of climate to large explosive volcanic eruptions [*Robock*, 2000] and all modeling studies conducted so far [e.g., *Teller et al.*, 1997, 2000, 2002; *Govindasamy and Caldeira*, 2000; *Govindasamy et al.*, 2002, 2003; *Wigley*, 2006; *Rasch et al.*, 2007, 2008; *Robock et al.*, 2008; *Lenton and Vaughan*, 2009] show that with sufficient stratospheric sulfate aerosol loading, backscattered insolation will cool Earth. The amount of cooling depends on the amount of aerosols and how long the aerosol cloud is maintained in the stratosphere. Many negative impacts of global warming are strongly correlated with global average surface air temperature, so it would in theory be possible to stop the rise of global-average temperature or even lower it, thus ameliorating these impacts. For example, reduced temperature would slow or reverse the current downward trend in Arctic sea ice, the melting of land glaciers, including Greenland, and the rise of sea level.

Observations after large volcanic eruptions show that stratospheric sulfate aerosols drastically change the partitioning of downward solar flux into direct and diffuse [*Robock*, 2000]. After the 1982 El Chichón eruption, observations at the Mauna Loa Observatory in Hawaii on mornings with clear skies, at a solar zenith angle of 60° equivalent to two relative air masses, showed a peak change of downward direct insolation, from 515 W m^{-2} to 340 W m^{-2}, while diffuse radiation increased from 40 W m^{-2} to 180 W m^{-2} [*Robock*, 2000]. A similar effect was observed after the 1991 Mt. Pinatubo eruption. While the change of net radiation after El Chichón was a reduction of 35 W m^{-2}, this shift to an increase of the diffuse portion actually produced an increase of the growth of terrestrial vegetation, and an increase in the terrestrial CO_2 sink. *Gu et al.* [1999, 2002, 2003], *Roderick et al.* [2001], and *Farquhar and Roderick* [2003] suggested that increased diffuse radiation allows plant canopies to photosynthesize more efficiently, increasing the CO_2 sink. *Gu et al.* [2003] actually measured this effect in trees following the 1991 Pinatubo eruption. While some of the global increase in CO_2 sinks following volcanic eruptions may have been due to the direct temperature effects of the eruptions, *Mercado et al.* [2009] showed that the diffuse radiation effect produced an increase sink of about 1 Pg C a^{-1} for about one year following the Pinatubo eruption. The effect of a permanent geoengineering aerosol cloud would depend on the optical depth of the cloud, and these observed effects of episodic eruptions may not produce a permanent vegetative response as the vegetation adjusts to this changed insolation. Nevertheless, this example shows that stratospheric geoengineering may provide a substantial increased CO_2 sink to counter anthropogenic emissions. This increase in plant productivity could also have a positive effect on agriculture.

3. Risks

The potential benefits of stratospheric geoengineering must be evaluated in light of a large number of potential negative effects [*Robock*, 2008a]. While most of those concerns are still valid, three of them can now be removed. As discussed above, the effects of the change in diffuse and direct radiation on plants would in general be positive. *Kravitz et al.* [2009] have shown that the excess sulfate acid deposition would not be enough to disrupt ecosystems. And below we show that there are potentially airplane-based injection systems that would not be overly costly as compared to the cost of mitigation. But there still remains a long list of negative effects (Table 1).

Two of the reasons in the list have been strengthened by recent work. *Tilmes et al.* [2008] used a climate model to show that indeed stratospheric geoengineering would produce substantial ozone depletion, prolonging the end of the Antarctic ozone hole by several decades and producing ozone holes in the Arctic in springs with a cold lower stratosphere. *Murphy* [2009] used observations of direct solar energy generation in California after the 1991 Pinatubo eruption and showed that generation went from 90% of peak capacity in non-volcanic conditions to 70% in summer 1991 and to less than 60% in summer 1992.

One additional problem with stratospheric geoengineering has also become evident. There would be a major impact on terrestrial optical astronomy. Astronomers spend billions of dollars to build mountain-top observatories to get above pollution in the lower troposphere. Geoengineering would put permanent pollution above these telescopes.

4. Costs

Robock [2008a] suggested that the construction and operation of system to inject aerosol precursors into the stratosphere might be very expensive. Here we analyze the costs of three suggested methods of placing the aerosol precursors into the stratosphere: airplanes, artillery shells, and stratospheric balloons (Figure 1, Table 2). Because such systems do not currently exist, the estimates presented here are rough but provide quantitative starting points for further discussions of the practicality of geoengineering. Even if sulfate aerosol precursors could be injected into the stratosphere, it is not clear that aerosols could be created of a size range with an effective radius of about 0.5 μm, like volcanic aerosols, that would be effective at cooling the planet. Some of these issues were discussed by *Rasch et al.* [2008]. Can injectors be designed to give appropriate initial aerosol sizes? If injected into an existing sulfate cloud, would the existing aerosols just grow at the expense of smaller ones? These important topics are currently being investigated by us, and here we limit the discussion to just getting the precursor gases into the stratosphere.

Figure 1 is drawn with the injection systems on a mountain and with the supplies arriving up the mountain by train. If the injection systems were placed on a mountain top, the time and energy needed to get the material from the surface to the stratosphere would be less than from sea level. Gunnbjorn Mountain, Greenland, is the highest point in the Arctic, reaching an altitude of 3700 m. In the tropics, there are multiple high altitude locations in the Andes.

The 1991 Mt. Pinatubo eruption injected 20 Tg SO_2 into the tropical lower stratosphere [*Bluth et al.*, 1992], which formed sulfate aerosols and cooled the climate for about two years. As discussed by *Robock et al.* [2008], the equivalent of one Pinatubo every 4-8 years would be required to stop global warming or even reduce global temperature in spite of continued greenhouse gas emissions.

While volcanic eruptions inject mostly SO_2 into the stratosphere, the relevant quantity is the amount of sulfur. If H_2S were injected instead, it would oxidize quickly to form SO_2, which would then react with water to form H_2SO_4 droplets. Because of the relative molecular weights, only 2.66 Tg of H_2S (molecular weight 34 g mol^{-1}) would be required to produce the same amount of sulfate aerosols as 5 Tg of SO_2 (molecular weight 64 g mol^{-1}). Since there are choices for the desired sulfate aerosol precursor, our calculations will be in terms of stratospheric injection of any gas. H_2S, however, is more corrosive than SO_2 [e.g., *Kleber et al.*, 2008] and is very dangerous, so it would probably not be the gas of choice. Exposure to 50 ppm of H_2S can be fatal [*Kilburn and Warshaw*, 1995]. H_2S was even used for a time as a chemical warfare agent in World War I [*Croddy et al.*, 2001]. However, 100 ppm of SO_2 is also considered "immediately dangerous to life and health" [*ATSDR*, 1998].

If the decision were ever made to implement geoengineering, the amount of gas to loft, the timing and location of injections, and how to produce aerosols, would have to be considered, and these are issues we address in other work [*Rasch et al.*, 2008]. Here we just examine the question of the cost of lofting 1 Tg of a sulfur gas per year into the stratosphere. Other more speculative geoengineering suggestions, such as engineered aerosols [e.g., *Teller et al.*, 1997], are not considered here.

Our work is an update and expansion of the first quantitative estimates by *COSEPUP* [1992]. While they listed "Stratospheric Bubbles; Place billions of aluminized, hydrogen-filled balloons in the stratosphere to provide a reflective screen; Low Stratospheric Dust; Use aircraft to maintain a cloud of dust in the low stratosphere to reflect sunlight; Low Stratospheric Soot; Decrease efficiency of burning in engines of aircraft flying in the low stratosphere to maintain a thin cloud of soot to intercept sunlight" among the possibilities for geoengineering, they did not evaluate the costs of aircraft or stratospheric bubble systems.

Rather than cooling the entire planet, it has been suggested that we only try to modify the Arctic to prevent a sea ice-free Arctic summer and to preserve the ice sheets in Greenland while mitigation is implemented [*Lane et al.*, 2007; *Caldeira and Wood*, 2008]. The disadvantage of Arctic injection is that the aerosols would only last a few months rather than a couple years for tropical injection [*Robock et al.*, 2008]. An advantage is that they would only need to be injected in spring, so their strongest effects would occur over the summer. They would have no effect in the dark winter. One important difference between tropical and Arctic injections is the height of the tropopause, which is about 16 km in the tropics but only about 8 km in the Arctic. These different heights affect the capability of different injection schemes to reach the lower stratosphere, and we consider both cases here.

In addition to these costs would be the cost of the production and transport to the deployment point of the sulfur gas. *COSEPUP* [1992] estimated the price of SO_2 to be $50,000,000 per Tg in 1992 dollars, and H_2S would be much cheaper, as it is currently removed from oil as a pollutant, so the price of the gases themselves would be a minor part of the total. The current bulk price for liquid SO_2 is $230/ton or $230,000,000 per Tg [*Chemical Profiles*, 2009].

4.1. Airplanes

Existing small jet fighter planes, like the F-15C Eagle (Figure 2a), are capable of flying into the lower stratosphere in the tropics, while in the Arctic, larger planes, such as the KC-135 Stratotanker or KC-10 Extender (Figure 2b), are capable of reaching the required altitude. Specialized research aircraft such as the American Lockheed ER-2 and the Russian M55 Geophysica, both based on Cold War spy planes, can also reach 20 km, but neither has a very large payload or could be operated continuously to deliver gases to the stratosphere. The

Northrop Grumman RQ-4 Global Hawk can reach 20 km without a pilot but costs twice as much as an F-15C. Current designs have a payload of 1-1.5 tons. Clearly it is possible to design an autonomous specialized aircraft to loft sulfuric acid precursors into the lower stratosphere, but the current analysis focuses on existing aircraft.

Options for dispersing gases from planes include the addition of sulfur to the fuel, which would release the aerosol through the exhaust system of the plane, or the attachment of a nozzle to release the sulfur from its own tank within the plane, which would be the better option. Putting sulfur in the fuel would have the problem that if the sulfur concentration were too high in the fuel, it would be corrosive and affect combustion. Also, it would be necessary to have separate fuel tanks for use in the stratosphere and in the troposphere to avoid sulfate aerosol pollution in the troposphere.

The military has already manufactured more planes than would be required for this geoengineering scenario, potentially reducing the costs of this method. Since climate change is an important national security issue [*Schwartz and Randall*, 2003], the military could be directed to carry out this mission with existing aircraft at minimal additional cost. Furthermore, the KC-135 fleet will be retired in the next few decades as a new generation of aerial tankers replaces it, even if the military continues to need the in-flight refueling capability for other missions.

Unlike the small jet fighter planes, the KC-135 and KC-10 are used to refuel planes mid-flight and already have a nozzle installed. In the tropics, one option might be for the tanker to fly to the upper troposphere, and then fighter planes would ferry the sulfur gas up into the stratosphere (Figure 2b). It may also be possible to have a tanker tow a glider with a hose to loft the exit nozzle into the stratosphere.

In addition to the issues of how to emit the gas as a function of space and time to produce the desired aerosols, another concern is the maximum concentration of sulfate aerosols through which airplanes can safely fly. In the past, noticeable damage has occurred to airplanes that fly through plumes of volcanic ash containing SO_2. In June, 1982, after the eruption of Galunggung volcano in Java, Indonesia, two passenger planes flew through a volcanic cloud. In one case the windows were pitted, volcanic ash entered the engines and thrust was lost in all four engines. In the other case, the same thing happened, with the plane descending 7.5 km before the engines could be restarted [*Smithsonian Institution*, 1982]. While the concentration of sulfate in the stratosphere would be less than in a plume like this, and there would be no ash, there could still be sulfuric acid damage to airplanes. In the year after the 1991 Pinatubo eruption, airplanes reported acid damage to windows and other parts. An engineering study would be needed to ascertain whether regular flight into a stratospheric acid cloud would be safe, and how much harm it would do to airplanes.

The calculations for airplanes are summarized in Table 2. We assume that the sulfur gas will be carried in the cargo space of the airplane, completely separate from the fuel tank. The cost of each plane comes from *Air Combat Command* [2008] for the F-15C ($29.9 million), *Air Mobility Command* [2008a] for the KC-10 ($88.4 million), and *Air Mobility Command* [2008b] for the KC-135 ($39.6 million), in 1998 dollars, and in the Table is then converted to 2008 dollars (latest data available) by multiplying by a factor of 1.32 using the Consumer Price Index [*Williamson*, 2008]. If existing aircraft were converted to geoengineering use, the cost would be much less and would only be for retrofitting of the airplanes to carry a sulfur gas and installation of the proper nozzles. The annual cost per aircraft for personnel, fuel, maintenance, modifications, and spare parts for the older E model of the KC-135 is $4.6 million, while it is about \$3.7 million for the newer R model, based on an average of 300 flying hours per year [*Curtin*, 2003].

We postulate a schedule of three flights per day, 250 days per year, for each plane. If each flight were 2 hours, this would be 1500 hours per year. As a rough estimate, we take \$5 million per 300 hours times 5, or \$25 million per year in operational costs per airplane. If we use the same estimates for the KC-10 and the F-15C, we can get an upper bound on the annual costs for using these airplanes for geoengineering, as we would expect the KC-10 to be cheaper, as it is newer than the KC-135, and the F-15C to be cheaper, just because it is smaller and would require less fuel and fewer pilots.

4.2. Artillery Shells

COSEPUP [1992] made calculations using 16-inch (41-cm) naval rifles, assuming that aluminum oxide (Al_2O_3) dust would be injected into the stratosphere. They envisaged 40 10-barrel stations operating 250 days per year with each gun barrel replaced every 1500 shots. To place 5 Tg of material into the stratosphere, they estimated the annual costs, including ammunition, gun barrels, stations, and personnel, as \$100 billion (1992 dollars), with the cost of the Al_2O_3 only \$2.5 million of the total. So the cost for 1 Tg would be \$30 billion (2008 dollars). It is amusing that they conclude, with a total lack of irony, “The rifles could be deployed at sea or in empty areas (e.g., military reservations) where the noise of the shots and the fallback of expended shells could be managed.”

4.3. Stratospheric Balloons

Requiring no fuel, weather balloons are launched on a daily basis to high levels of the atmosphere. Balloons can made out of either rubber or plastic, but plastic would be needed due to the cold temperatures at the tropical tropopause or in the Arctic stratosphere, as rubber balloons would break prematurely. Weather balloons are typically filled with helium, but hydrogen (H_2) is less expensive and more buoyant than helium and can also be used safely to inflate balloons.

Balloons could be used in several ways for geoengineering. As suggested by L. Wood (personal communication, 2008), a tethered balloon could float in the stratosphere, suspending a hose to pump gas upwards. Such a system has never been demonstrated and should probably be included in the next section of this paper on exotic future ideas. Another idea is to use aluminized long-duration balloons floating as reflectors [*Teller et al.*, 1997], but again, such a system depends on future technology development. Here we discuss two options based on current technology: lofting a payload under a balloon or mixing H_2 and H_2S inside a balloon. In the first case, the additional mass of the balloon and its gas would be a weight penalty, but in the second case, when the balloons burst, the H_2S would be released into the stratosphere.

COSEPUP [1992] discussed a system to loft a payload under large H_2 balloons, smaller multi-balloon systems, and hot air balloons. To inject 1 Tg of H_2S into the stratosphere with H_2 balloons, the cost including balloons, dust, dust dispenser equipment, hydrogen, stations, and personnel, was estimated to be \$20 million, which would be \$30 million in 2008 dollars. Hot air balloon systems would cost 4 to 10 times that of using H_2 balloons.

We examined another idea, of mixing H_2 and H_2S inside a balloon, and then just releasing the balloons to rise themselves and burst in the stratosphere, releasing the gases. The H_2S would then oxidize to form sulfate aerosols, but the H_2 would also have stratospheric impacts. Since H_2S has a molecular weight of 34 g/mol, as compared to 29 g/mol for air, by mixing it with H_2, balloons can be made buoyant. The standard buoyancy of weather balloons as compared to air is 20%. The largest standard weather balloon available is model number SF4-

0.141-.3/0-T from Aerostar International, with a maximum volume of 3990 m^3, and available in quantities of 10 or more for $1,711 each. The balloons would burst at 25 mb.

To calculate the mix of gases, if the temperature at 25 mb is 230 K and the balloon is filled at the surface at a pressure of 1000 mb and a temperature of 293 K, then the volume of the balloon would be:

$$V = 3990\,\mathrm{m}^3 \text{ x } \frac{25\,\mathrm{mb}}{1000\,\mathrm{mb}} \text{ x } \frac{293\,\mathrm{K}}{230\,\mathrm{K}} = 127\,\mathrm{m}^3 \tag{1}$$

The mass of air displaced would be:

$$m = \frac{pV}{RT} = \frac{1000\,\mathrm{mb} \text{ x } 127\,\mathrm{m}^3}{287 \frac{\mathrm{J}}{\mathrm{kg\,K}} \text{ x } 293\,\mathrm{K}} = 151 \text{ kg} \tag{2}$$

To produce the required buoyancy, the balloon with its mixture of H_2 and H_2S would have a mass $m' = m/1.2 = 125.9$ kg. Normally a weather balloon is filled with He, allowing it to lift an additional payload beneath it. In our case, the payload will be the H_2S inside the balloon. Since each balloon has a mass of 11.4 kg, the total mass of the gases would be 114.5 kg. To produce that mass in that volume would require a mixture of 37.65% H_2 and 62.35% H_2S by volume, for a total mass of H_2S of 110.6 kg. To put 1 Tg of gas into the stratosphere per year would therefore require 9 million balloons, or 36,000 per day (using 250 days per year). This would cost $15.5 billion per year just for the balloons. According to *COSEPUP* [1992], the additional costs for infrastructure, personnel, and H_2 would be $3,600,000,000 per year, or $5.5 billion in 2008 dollars, for their balloon option, and as rough guess we adopt it for ours, too. So our balloon option would cost $21 billion per year in 2008 dollars.

The option above would also inject 0.04 Tg H_2 into the stratosphere each year. This is 2 to 3 orders of magnitude less than current natural and anthropogenic H_2 emissions [*Jacobson*, 2008], so would not be expected to have any detectable effects on atmospheric chemistry.

Because about 1/10 of the mass of the balloons would actually be the balloons, this would mean 100 million kg of plastic falling to Earth each year. As *COSEPUP* [1992] said, “The fall of collapsed balloons might be an annoying form of trash rain.”

We repeated the above calculations using SO_2. Since SO_2 has a molecular weight of 64 g/mol, it would require a much higher ratio of H_2 to the sulfur gas to make the balloons buoyant. The number of balloons and the cost to loft 1 Tg of S as SO_2 would be approximately twice that as for H_2S, as it would be for the other means of lofting.

4.4. Ideas of the Future

All the above systems are based on current technology. With small changes, they would all be capable of injecting gases into the stratosphere within a few years. However, more exotic systems, which would take longer to realize, could also be considered.

Tall Tower. The tallest structure in the world today is the KTHI-TV transmission tower in Fargo, North Dakota, at 629 m high [*Smitherman*, 2000]. However, as *Smitherman* [2000] explains, the heights of this tower and current tall buildings are not limited by materials or construction constraints, but only because there has been no need. Currently, an untapered column made of aluminum that can just support its own weight could be built to a height of 15 km. One made of carbon/epoxy composite materials could be built to 114 km (Figure 3). If the tower were tapered (with a larger base), had a fractal truss system, were stabilized with guy wires (like the KTHI-TV tower), or included balloons for buoyancy, it could be built much higher.

We can imagine such a tower on the Equator with a hose to pump the gas to the stratosphere. The weather on the Equator would present no strong wind issues, as tornadoes and hurricanes cannot form there, but icing issues for the upper portion would need to be addressed. If the gas were pushed up a hose, adiabatic expansion would cool it to temperatures colder than the surrounding atmosphere, exacerbating icing problems. Because such a tower has never been built, and many engineering issues would need to be considered, from the construction material to the pumping needed, we cannot offer an estimate of the cost. However, only one tower would be needed if the hoses were large enough to pump the required amount of gas. Weather issues, such as strong winds, would preclude such a tower at high latitudes, even though it would not need to be as tall. (A tethered balloon system would have all the same issues, but weather would be even more of a factor.)

Space Elevator. The idea of a geostationary satellite tethered to Earth, with an elevator on the cable was popularized by *Clarke* [1978]. A material for the cable that was strong enough to support its own weight did not exist at the time, but now carbon nanotubes are considered a possibility [*Smitherman*, 2000; *Pugno*, 2006]. Such a space elevator could use solar power to lift material to stratospheric levels for release for geoengineering. However, current designs for such a space elevator would have it anchored to Earth by a tower taller than the height to which we would consider doing geoengineering [*Smitherman*, 2000]. So a tall tower would suffice without an exotic space elevator.

5. Conclusions

Using existing airplanes for geoengineering would cost several billion dollars per year, depending on the amount, location, and type of sulfur gas injected into the stratosphere. As there are currently 522 F-15C Eagles, 481 KC-135 Stratotankers, and 59 KC-10 Extenders, if a fraction of them were dedicated to geoengineering, equipment costs would be minimal. Systems using artillery or balloons would cost much more and would produce additional potnetinal problems of falling spent artillery shells or balloons, or H_2 injections into the stratosphere. However, airplane systems would still need to address several issues before being practical, including the effects of acid clouds on the airplanes, whether nozzles could be designed to produce aerosol particles of the desired size distributions, and whether injection of sulfur gases into an existing sulfuric acid cloud would just make existing droplets grow larger rather than producing more small droplets. All the systems we evaluate would produce serious pollution issues, in terms of additional CO_2, particles, and noise in the production, transportation, and implementation of the technology at the location of the systems.

Several billion dollars per year is a lot of money, but compared to the international gross national product, this amount would not be a limiting factor in the decision of whether to proceed with geoengineering. Rather, other concerns, including reduction of Asian monsoon rainfall, ozone depletion, reduction of solar power, psychological effects of no more blue skies, and political and ethical issues (Table 1), will need to be compared to the potential advantages before society can make this decision. As *COSEPUP* [1992] already understood, “The feasibility and possible side-effects of these geoengineering options are poorly understood. Their possible effects on the climate system and its chemistry need considerably more study and research. They should not be implemented without careful assessment of their direct and indirect consequences.”

Table 1 gives a list of the potential benefits and problems with stratospheric geoengineering. But for society to make a decision as to whether eventually implement this response to global warming, we need somehow to quantify each item on the list. While it may be impossible for some of them, additional research can certainly provide valuable information about some of them. For example, reduction of summer precipitation in Asia and Africa could have a negative impact on crop productivity, and this is why this climate change is a potential major concern. But exactly how much will precipitation go down? How will the effects of increased diffuse insolation and increased CO_2 ameliorate the effects of reduced soil moisture on agricultural production?

If stratospheric geoengineering were to be implemented, it would be important to be able to observe the resulting stratospheric aerosol cloud. After the 1991 Pinatubo eruption, observations with the Stratospheric Aerosol and Gas Experiment II (SAGE II) instrument on the Earth Radiation Budget Satellite [*Russell and McCormick*, 1989] showed how the aerosols spread, but there was a blind spot in the tropical lower stratosphere where there was so much aerosol that too little sunlight got through to make measurements [*Antuña et al.*, 2002]. To be able to measure the vertical distribution of the aerosols, a limb-scanning design, such as that of SAGE II, is optimal. Right now, the only limb-scanner in orbit is the Optical Spectrograph and InfraRed Imaging System (OSIRIS), a Canadian instrument on Odin, a Swedish satellite. SAGE III flew from 2002 to 2006, and there are no plans for a follow on mission. A spare SAGE III sits on a shelf at a NASA lab, and could be used now. Certainly, a dedicated observational program would be needed as an integral part of any geoengineering implementation.

As already pointed out by *Robock* [2008b], a well-funded national or international research program, perhaps as part of the currently ongoing Intergovernmental Panel on Climate Change Fifth Scientific Assessment, would be able to look at several other aspects of geoengineering and provide valuable guidance to policymakers trying to decide how best to address the problems of global warming. Such research should include theoretical calculations as well as engineering studies. While small-scale experiments could examine nozzle properties and initial formation of aerosols, they could not be used to test the climatic response of stratospheric aerosols. Because of the natural variability of climate, either a large forcing or a long-term (decadal) study with a small forcing would be necessary to detect a response above climatic noise. Because volcanic eruptions occasionally do the experiment for us and climate models have been validated by simulating volcanic eruptions, it would not be important to fully test the climatic impact of stratospheric geoengineering in situ as part of a decision about implementation. However, the evolution of aerosol properties, including size distribution, for an established stratospheric aerosol cloud would need careful monitoring during any full-scale implementation.

Acknowledgments. We thank the reviewers of a previous version of this paper for valuable comments and Brian West for drawing Figure 1. This work is supported by NSF grant ATM-0730452.

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Table 1. Benefits and risks of stratospheric geoengineering. The right column is an update of *Robock* [2008a].

Benefits	**Risks**
1. Cool planet	1. Drought in Africa and Asia
2. Reduce or reverse sea ice melting	2. Continued ocean acidification from CO_2
3. Reduce or reverse land ice sheet melting	3. Ozone depletion
4. Reduce or reverse sea level rise	4. No more blue skies
5. Increase plant productivity	5. Less solar power
6. Increase terrestrial CO_2 sink	6. Environmental impact of implementation
	7. Rapid warming if stopped
	8. Cannot stop effects quickly
	9. Human error
	10. Unexpected consequences
	11. Commercial control
	12. Military use of technology
	13. Conflicts with current treaties
	14. Whose hand on the thermostat?
	15. Ruin terrestrial optical astronomy
	16. Moral hazard – the prospect of it working would reduce drive for mitigation
	17. Moral authority – do we have the right to do this?

Table 2. Costs for different methods of injecting 1 Tg H_2S per year to the stratosphere. Airplane data from *Air Combat Command* [2008], *Air Mobility Command* [2008a, 2008b]. 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 [*Williamson*, 2008].

Method	**Payload (tons)**	**Ceiling (km)**	**# 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*
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*
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

* if operation costs were the same per plane as for the KC-135

Figure 1. Proposed methods of stratospheric aerosol injection. A mountain top location would require less energy for lofting to stratosphere. Drawing by Brian West.

Figure 2. U.S. military planes that could be used for geoengineering. a. F-15C Eagle (http://www.af.mil/shared/media/photodb/photos/060614-F-8260H-310.JPG), b. KC-10 Extender (http://www.af.mil/shared/media/factsheet/kc_10.jpg)

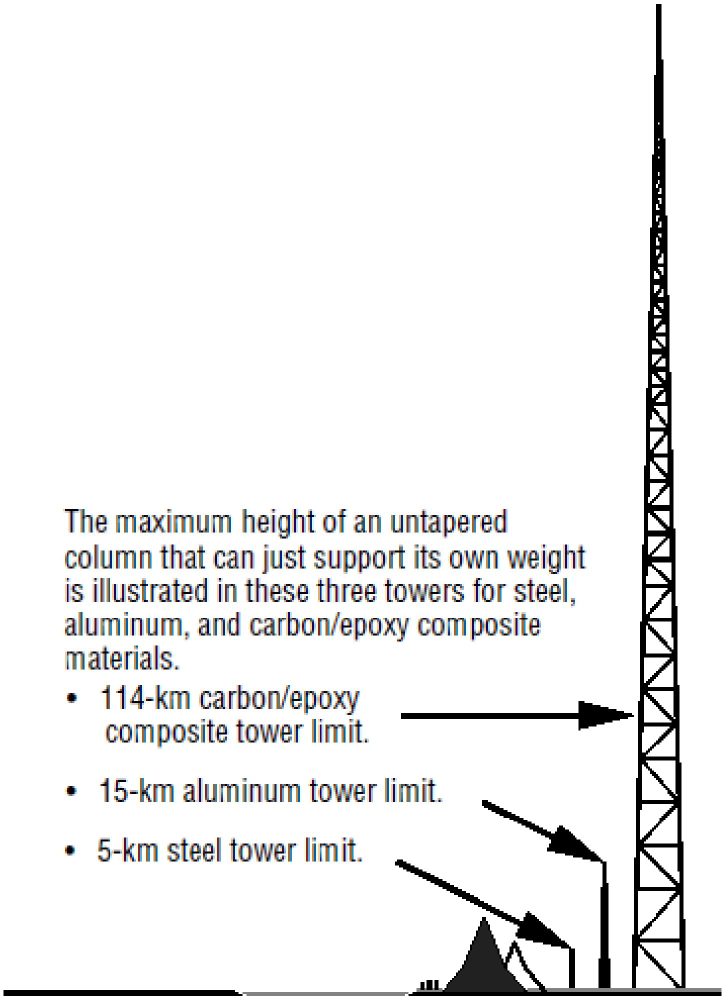

Figure 3. The maximum height of an untapered tower that can support its own weight, showing that one tower on the Equator could be used for stratospheric geoengineering. (From "Space Elevator Schematics" page at end of *Smitherman* [2000]).