THE PRACTICALITY OF GEOENGINEERING

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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. Here we evaluate the practicality of this means of geoengineering by examining the costs of using airplanes, balloons, or artillery to place hydrogen sulfide (H_2S) into the lower stratosphere, in either the tropics or the Arctic. Existing U.S. military fighter and tanker planes could be retrofitted, and the annual costs 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. While the cost of injecting aerosol precursors would not be a limiting factor, there are many other potential problems with geoengineering, and they need to be evaluated and compared to the potential benefits before a decision to proceed with geoengineering can be made.

Introduction

With global warming becoming more of a concern to our society and our planet, many scientists have recently begun researching means of modifying climate to reduce the harmful effects, inspired by the papers of *Crutzen* [2006] and [*Wigley*, 2006]. Here we examine their proposal for "solar radiation management," to reduce insolation with an anthropogenic stratospheric aerosol cloud, which we will call "geoengineering" here, recognizing that some others have a more inclusive definition that includes tropospheric cloud modification, carbon capture and sequestration, and other, hypothesized techniques.

Geoengineering today is impossible, as there are no means of injecting aerosols or their precursors into the stratosphere. *Robock* [2008] suggested that the construction and operation of such a system 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 1). 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.

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 H_2S. Using H_2S, which is rather corrosive and dangerous, could potentially exacerbate the inherent difficulties of this problem, but we do not address that issue here. For actual implementation, a specific gas would need to be chosen, and the results presented would be scaled appropriately. For example, if SO_2 were to be injected rather than H_2S, approximately twice as many resources as the values given here would be needed.

If the decision were ever made to actually conduct 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 H_2S 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]. Along these lines, *Robock et al.* [2008] tested a scenario of annual injection of 3 Tg of SO_2 at 68°N in addition to tropical injection scenarios. 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.

Airplanes

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. 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. Certainly aircraft systems could be designed and built to inject gases into the stratosphere, but here we evaluate existing aircraft.

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, 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 1. 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 is then converted to 2007 dollars (latest data available) by multiplying by a factor of 1.27 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 H_2S 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.

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 (2007 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.”

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. Hydrogen (H_2), which is less expensive than helium, can also be used to inflate balloons but is not normally used due to its flammability, as demonstrated in the Hindenburg disaster.

Balloons could be used in several ways for geoengineering. As suggested by L. Wood (personal communication, 2008), a 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 2007 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 we have not examined the chemical effects of the H_2. 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:

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

The mass of air displaced would be:

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

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 $5.3 billion in 2007 dollars, for their balloon option, and as rough guess we adopt it for ours, too. So our balloon option would also cost $21 billion per year in 2007 dollars.

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.”

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. 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 near the top would need to be addressed. 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 hose was 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.

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.

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 problems of falling spent artillery shells or balloons, or massive 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 and whether nozzles could be designed to produce aerosol particles of the desired size distributions. 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 [*Robock*, 2008], 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."

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Table 1. 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 2007 dollars (latest data available) using the Consumer Price Index [*Williamson*, 2008].

Method	**Payload (tons)**	**Ceiling (km)**	**# of Units**	**Purchase Price (2007 dollars)**	**Annual Cost**
F-15C Eagle	8	20	167 with 3 flights/day	$6,363,000,000	$4,175,000,000*
KC-135 Tanker	91	15	15 with 3 flights/day	$755,000,000	$375,000,000
KC-10 Extender	160	13	9 with 3 flights/day	$1,080,000,000	$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)