Solar Radiation Management: Is it worth the risk?

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Introduction

Recent evidence from climate modeling efforts on the subject of “dangerous” anthropogenic interference shows the potential for catastrophic extremes to exist in the future climate. Extended periods of drought in the middle latitude regions (as moisture bearing jet streams track towards higher latitudes); flash floods at higher latitudes; and intensified tropical cyclones in the lower latitudes are but a few of the extremes that humans could potentially be exposed to in the future (Schneider et al. 2007).

Human societies have 2 choices – mitigation, or adaptation. The best option, from a climate point of view, would be to reduce greenhouse gas emissions to limit the level of anthropogenic forcing on our climate. Given the realization that it is highly unlikely we can quickly implement major cuts in greenhouse gas emissions without significant negative consequences to economic growth, the probability of occurrence of such extreme events will increase in the future, as will the magnitude of such extremes. This leaves us with trying to adapt to a world of extremes, or developing some artificial means to tinker with the climate.

Adaptation will certainly be necessary in the future, for even if a 100% abatement of our emissions were to happen today, Gillet et al (2011) suggest we would, at a minimum, still see a significant further (0.2m) rise in global mean sea level, and a further 1^{o}C warming of the ocean, amongst other effects. Adaptation, however, is most easily accomplished when we can make predictions on what the future climate may look like. Predicting the day-to-day climate normal, though not trivial, is more easily done than predicting the magnitude and frequency of extremes, meaning adaptation will be most effective at preparing us for climate “normals”, and will likely fail to address weather of the extreme variety. Given this, there has been talk, in some scientific circles, of developing artificial means to tinker with the climate, or “geoengineering” projects.

A number of geoengineering proposals have been put forward, each focusing on different aspects of the climate system. These include proposals to dump iron into the open oceans, to fertilize plankton growth (and thus ocean CO_2 uptake); proposals for various forms of carbon capture and storage, and proposals to inject reflective aerosols into the stratosphere with the intent to increase the overall albedo of the earth - “solar radiation management” (SRM). This paper will focus on SRM geoengineering, given the recent suggestions that it could be relatively cheaply implemented in the future (Victor, 2011) with particular attention on:

- the effects of aerosols on climate – the direct effect (which is the source of inspiration for SRM), the first and second indirect effects;
- other potential side effects of implementing SRM;

- the projected costs of implementation, as well as political and diplomatic roadblocks to its implementation.

What are aerosols and where are they found?

Aerosols, defined as “suspensions of liquid or solid [particulate matter], excluding cloud droplets and precipitation”, (Power 2003, p.3), include naturally occurring meteoric dust, oceanic salts, dust (of crustal or desert origin), volcanic particulates, and particulates originating from forest fires. They also include those of anthropogenic origin, such as those originating from industry, agriculture, or transportation (Power 2003).

The effect of aerosols on the climate system varies based on their composition, size, shape, and the albedo of the surface directly below them. Certain non-absorbing aerosols, such as sulphates, can increase the local albedo (reflectivity) and thus have a cooling effect if located above surfaces which have a lower albedo (such as an ocean) and thus normally absorb much of the incoming solar radiation. Others, such as black carbon soot, can decrease the local albedo, and thus are not of interest to geo-engineering projects (Power 2003). The effect of aerosols on Earth’s climate will be returned to, and explored in further detail, in the “Effect of aerosols on climate” section.

Aerosols range in size from less than 0.1 μm to about 20 μm. Particles smaller than 0.1 μm (“Aitken particles”) diffuse relatively quickly, while “giant particles” greater than 1.0 μm are removed relatively quickly through gravitational settling. Particles with a size between 0.1 μm and 1.0 μm (“large particles”) have the longest lifetime in the atmosphere, being too large to quickly diffuse, but too small for gravity to act readily upon, and thus are of the most importance to geoengineering (Power 2003).

Aerosols can be found in both the troposphere and stratosphere, but given that the lifetime of tropospheric aerosols is at best a few weeks (Power 2003), stratospheric aerosol, with lifetimes on the order of a year (Rasch et al. 2008a), are of greater importance to albedo. In the stratosphere, the vast majority of aerosols consist of sulphuric acid droplets with radii of 0.1-0.5 μm (falling within the “large” category) (Deshler 2008). During periods of relatively low volcanic activity, background stratospheric aerosols have negligible effects on albedo (reductions of less than 0.01 on albedo). After large volcanic eruptions (such as the Pinatubo eruption of 1991), however, stratospheric aerosol concentrations can be up to a magnitude of 10^3 higher; enough to reduce albedo by up to 0.1, and have noticeable effects on the climate for several years (2-5 years, depending on the explosivity of the eruption, and the sulphur content of the plume) (Deshler 2008).

How do stratospheric sulphate aerosols form?

Sulphate aerosols arise from sulphur-bearing reduced gases such as dimethyl sulphide (DMS), SO_2, H_2S, and carbonyl sulphide (OCS). Oxidization of these precursor gases result in end products containing a sulphate anion $(SO_4)^{2-}$. In the troposphere, most of the oxidized aerosols exist in the form of ammonium sulphate ($(NH_4)_2SO_4$), and bisulphate ($(NH_4)HSO_4$). In the stratosphere, the majority of sulphate aerosols exist as sulphuric acid (H_2SO_4), with a small number existing as hydrates with nitric acid (HNO_3) (Rasch et al. 2008a). Rasch et al. (2008a) note that OCS is the dominant precursor species in the stratosphere, owing to its relative stability, where its oxidation can account for near 50% of the stratospheric aerosols during volcanically quiescent periods.

Processes influencing aerosol life-cycle

Formation of aerosol particles begins with nucleation (the process whereby water vapour attaches to precursors). Hamill et al. (1997) note that the majority of non-volcanic stratospheric sulphate particles originate in the tropics. Here, the vast majority of nucleation occurs near the tropopause, between altitudes of 15-18km with a maximum nucleation rate of $300s^{-1}$ occurring at about an altitude of 17km. In comparison, the maximum nucleation rates in mid-latitudes, where the tropopause is significantly lower, are about 10^{-5} s^{-1} (Hamill et al. 1997). Following nucleation, aerosol particles tend to coagulate to form larger ones. If the concentration of ice particles in the upper troposphere is sufficiently high (at least 10 ice crystals cm^{-3} of 10μm), however, newly formed aerosol particles will tend to be quickly scavenged by ice before they can coagulate with one another (Hamill et al. 1997). Growth by condensation is another way that aerosols can increase in size, and tends to have the effect of causing "particles of all sizes to increase equally in radius, [such that] the size distribution has the same 'width' at all times" (Hamill et al. 1997, p 1401). Changes in air temperature will have an effect on the size of an aerosol particle. As the temperature drops, the aerosol will absorb further water molecules to maintain equilibrium with the environmental water vapour, while an increase in temperature will cause the aerosol to release some of its water (Hamill et al 1997).

The loss of stratospheric aerosol is primarily accomplished through one of four means: isentropic transport, cloud scavenging by cloud intrusions into the stratosphere, sedimentation, and polar vortex removal (Hamill et al 1997). In isotropic transport, the most common means of aerosol loss, Rosby waves in the upper atmosphere cause air to be driven upward from the tropical lower stratosphere, poleward, and then downward in the extratropics. Here, long thin streams of air (~2000km long by 200km wide) may develop, and cross the tropopause. Once in the tropopause, aerosols will very quickly be removed (Hamill et al 1997). In the second case, cloud tops of large cumulonimbus (thunderstorm) clouds in the middle latitudes, where the tropopause is significantly lower, may occasionally penetrate into the stratosphere, causing nearby aerosols to be scavenged (Hamill et al 1997. Sedimentation, the third means of stratospheric aerosol loss, is a function of gravity, and is not an effective means of removal except for particles with a radius on the order of a micron (Hamill et al 1997). For aerosols of radius 0.25 microns, the settling time is about 1.3 years. For a particle with a radius of 0.06 microns, the average settling time is about 6.3 years; leaving plenty of time for the aerosol to leave the stratosphere via one of the other aforementioned mechanisms. Finally, during the winter, cold air in the polar regions (especially in Antarctica) creates a vortex as it contracts and descends. Hamill et al (1997) note that on average, about 1/16 of the stratospheric air mass is pulled into this vortex, and with it, the aerosols it was carrying.

Effects of aerosols on climate

The effects of aerosols on the physical climate can be grouped into four main groups:

1) Direct effects
2) 1st indirect effect or cloud albedo effect
3) 2nd indirect effect or cloud lifetime effect
4) Semi-direct effects (not explored here since it only pertains to absorbing aerosols)

Direct effects

The direct effect of aerosols on climate is their ability to scatter and absorb shortwave (SR) and longwave radiation (LR), which has the effect of "altering the radiative balance of the Earth-atmosphere system" (Forster et al. 2007, pg 153). Factors influencing the degree to which an aerosol will scatter or absorb SR and LR include the aerosol's optical properties (scattering albedo (ω_o), specific extinction coefficient (k_e), and scattering phase function), all of which vary with wavelength and the relative humidity of the environment, as well as the atmospheric loading and geographic distribution of aerosols (Forster et al 2007). The single scattering albedo of an aerosol is defined as "the ratio of scattering optical depth to the total optical depth (scattering + extinction) of the atmosphere. It is a dimensionless quantity and ranges from 0 to 1" (Kempler 2009).

Scattering aerosols, such as sulphate aerosols, will exert a negative top-of-the-atmosphere (TOA) direct radiative forcing (RF); in other words they increase the local albedo (Denman et al. 2007). According to Forster et al. (2007) the direct RF effect for sulphate aerosols ranges from -0.21 Wm^{-2} to -0.96 Wm^{-2}. The authors note that these results were highly sensitive to a wide range of factors relating to the differences in modeling of aerosols and their properties across models. If the strongest and weakest direct RF estimates are ignored, an estimate at the 90% confidence interval of -0.4±0.2 Wm^{-2} can be deduced (Forster et al 2007).

Robock et al (2009) note that aerosols also "drastically change the partitioning of [incoming solar radiation] into direct and diffuse radiation (pg 2). Observations following the 1982 El Chicon eruption showed reductions in the peak downward direct insolation, at the Mauna Loa Observatory in Hawaii, from 515 Wm^{-2} to 340 Wm^{-2}, and an increase in diffuse radiation from 40 Wm^{-2} to 180 Wm^{-2} (with an overall net radiation decrease of 35Wm^{-2}).

1st indirect effect or cloud albedo effect

In addition to directly affecting incoming and outgoing SR and LR, aerosols can also affect the formation, and albedo of clouds. Some aerosols, including sulphates, can act as cloud condensation nuclei (CCN), and/or ice nuclei (IN). Increases in the aerosol concentrations, assuming a fixed cloud water content, can lead to an increase in the overall albedo of clouds; this effect is known as the cloud albedo effect, or 1st indirect effect (Forster et al 2007).

An increase in the number of cloud condensation nuclei, and/or ice nuclei will lead to an increased cloud droplet number. Assuming fixed water content, this will mean that the average cloud droplet size will be smaller. The relationship between aerosol concentration and cloud droplet number is non-linear and can be estimated using the following function: $N_d \approx (N_a)^b$, where N_d is the cloud droplet number, N_a is the aerosol number concentration, and b is a parameter that varies from 0.06 to 0.48, depending on aerosol characteristics (especially their size), and updraft velocity (Forster et al 2007). Estimates of the global mean RF associated with the cloud albedo effect (for all aerosols combined) are quite variable, ranging from -0.22 to -1.85 Wm^{-2}, and vary due to differences in the modeling of aerosol properties, cloud physics, and interactions between clouds and aerosols across models (Forster et al 2007). For models that focused on a restricted number of aerosol species (sulphate and organic carbon), the range was much smaller, with a mean and standard deviation of -1.37 ± 0.14 Wm^{-2} (Forster et al 2007). Forster et al (2007) caution however, that it was difficult to directly compare results across different models, given that model uncertainties were not well defined nor well quantified.

Denman et al (2007) note that some of the more recent modeling efforts, which included dispersion effects (the widening of the size distribution of cloud droplets in polluted clouds), found that this dispersion effect partly counteracted the reduction in overall cloud droplet radius, reducing the radiative forcing by 12-42%. They also note that a related effect of overall increased cloud cover due to the increased presence of aerosols may also contribute to the 1st indirect effect.

2nd indirect effect or cloud lifetime effect

The 2nd indirect effect or cloud lifetime effect stems from the fact that under increased aerosol concentrations, cloud droplets are smaller. For clouds primarily consisting of water droplets, these smaller cloud droplets generally have the effect of decreasing precipitation formation (in the absence of giant

CCN), which in turn has the effect of increasing the overall lifetime of the cloud (Denman et al 2007). The effect of aerosols will vary by cloud type to some degree, however.

For warm, liquid clouds, the increased presence of anthropogenic aerosols, in the absence of giant CCN, will generally decrease precipitation and thus prolong the cloud's lifetime. In the presence of giant sea-salt nuclei, however, sulphate aerosols may actually act to increase precipitation (Denman et al 2007). It is also noted by Denman et al (2007) that aerosols may also reduce the frequency of extreme precipitation events.

The cloud lifetime effect on mixed-phase clouds comes in the form of both the "glaciation effect", and the cloud droplet effect described above. In the glaciation effect, the increase in aerosol concentration, which act as IN, can accelerate the glaciation (or transformation of water droplets into ice crystals) of stratiform clouds, which results in an increase in precipitation, and thus shorter cloud life-time; having a net positive radiative effect (Denman et al 2007). Modeling studies have shown, however, that in convective clouds, pollution aerosols have the opposite effect and delay the onset of glaciation, which results in reduced precipitation (an effect known as the thermodynamic effect).

Estimates of the radiative forcing contribution of the cloud lifetime effect, for all cloud types and aerosols combined, range from -0.3 to -1.4 Wm^{-2}, and vary with differences in the modeling of the relationship between aerosol mass and cloud droplet number, the assemblage of aerosols used in the model, and differences in the way cloud-microphysics are modeled (Denman et al 2007).

Potential benefits from SRM geoengineering

Owing to the ability of aerosols to reduce radiative forcing (and the associated reduction in temperature), Robock et al (2009) note several potential benefits of SRM geoengineering. First, there would be a large number of benefits for Earth's cryosphere, including a reduction or reversal of sea ice melting, land ice sheet degradation, and thus a reduction in the rate of sea level rise. A study by Matthews and Caldeira (2007), using the UVic Earth System Climate Model, investigated the effects of SRM geoengineering on the climate and found that under an A2 emissions scenario (where the global atmospheric CO_2 levels double by 2100), the global mean temperature increased by 3.5^oC (ranging from a 2.5^oC increase in the south Pacific to a >5^oC warming at high latitudes). To simulate SRM geoengineering, Matthews and Caldeira applied a globally uniform reduction factor to the incoming solar insolation (which resulted in the largest absolute reductions in the tropics, and the smallest reductions at the poles), resulting in an overall average reduction of 3.7Wm^{-2}. When geoengineering was implemented in simulation year 2000 and consistently applied through the year 2100, it produced year 2100 temperatures very close to year 1900 temperatures, with a small, -0.35^oC, anomaly in the south Pacific, and an anomaly of <+1.0°C in the Arctic. Temperatures returned to near pre-industrial levels within 5 years of implementation of geoengineering, suggesting that its effects are rapid.

Next, Robock et al (2009) suggest that SRM projects have the potential to increase plant productivity (and thus increase the ability of terrestrial carbon sinks to uptake carbon from the atmosphere). For example, the increased partitioning of incoming solar insolation into diffuse radiation following the 1991 Pinatubo eruption temporarily increased the terrestrial carbon uptake by about 1 Pg C per annum (Robock et al 2009). However, when one considers that the global terrestrial CO_2 uptake is 123 ± 8 Pg C yr^{-1} (Beer et al 2010), this represents an increase of less than one percent, meaning Robock et al (2009) may be overemphasizing the fertilization effects arising from SRM geoengineering. In addition, Matthews and Caldeira (2007) suggest that the fertilization effects of increased atmospheric CO_2 on plant productivity (and thus global terrestrial CO_2 uptake) would dwarf the effects arising from an increased partitioning of diffuse radiation.

Geoengineering of stratospheric sulphate aerosols

What concentration of aerosol is necessary, and what particle size is best?

According to Rasch et al (2008a) note that a sulphate aerosol concentration of 15-30 times that of current non-volcanic sources (~1.5-5Tg S yr^{-1}) would be necessary to balance the warming associated with a doubling of CO_2. Based on data taken from the 1991 Pinatubo eruption, Crutzen (2006) notes that sulphate aerosols have an average radiative forcing of around $-0.75Wm^{-2}$ per Tg sulphur in the stratosphere. This falls within the range suggested by the IPCC in the Fourth Assessment Report of $-0.21Wm^{-2}$ to $-0.96Wm^{-2}$, though Forster et al (2007) did not specify the aerosol load that these estimates pertain to. The estimates provided by Crutzen (2006), however, do not specify whether the estimate of $-0.75Wm^{-2}$ per Tg of S is the direct forcing, or whether it is a composite value that also takes into account indirect forcing considerations. It also did not specify the aerosol size required to induce such an effect.

Rasch et al (2008b) employed the NCAR Community Atmosphere Model, a coupled Atmosphere Ocean General Circulation Model (AOGCM), to investigate the effects of aerosol particle size on the effectiveness of solar radiation management geo-engineering, assuming an aerosol consisting of 75% H_2SO_4 and 25% H_2O by weight. They found that when a small aerosol particle regime (with a dry mode radius of 0.05μm, standard deviation of 2.03 μm and an effective radius of 0.17 μm) was employed, 1.5Tg S/yr was sufficient, in a 2X CO_2 rise scenario, to produce a surface temperature within 0.1°C of that of the present day. The simulated small particle regime was found to be more effective than a regime that mimicked volcanic eruption sized particles (with dry mode radius of 0.376 μm, standard deviation of 1.25

μm and an effective radius of 0.43 μm), which required nearly double the amount of sulphur to produce a similar effect.

The smaller particle sizes – those on the order of 0.1 μm, have a near maximum backscattering cross section per unit mass, and have a longer residence time in the stratosphere than their larger counterparts (Rasch et al 2008b).

What are the proposed lofting mechanisms, and what would they cost?

In addition to the material composition and the amount and size of aerosols previously discussed, Blackstock et al (2009) note that the geographical and vertical location(s) of aerosol dispersal, and the temporal sequencing of aerosol dispersion are also important variables to consider. Given the findings of Hamill et al (1997) in regards to aerosol life cycle, it appears that application of aerosols should be initiated in the upper troposphere or lower stratosphere of the tropical latitudes, where nucleation rates are the greatest, and aerosols are not subject to descending airflows.

A number of aerosol delivery mechanisms have been suggested, including the use of aircraft, cannons (eg Davis guns), rockets, and hoses supported by balloons (Blackstock et al. 2009). This area is still an active area of research (Hemming and Hagler 2011), and thus cost estimates for each of the delivery mechanisms are still preliminary.

With estimated yearly operational costs in the range of $10,000,000/yr to $60,000,000,000/yr for most proposed SRM geoengineering lofting mechanisms (Table 2, Table 3), it appears that SRM geoengineering could be accomplished relatively cheaply. Considering that the US government's annual expenditures in 2010 were nearly $3.5 trillion dollars (US Office of Management and Budget 2011), even some of the most expensive SRM geoengineering solutions (excluding rockets) would represent less than 17% of the US' annual budget, with most representing less than 10% (Table 2, Table 3). This is also a tiny fraction of the estimated costs of conventional mitigation, which the Royal Society (2009) suggests could be on the order of $70 trillion/yr! Thus, Nordhaus (1992) suggests that we can effectively treat geoengineering solutions as "costless" in economic analyses.

The cheapest solution (by far) appears to be Intellectual Ventures (2009) hose approach, which proposes that a very long hose, supported by a series of balloons, would deliver 100,000 metric tons SO_2/yr to an altitude of 30km. Though cheap ($10 million/yr to operate), this proposal has a number of issues (Table 1) including the fact that it disperses aerosols over a very limited region (not taking advantage of global circulation patterns), and the fact that the hose would be subjected to very high winds at altitude, potentially causing it to be blown off course, or break.

The most expensive lofting mechanisms appear to be rockets ($900,000,000,000/yr), naval guns and tank rifles ($30,000,000,000-$182,000,000,000/yr), though there appears to be large disagreement on their estimated costs (Table 2). Blackstock et al (2009) and Robock et al (2009) suggest that the use of tank or naval rifles would have costs on the order of $30,000,000,000-$60,000,000,000/yr, while the National Academy of Science (1992) suggests that the costs would instead be on the order of $182,500,000,000/yr. This can be accounted for buy the fact that the NAS (1992) scenario assumes that rifles would be firing 10,000,000 shots per year (and providing 10^{10}kg of aerosol payload) compared to on the order of 3,000,000 shots per year for the Blackstock et al (2009) and the Robock et al (2009) scenarios (providing 10^9kg of aerosol payload). Given that Rasch et al (2008) suggest that 1.5-5Tg of sulphur is sufficient ($1.5 \times 10^9 - 5 \times 10^9$ kg sulphur), it would suggest that the estimates Blackstock et al (2009) and Robock et al (2009) might be closer to reality.

The costs of employing rockets for an SRM geoengineering application appear to be even less unsure. NAS (1992) suggest that the cost of employing rockets to loft aerosol payload would be close to $100/kg of payload (or about five times that of the per kg cost of naval or tank rifles), which would suggest a cost of close to $1,000,000,000,000/yr for 10^{10}kg of payload (Table 2)! On the other hand, though Blackstock et al (2009) did not calculate an estimated cost for rockets, they suggested it might actually be cheaper to use rockets than naval or tank rifles. Thus it appears there is not yet a consensus on the costs of employing rockets for geoengineering.

The best overall candidate proposal, when both cost and effectiveness are considered, appears to be the utilization of a dedicated aircraft fleet. Though the costs vary significantly with aircraft type; from a low of $275,000,000 per year for a small fleet of KC-10 Extenders (Robock et al 2009) to a high of $9,875,000,000 per year for a fleet of 133 Boeing F-15s (McClellan et al 2010), these costs are all significantly less than the estimates for using stratospheric balloons, rockets, naval rifles, or tank rifles, and planes have the ability to take advantage of global circulation patterns far more effectively than any of the other proposed mechanisms.

The most effective aircraft will be those whose maximum ceiling resides in the stratosphere (at or above 17-18km). It is true that such aircraft tend to fall at the upper end of the cost estimates, especially for supersonic fighter class jets such as the F-15, however McClellan et al (2010) suggests that by upgrading a business jet (the Gulfstream C37) with higher performance engines (at a cost of $5million a piece), one could extend its maximum ceiling to 18.2km, and operate a fleet of 43 jets at a yearly cost of $2.78 billion (in line with operating costs of a small regional cargo airline). The major drawback to using aircraft as a lofting mechanism, however, is that they are the most CO_2 emission intensive option (Table 1) (and thus would be further contributing to the very issues geoengineering is trying to correct).

Mechanism	**Benefits**	**Disadvantages**
Aircraft – sulphur exhaust additive Blackstock et al 2009)	• Injection of sulphur into aircraft fuel is relatively simple • Doesn't require extra aircraft flight to apply sulphate aerosols • Likely significantly less expensive option than employing dedicated aircraft	• Assumes we continue to use kerosene for jet fuel (further adding to the CO_2 emission problem!) • Aerosols would only be dispers along commercial flight paths; unable to target application to specific regions of earth • Sulphate release rate would like be determined by fuel consumption rate • McClellan et al (2010) note tha higher levels of sulphur (above 0.3% by mass) in fuel can resul in corrosion of downstream engine components
Aircraft – dedicated fleet employing payload releases (McClellan et al 2010)	• Necessary modifications are relatively easy to make to aircraft (Blackstock et al 2009) • Can target exactly where you want particles to go – best possible range of coverage! • Can control release rate of sulphur/sulphate • Manageable operational costs, once necessary modifications are made; ~$2 billion per year for most aircraft (McClellan et al 2010)	• Greater operation cost than fuel additive option • Extra flights mean more CO_2 emissions
Guns/Cannons (National Academy of Sciences 1992; Blackstock et al 2009)	• Relatively easy to deploy • Less CO_2 emissions intensive than aircraft fleet	• Hard to ensure shell will explo in stratosphere • Shells costly (potentially upwar of $10,000-20,000 each) (Blackstock et al 2009) • Coverage is less than for aircraf
Rockets (Blackstock et al 2009)	• May penetrate stratosphere more effectively than shells? • Milder launch environment than shells (Blackstock et al 2009) • Less prone to air drag than shells (Blackstock et al 2009) • Lighter than artillery shells – could deliver more aerosol payload per unit mass than artillery shells (up to 60-70% of the launch weight could be payload) (Blackstock et al 2009)	• Coverage is less than for aircraf • Very high CO2
Balloons carrying hose (Intellectual Ventures (2009)	• Relatively cheap; Intellectual Ventures (2009) estimates operational costs of ~ $10 million/yr • No CO_2 emissions associated with the end product	• Very limited coverage • Hose would be subjected to ver strong winds at high altitude • 30km hose with stationary balloons represents a hazard fo aircraft

Table 1. Merits and Disadvantages with various mechanisms for sulphate aerosol application.

Table 2. Estimated upfront and yearly operational costs for a variety of proposed lofting mechanisms.

Proposed Mechanism	Maximum Altitude (km)	Upfront Cost Range	Yearly Operation Cost Range	Sources
Hose/Chimney [1]	30	$24,000,000.00	$10,000,000	Intellectual Ventures (2009)
Stratospheric Balloons [2]	?	included in annual cost	$21,000,000,000 to $30,000,000,000	Robock et al (2009)
Naval Guns [3]	?	included in annual cost	$30,000,000,000.00	Robock et al (2009)
Naval Guns [4]	24	?	$31,536,000,000 to $63,072,000,000	Blackstock et al (2009)
Naval Guns [5,6]	20	?	$182,500,000,000	NAS (1992)
Tank Gun [7]	63	?	$30,000,000,000 to $60,000,000,000	Blackstock et al (2009)
Rockets [6,8]	70	?	$900,000,000,000	NAS (1992)

1. Preliminary estimates
2. Assumes 37,000 hydrogen balloons launched per day, each carrying 4 tons of aerosol payload
3. Assumes 8000 shots per day, or 2.9 million shots per year
4. Assumes 2 shots/minute each for 3 guns (3,153,600 shots per year total). Cost estimates are for shells and 10^9kg payload only, though Blackstock et al (2009) and NAS (1992) suggest that these will make up nearly 90% of costs
5. Undiscounted costs for 10^{10}kg payload (10,000,000 shots per year)
6. Converted from 1992 dollars using www.dollartimes.com/calculators/inflation.htm (assumes average 2.47% inflation per year).
7. Assumes 3,000,000 shots per year; cost estimates are for shells and 109 kg aerosol payload only, though blackstock et al (2009) argue that these will make up the bulk of the cost
8. Includes rocket and payload costs only (assumes lofting costs of ~$100/kg and 10^{10}kg of payload)

Table 3. Estimated acquisition, modification and yearly operation costs of utilising various planes for an SRM geoengineering application.

Aircraft	Maximum Altitude (km)	Fleet Size	Fleet Acquisition Cost	Fleet Modification Costs	Yearly Operational Costs	Source
KC-10 Extender [1,2]	13	9	$1,050,000,000	N/A	$275,000,000	Robock et al (2009)
KC-135 tanker [2]	15	15	$784,000,000	N/A	$375,000,000	Robock et al (2009)
Boeing 747	13.7	14	$392,000,000	$426,426,000.00	$1,180,000,000	McClellan et al (2010)
Gulfstream C37 (modified)	18.2	43	$2,575,700,000	$860,000,000.00	$2,670,000,000	McClellan et al (2010)
Gulfstream C37 (new)	15.5	43	$2,575,700,000	$430,000,000.00	$2,780,000,000	McClellan et al (2010)
Gulfstream C37 (used)	15.5	43	$978,250,000	$430,000,000.00	$2,780,000,000	McClellan et al (2010)
Boeing C-17	18.2	24	$5,760,000,000	$1,207,680,000.00	$3,980,000,000	McClellan et al (2010)
Boeing F-15 [1]	20	167	$6,613,000,000	included	$4,175,000,000	Robock et al (2009)
Boeing F-15	25.9	133	$6,650,000,000	$665,000,000.00	$9,520,000,000	McClellan et al (2010)
umnanned WK2	20	150	$30,000,000,000	included	$8,000,000,000	Blackstock et al (2009)

1. assumes payroll costs comparable to KC-135 Tanker
2. Robock et al (2009) suggest that fighter jets ferry sulphur payload beyond this ceiling, or have glider towed behind

Unintended side effects of SRM

Though SRM geoengineering solutions may represent a relatively inexpensive “emergency” solution to reduce the temperature related effects of climate change, they do not address the root of the problem; the rising levels of atmospheric CO_2, and thus do nothing to address other effects such as shifts in precipitation patterns, and rising ocean acidification (Barret 2008).

Matthews and Caldeira (2007) found that model simulations of SRM geoengineering (implemented in the simulation year 2000) caused a 0.02mm/day globally averaged precipitation decrease from 1900-2100. Slight increases in precipitation over oceans (due to slight warming) were counteracted by decreased precipitation over land, with the largest decreases occurring in tropical and suptropical regions such as the Amazonian basin, the Congo region of Africa, and sub-Saharan Africa (up to 1mm/day). Similarly, a study by Bala et al (2008) found that geoengineering reduced the global mean annual precipitation by 5.7%. Vaughan and Lenton (2011) explain, “in a successfully geoengineered climate…the net change in radiation at the surface…is balanced by reductions in [evapotranspiration] and sensible heat loss…[and that the] reduced evaporation in turn causes reduced precipitation” (pg 763).

Ocean acidification is another consequence of increased atmospheric CO_2 concentrations that SRM geoengineering fails to address. As a consequence of the differing partial pressures of CO_2 between the atmosphere and ocean, a pressure gradient develops in which the ocean will uptake excess CO_2 from the atmosphere. In doing so, however, carbonic acid (H_2CO_3) is produced (Kump et al 2009):

$$CO_2 + H_2O \leftrightarrow H_2CO_3$$

Carbonic acid is then free to react with calcium carbonate ($CaCO_3$) present in the water column (both in the shells of marine organisms, or as inorganic material):

$$CaCO_3 + H_2CO_3 \leftrightarrow Ca^{2+} + 2HCO_3$$

When the partial pressures of atmospheric and oceanic CO_2 are in equilibrium with one another, the overall effect favours the production of $CaCO_3$. As atmospheric concentrations of CO_2 increase, however, the rate of carbonic acid production increases, shifting the balance in favour of carbonate dissolution, which would be disastrous for marine organisms and marine food webs (Kemp et al 2009). The Royal Society (2005) suggests that a doubling of atmospheric CO_2 could reduce coral calcification rates by 10-30%, and a 3-54% overall decrease in oceanic carbonate production!

Another concern with SRM geoengineering is that its cooling effect is not permanent, and will only exist while a continuous supply of sulphate aerosols is present in the stratosphere. If this supply were to cease due to project failure or funding cuts, for example, the world would experience very rapid warming. The experiments of Matthews and Caldeira (2007), described above, included runs simulating failure of geoengineering in 2025, in 2050, and in 2075. Results from these runs showed very rapid rates of warming following cessation of geoengineering; on the order of 2°C per decade (ten times the current rate of warming) following cessation in 2025, and near 4°C per decade following cessation of geoengineering in 2075! Such rapid rates of warming, it is suggested, would be dangerous to both humans and the biosphere (Matthews and Caldeira 2007).

In addition to the above shortcomings, SRM projects have a number of risks directly associated with the increased sulphate aerosol concentrations in the atmosphere. These include the acceleration of ozone decay in the stratosphere (by up to 60-80 dobson units per year, and inducing a decadal delay in recovery of the Antarctic ozone hole); a weakening of the Asian and African summer monsoons (further exacerbating precipitation declines in these regions); and an increase in wet and dry acid deposition (acid rain) (Robock et al 2009; Vaughan and Lenton 2011).

Political feasibility of SRM

Owing to the relative simplicity and low cost of the aforementioned geoengineering proposals, it would be relatively easy for a single country, trying to reduce the impact of climatic change on its citizens, to go ahead and experiment with SRM geoengineering, without a global agreement in place.

Given that there is currently no legal framework regarding geoengineering projects, and no explicitly applicable framework to work from yet either (Kintisch 2010), a rogue nation would, under current rules, be "pretty much free to explore geoengineering options…as they please" (Barrett 2007, pg 9).

To properly assess the risks associated with SRM geoengineering proposals, however, Blackstock et al (2009) suggest that a precautionary approach should be taken when researching and implementing a geoengineering plan, involving three phases:

1. Non-invasive laboratory/computer simulations
2. Small scale field experiments
3. Monitored deployment

The precautionary approach would require careful consideration to the tradeoffs between potential risks and benefits after each phase of research is completed, much like in medical research (Blackstock et al 2009). Once the go ahead for deployment is given, careful monitoring of potential side effects would be necessary, especially considering that it may take time for the side effects to appear (Blackstock et al 2009). In light of the results from the "geoengineering failure" runs that cessation of geoengineering could result in extremely rapid warming, it would be crucial to make a decision quickly on whether or not to end the project if dangerous side effects do begin to appear, to minimize the rapidity of the climate warming.

A global standard on the protocols to implementation of SRM geoengineering, however, would require international negotiation, and would likely be part of a greater global agreement on climate mitigation and adaptation. International agreement on geoengineering will inevitably be difficult, considering it will involve a number of issues, including:

1. Whether or not one has the right to inflict hardship on some regions (such as the sub-Saharan African region) if it is perceived that a geoengineering project will have a global net benefit
2. Are the "winners" of a geoengineering project obligated to provide compensation to the "losers"?
3. How does one prevent the use of such projects for warfare purposes?

Since SRM projects involve the alteration of the stratosphere, an agreement would also need to explore the question surrounding who owns the stratosphere (Victor 2011).

Barret (2007) suggests that three major steps are required to develop an international agreement. First, the Intergovernmental Panel on Climate Change should explore the potential for geoengineering, and issue a special report. Next, the United Nations Framework Convention on Climate Change would need to be revised, to include the findings of the IPCC report, and broaden its objectives to reflect the need to "reduce climate risk" from "stabilizing atmospheric concentrations of greenhouse gases". Reducing climate risk, Barret (2007) suggests, would include mitigation of greenhouse gases, a need for adaptation funds, a push for R&D of clean energy technologies, and geoengineering. Finally, he suggests that a protocol must be established clearly outlining under what circumstances should geoengineering be allowed (and not allowed), and how the costs of geoengineering efforts should be distributed.

However, Blackstock and Long (2010) note that even with an agreement in place, and careful monitoring of field tests, it would be very difficult to attribute, with certainty, climatic impacts to any particular SRM test. Thus, "liability for damages, real or perceived, would become a [major] political challenge" (pg 527).

Final Diagnosis: is SRM worth it?

Results from current climate models have researchers, society, and a growing number of political interest groups concerned about what our future climate will look like. Combining diplomatic gridlock on climate policies into the equation has many concerned about "climate emergencies" and what could be done to reduce their effects. The low cost, and quick response of SRM applications has garnered much attention recently, with a number of researchers and investment firms racing to develop "the solution", though most proposals are still in their preliminary stages.

Given that our current understanding of the effects of SRM geoengineering come only from observations of the effects of volcanic eruptions and computer simulations, and that there has yet to be detailed field experiments testing SRM proposals, going ahead with a full scale implementation of SRM geoengineering could be very risky (Blackstock et al 2009). In addition to the currently understood side-effects, there are likely numerous other unforeseen risks that could arise from the use of SRM geoengineering, and thus a precautionary approach would be wise.

Victor (2011) suggests that some of the known side effects could be accounted for by employing "cocktail" solutions, which include measures to reduce or reverse some of the side effects, and that we could try to build in a buffer capacity against future unknown risks. What these cocktail solutions would entail is a huge unknown, and even Victor himself failed to make concrete suggestions.

One could make the analogy that cocktail solutions are to climate as biological control measures are to pest species. There have been countless examples over history of biological control experiments going wrong; where the agent brought in to control a pest species becomes a pest itself. Just as the introduction of an exotic biological control agent can upset the delicate equilibrium of an ecosystem, blindly tweaking geoengineering projects with counter-measures against known side effects could very easily cause further problems in our complex climate system.

Clearly, SRM geoengineering is no substitute for mitigation of greenhouse gases (Blackstock and Long 2010). Doing little more than temporarily mask the temperature signal, it fails to address the root cause of climate warming, and many of the other consequences linked to it, including ocean acidification, and changes in precipitation patterns. Worse, in the case of precipitation, it may actually exacerbate effects of drought. Furthermore, failure of SRM could induce rates of warming on the order of 10-20 times that of the current rate. Do we as a society really want to partake in such a high stakes gamble?

There have been suggestions for other forms of geoengineering, such as the various forms carbon capture and storage, but these operate over much longer timescales than SRM, and thus do not hold the same potential as an emergency stop-gap solution. The only safe solution is to develop serious plans to address rising levels of CO_2. Perhaps other these other forms of geoengineering that target CO_2, could be a viable part of such a plan, but one thing is for sure; SRM geoengineering will not.

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