ALBEDO ENHANCEMENT BY STRATOSPHERIC SULFUR INJECTIONS: A CONTRIBUTION TO RESOLVE A POLICY DILEMMA?

An Editorial Essay

Fossil fuel burning releases about 25 Pg of CO_2 per year into the atmosphere, which leads to global warming (Prentice et al., 2001). However, it also emits 55 Tg S as SO_2 per year (Stern, 2005), about half of which is converted to sub-micrometer size sulfate particles, the remainder being dry deposited. Recent research has shown that the warming of earth by the increasing concentrations of CO_2 and other greenhouse gases is partially countered by some backscattering to space of solar radiation by the sulfate particles, which act as cloud condensation nuclei and thereby influence the micro-physical and optical properties of clouds, affecting regional precipitation patterns, and increasing cloud albedo (e.g., Rosenfeld, 2000; Ramanathan et al., 2001; Ramaswamy et al., 2001). Anthropogenically enhanced sulfate particle concentrations thus cool the planet, offsetting an uncertain fraction of the anthropogenic increase in greenhouse gas warming. However, this fortunate coincidence is "bought" at a substantial price. According to the World Health Organization, the pollution particles affect health and lead to more than 500,000 premature deaths per year worldwide (Nel, 2005). Through acid precipitation and deposition, SO_2 and sulfates also cause various kinds of ecological damage. This creates a dilemma for environmental policy makers, because the required emission reductions of SO_2, and also anthropogenic organics (except black carbon), as dictated by health and ecological considerations, add to global warming and associated negative consequences, such as sea level rise, caused by the greenhouse gases. In fact, after earlier rises, global SO_2 emissions and thus sulfate loading have been declining at the rate of 2.7% per year, potentially explaining the observed reverse from dimming to brightening in surface solar radiation at many stations worldwide (Wild et al., 2005). The corresponding increase in solar radiation by 0.10% per year from 1983 to 2001 (Pinker et al., 2005) contributed to the observed climate warming during the past decade. According to model calculations by Brasseur and Roeckner (2005), complete improvement in air quality could lead to a decadal global average surface air temperature increase by 0.8 K on most continents and 4 K in the Arctic. Further studies by Andreae et al. (2005) and Stainforth et al. (2005) indicate that global average climate warming during this century may even surpass the highest values in the projected IPCC global warming range of 1.4–5.8 °C (Cubasch et al., 2001).

By far the preferred way to resolve the policy makers' dilemma is to lower the emissions of the greenhouse gases. However, so far, attempts in that direction have

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been grossly unsuccessful. While stabilization of CO_2 would require a 60–80% reduction in current anthropogenic CO_2 emissions, worldwide they actually increased by 2% from 2001 to 2002 (Marland et al., 2005), a trend, which probably will not change at least for the remaining 6-year term of the Kyoto protocol, further increasing the required emission restrictions. Therefore, although by far not the best solution, the usefulness of artificially enhancing earth's albedo and thereby cooling climate by adding sunlight reflecting aerosol in the stratosphere (Budyko, 1977; NAS, 1992) might again be explored and debated as a way to defuse the Catch-22 situation just presented and additionally counteract the climate forcing of growing CO_2 emissions. This can be achieved by burning S_2 or H_2S, carried into the stratosphere on balloons and by artillery guns to produce SO_2. To enhance the residence time of the material in the stratosphere and minimize the required mass, the reactants might be released, distributed over time, near the tropical upward branch of the stratospheric circulation system. In the stratosphere, chemical and micro-physical processes convert SO_2 into sub-micrometer sulfate particles. This has been observed in volcanic eruptions e.g., Mount Pinatubo in June, 1991, which injected some 10 Tg S, initially as SO_2, into the tropical stratosphere (Wilson et al., 1993; Bluth et al., 1992). In this case enhanced reflection of solar radiation to space by the particles cooled the earth's surface on average by 0.5 °C in the year following the eruption (Lacis and Mishchenko, 1995). Although climate cooling by sulfate aerosols also occurs in the troposphere (e.g., Ramaswamy et al., 2001), the great advantage of placing reflective particles in the stratosphere is their long residence time of about 1–2 years, compared to a week in the troposphere. Thus, much less sulfur, only a few percent, would be required in the stratosphere to achieve similar cooling as the tropospheric sulfate aerosol (e.g., Dickinson, 1996; Schneider, 1996; NAS, 1992; Stern, 2005). This would make it possible to reduce air pollution near the ground, improve ecological conditions and reduce the concomitant climate warming. The main issue with the albedo modification method is whether it is environmentally safe, without significant side effects.

We will next derive some useful metrics. First, a loading of 1 Tg S in the stratosphere yields a global average vertical optical depth of about 0.007 in the visible and corresponds to a global average sulfur mixing ratio of $\sim$1 nmol/mole, about six times more than the natural background (Albritton et al., 2001). Second, to derive the radiative forcing caused by the presence of 1 Tg S in the stratosphere, we adopt a simple approach based on the experience gained from the Mount Pinatubo volcanic eruption. For the Mount Pinatubo eruption, Hansen et al. (1992) calculated a radiative cooling of 4.5 W/m^2 caused by 6 Tg S, the amount of S that remained in the stratosphere as sulfate six months after the eruption from initially 10 Tg S (Bluth et al., 1992). Linear downscaling results in a sulfate climate cooling efficiency of 0.75 W/m^2 per Tg S in the stratosphere. The estimated annual cost to put 1 Tg S in the stratosphere, based on information by the NAS (1992), at that time would have been US $25 billion (NAS, 1992; Ron Nielsen, personal communication). Thus, in order to compensate for enhanced climate warming by the removal of anthropogenic aerosol (an uncertain mean value of 1.4 W/m^2, according to Crutzen and Ramanathan (2003)), a stratospheric sulfate loading of 1.9 Tg S would be required, producing an optical depth of 1.3%. This can be achieved by a continuous deployment of about 1–2 Tg S per year for a total price of US \$25–50 billion, or about \$25–50 per capita in the affluent world, for stratospheric residence times of 2 to 1 year, respectively. The cost should be compared with resulting environmental and societal benefits, such as reduced rates of sea level rise. Also, in comparison, current annual global military expenditures approach US\$1000 billion, almost half in the U.S.A. The amount of sulfur that is needed is only 2–4% of the current input of 55 Tg S/year (Stern, 2005). Although the particle sizes of the artificial aerosols are smaller than those of the volcanic aerosol, because of greater continuity of injections in the former, the radiative forcings are rather similar for effective particle radii ranging between 0.1 and 1 μm (see Table 2.4, page 27, Lacis and Mishchenko, 1995). However the smaller particles have a longer stratospheric residence time, so that less material needs to be injected to cool climate, compared to the volcanic emission case. It should be mentioned that Anderson et al. (2003a,b) state that the radiative cooling by the aerosol could be much larger than the figure of 1.4 W/m^2, derived by Crutzen and Ramanathan (2003), which is based on the assumption of constant relative humidity in the troposphere. If Anderson et al. (2003a,b) are indeed correct, the result might be a stronger climate heating from air pollution cleanup than derived above (see also Andreae et al., 2005).

To compensate for a doubling of CO_2, which causes a greenhouse warming of 4 W/m^2, the required continuous stratospheric sulfate loading would be a sizeable 5.3 Tg S, producing an optical depth of about 0.04. The Rayleigh scattering optical depth at 0.5 μm is about 0.13, so that some whitening on the sky, but also colorful sunsets and sunrises would occur. It should be noted, however, that considerable whitening of the sky is already occurring as a result of current air pollution in the continental boundary layer.

Locally, the stratospheric albedo modification scheme, even when conducted at remote tropical island sites or from ships, would be a messy operation. An alternative may be to release a S-containing gas at the earth's surface, or better from balloons, in the tropical stratosphere. A gas one might think of is COS, which may be the main source of the stratospheric sulfate layer during low activity volcanic periods (Crutzen, 1976), although this is debated (Chin and Davis, 1993). However, about 75% of the COS emitted will be taken up by plants, with unknown long-term ecological consequences, 22% is removed by reaction with OH, mostly in the troposphere, and only 5% reaches the stratosphere to produce SO_2 and sulfate particles (Chin and Davis, 1993). Consequently, releasing COS at the ground is not recommended. However, it may be possible to manufacture a special gas that is only processed photochemically in the stratosphere to yield sulfate. The compound should be non-toxic, insoluble in water, non-reactive with OH, it should have a relatively short lifetime of less than about 10 years, and should not significantly contribute to greenhouse warming, which for instance disqualifies SF_6.

The albedo modification scheme presented here has been discussed before, however, without linking opposite climate warming and improved air quality considerations. Instead of sulfur, it has also been proposed to launch reflecting small balloons or mirrors, or to add highly reflective nano-particles of other material than sulfur (Teller et al., 1997; Keith, 2000). An interesting alternative could be to release soot particles to create minor "nuclear winter" conditions. In this case earth's albedo would actually decrease, but surface temperatures would, nevertheless, decline. Only 1.7% of the mass of sulfur would be needed to effect similar cooling at the earth's surface, making the operations much cheaper and less messy. However, because soot particles absorb solar radiation very efficiently, differential solar heating of the stratosphere could change its dynamics. It would, however, also counteract stratospheric cooling by increasing CO_2 and may even prevent the formation of polar stratospheric cloud particles, a necessary condition for ozone hole formation.

Since it is likely that the greenhouse warming is substantially negated by the cooling effect of anthropogenic aerosol in the troposphere, by 25–65% according to an estimate by Crutzen and Ramanathan (2003), but possibly greater (Anderson et al., 2003a,b), air pollution regulations, in combination with continued growing emissions of CO_2, may bring the world closer than is realized to the danger described by Schneider (1996): "Supposing, a currently envisioned low probability but high consequence outcome really started to unfold in the decades ahead (for example, 5 °C warming in this century) which I would characterize as having potential catastrophic implications for ecosystems . . . Under such a scenario, we would simply have to practice geo-engineering . . ."

There are some worrying indications of potentially large climate changes: for instance the locally drastic atmospheric warming by up to 3 W/m^2 per decade in Alaska due to surface albedo decreases through tree and shrub expansion (Chapin III et al., 2005), the projected increase in surface temperatures by 2–3 K by the middle of this century in Africa even with the Kyoto protocol in force (B. Hewitson, University of Cape Town, quoted by Cherry, 2005) with great impacts on biodiversity, and potentially also the 30% slowdown in the north Atlantic overturning circulation during the past half century (Bryden et al., 2005). Given the grossly disappointing international political response to the required greenhouse gas emissions, and further considering some drastic results of recent studies (Andreae et al., 2005; Stainforth et al., 2005), research on the feasibility and environmental consequences of climate engineering of the kind presented in this paper, which might need to be deployed in future, should not be tabooed. Actually, considering the great importance of the lower stratosphere/upper troposphere (LS/UT) for the radiation balance, chemistry, and dynamics of the atmosphere, its research should anyhow be intensified. For instance, it is not well known how much of the large quantities of anthropogenic SO_2 emitted at ground level reaches the LS/UT to produce sulfate particles, what regulates temperatures, water vapour concentrations and cirrus cloud formation in the LS/UT region, and how these factors may change in response to growing CO_2 concentrations, which are already 30–40% higher than ever experienced during the past 650,000 years (Siegenthaler et al., 2005). Progress in the understanding of the complicated earth climate system is generally slow. Therefore it is recommended to intensify research in order to challenge the climate modification idea here presented, starting with model investigations and, dependent on their outcome, followed step by step by small scale atmospheric tests. Also, as natural sulfur injection experiments occur intermittently in the form of explosive volcanic eruptions, often at low latitudes, they provide excellent opportunities for model development and testing (e.g., Robock, 2000).

Researchers at the Lawrence Livermore Laboratory are so far the only ones who have modelled the stratospheric albedo modification scheme. In a first study, Govindasamy and Caldeira (2000) simulated this by reducing the solar luminosity by 1.8%, to balance future climate warming by a doubling of CO_2. Although solar radiative forcing has a different physics and spatial distribution than the infrared effects caused by CO_2, the model results indicated that the global temperature response by both perturbations at the Earth' surface and atmosphere largely cancelled out. Although these preliminary model results would be in favor a stratospheric sulfur injection operation, the required annual S inputs are large, so that the possibility of adverse environmental side effects needs to be fully researched before the countermeasure to greenhouse warming is attempted. What has to be done first, is to explore whether using a sulfur injection scheme with advanced micro-physical and radiation process descriptions will show similar model results as the simple solar luminosity adjustment scheme of Govindasamy and Caldeira (2000). Further studies, following those conducted by Govindasamy (2003), should address the biological effects of the albedo modification scheme. As already mentioned, injection of soot may be an alternative, but in need of critical analysis. Such studies by themselves, even when the experiment is never done, will be very informative.

Among possible negative side effects, those on stratospheric ozone first spring to mind. Fortunately, in this case one can build on the experience with past volcanic eruptions, such as El Chichón in 1982 and Mount Pinatubo in 1991, which injected 3–5 Tg S (Hofmann and Solomon, 1989) and 10 Tg S (Bluth et al., 1992), respectively, in the stratosphere. Local ozone destruction in the El Chichón case was about 16% at 20 km altitude at mid-latitudes (Hofmann and Solomon, 1989). For Mount Pinatubo, global column ozone loss was about 2.5% (Kinnison et al., 1994). For the climate engineering experiment, in which the cooling effect of all tropospheric anthropogenic aerosol is removed, yielding a radiative heating of 1.4 W/m^2 (Crutzen and Ramanathan, 2003), a stratospheric loading of almost 2 Tg S, and an input of 1–2 Tg S/yr is required, depending on stratospheric residence times. In this case, stratospheric sulfate injections would be 5 times less than after the Mount Pinatubo eruption, leading to much smaller production of ozone-destroying Cl and ClO radicals, whose formation depends on particle surface-catalyzed heterogeneous reactions (Wilson, 1993). Compensating for a CO_2 doubling would lead to larger ozone loss but not as large as after Mount Pinatubo. Furthermore, the amounts of stratospheric chlorine radicals, coming from past production of the chloro-fluoro-carbon gases, are now declining by international regulation, so that ozone will significantly recover by the middle of this century. If instead of SO_2, elemental carbon would be injected in the stratosphere, higher temperatures might prevent the formation of polar stratospheric ice particles and thereby hinder the formation of ozone holes. This and the consequences of soot deposition on polar glaciers should be checked by model calculations.

In contrast to the slowly developing effects of greenhouse warming associated with anthropogenic CO_2 emissions, the climatic response of the albedo enhancement experiment would start taking effect within about half a year, as demonstrated by the Mount Pinatubo eruption (Hansen et al., 1992). Thus, provided the technology to carry out the stratospheric injection experiment is in place, as an escape route against strongly increasing temperatures, the albedo adjustment scheme can become effective at rather short notice, for instance if climate heats up by more than 2 °C globally or when the rates of temperatures increase by more than 0.2 °C/decade), i.e. outside the so-called "tolerable window" for climate warming (e.g., Bruckner and Schellnhuber, 1999). Taking into account the warming of climate by up to 1 °C by air pollution reduction (Brasseur and Roeckner, 2005), the tolerable window for greenhouse gas emissions might be as low as 1 °C, not even counting positive biological feedbacks. As mentioned before, regionally more rapid climate changes are already happening in the Arctic (Chapin et al., 2005) or are in petto for Africa (Cherry, 2005). Already major species extinctions by current climate warming have been reported by Pounds et al. (2005) and Root et al. (2003). If sizeable reductions in greenhouse gas emissions will not happen and temperatures rise rapidly, then climatic engineering, such as presented here, is the only option available to rapidly reduce temperature rises and counteract other climatic effects. Such a modification could also be stopped on short notice, if undesirable and unforeseen side effects become apparent, which would allow the atmosphere to return to its prior state within a few years. There is, therefore, a strong need to estimate negative, as well as positive, side effects of the proposed stratospheric modification schemes. If positive effects are greater than the negative effects, serious consideration should be given to the albedo modification scheme.

Nevertheless, again I must stress here that the albedo enhancement scheme should only be deployed when there are proven net advantages and in particular when rapid climate warming is developing, paradoxically, in part due to improvements in worldwide air quality. Importantly, its possibility should not be used to justify inadequate climate policies, but merely to create a possibility to combat potentially drastic climate heating (e.g. Andreae et al., 2005; Stainforth et al., 2005; Crutzen and Ramanathan, 2003; Anderson et al., 2003a,b). The chances of unexpected climate effects should not be underrated, as clearly shown by the sudden and unpredicted development of the antarctic ozone hole. Current CO_2 concentrations are already 30–40% larger than at any time during the past 650,000 years (Siegenthaler et al., 2005). Climate heating is known to be particularly strong in arctic regions (Chapin et al., 2005), which may trigger accelerated CO_2 and

CH_4 emissions in a positive feedback mode. Earth system is increasingly in the non-analogue condition of the Anthropocene.

Reductions in CO_2 and other greenhouse gas emissions are clearly the main priorities (Socolow et al., 2004; Lovins, 2005). However, this is a decades-long process and so far there is little reason to be optimistic. There is in fact a serious additional issue. Should the proposed solutions to limit CO_2 emissions prove unsuccessful and should CO_2 concentrations rise to high levels with risk of acidification of the upper ocean waters, leading to dissolution of calcifying organisms (Royal Society, 2005; Orr et al., 2005), underground CO_2 sequestration (Lackner, 2003), if proven globally significant, will be needed to bring down atmospheric CO_2 concentrations. However, that kind of sequestration does not allow for rapid remedial response. Reforestation could do so, but has its own problems. A combination of efforts may thus be called for, including the stratospheric albedo enhancement scheme.

In conclusion: The first modelling results and the arguments presented in this paper call for active scientific research of the kind of geo-engineering, discussed in this paper. The issue has come to the forefront, because of the dilemma facing international policy makers, who are confronted with the task to clean up air pollution, while simultaneously keeping global climate warming under control. Scientific, legal, ethical, and societal issues, regarding the climate modification scheme are many (Jamieson, 1996; Bodansky, 1996). Building trust between scientists and the general public would be needed to make such a large-scale climate modification acceptable, even if it would be judged to be advantageous. Finally, I repeat: the very best would be if emissions of the greenhouse gases could be reduced so much that the stratospheric sulfur release experiment would not need to take place. Currently, this looks like a pious wish.

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Benefits, risks, and costs of stratospheric geoengineering

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[1] 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. **Citation:** Robock, A., A. Marquardt, B. Kravitz, and G. Stenchikov (2009), Benefits, risks, and costs of stratospheric geoengineering, *Geophys. Res. Lett.*, *36*, L19703, doi:10.1029/2009GL039209.

1. Introduction

[2] Global warming will continue for decades due to anthropogenic emissions of greenhouse gases and aerosols [*Intergovernmental Panel on Climate Change* (*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] and *Rasch et al.* [2008a] 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.

[3] 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.

[4] *Crutzen* [2006], *Wigley* [2006], and others who have suggested that geoengineering be considered as a response to global warming have emphasized that mitigation is the preferable response and that geoengineering should only be considered should the planet face a climate change emergency. However, there are no international governance mechanisms or standards that would allow the determination of such an emergency. Furthermore, should geoengineering begin, it would have to continue for decades, and the decision to stop would be even more difficult, what with commercial and employment interests in continuing the project as well as concerns for the additional warming that would result.

[5] *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

[6] 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, 1999, 2002; *Govindasamy and Caldeira*, 2000; *Govindasamy*

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Table 1. Benefits and Risks of Stratospheric Geoengineering[a]

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?

[a]The right column is an update of *Robock* [2008a].

et al., 2002, 2003; *Wigley*, 2006; *Rasch et al.*, 2008a, 2008b; *Robock et al.*, 2008; *Lenton and Vaughan*, 2009] show that with sufficient stratospheric sulfate aerosol loading, back-scattered 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.

[7] 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

[8] 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).

[9] 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.

[10] 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

[11] *Robock* [2008a] suggested that the construction and operation of a 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 and 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.* [2008a]. 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

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

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.

[12] 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.

[13] 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

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

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

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

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

a.

b.

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).

required to stop global warming or even reduce global temperature in spite of continued greenhouse gas emissions.

[14] 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" [*Agency for Toxic Substances and Disease Registry*, 1998].

[15] 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.*, 2008a]. 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.

[16] Our work is an update and expansion of the first quantitative estimates by *Committee on Science Engineering and Public Policy* (*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.

[17] 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]. A 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.

[18] 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

[19] 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.

[20] 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.

[21] 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.

[22] 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.

[23] 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 [*McClelland et al.*, 1989]. 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.

[24] 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 (F-15 Eagle, Air Force Link Factsheets, 2008, available at http://www.af.mil/information/factsheets/factsheet.asp?id=101) for the F-15C ($29.9 million), Air Mobility Command (KC-10 Extender, Air Force Link Factsheets, 2008, available at http://www.af.mil/information/factsheets/factsheet.asp?id=109) for the KC-10 ($88.4 million), and Air Mobility Command (KC-135 Stratotanker, Air Force Link Factsheets, 2008, available at http://www.af.mil/information/factsheets/factsheet.asp?id=110) for the KC-135 ($39.6 million), in 1998 dollars, and in Table 2 is then converted to 2008 dollars (latest data available) by multiplying by a factor of 1.32 using the Consumer Price Index (S. H. Williamson, Six ways to compute the relative value of a U.S. dollar amount, 1774 to present, MeasuringWorth, 2008, available at http://www.measuringworth.com/uscompare/). 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].

[25] 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

[26] *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

[27] 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.

[28] 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,

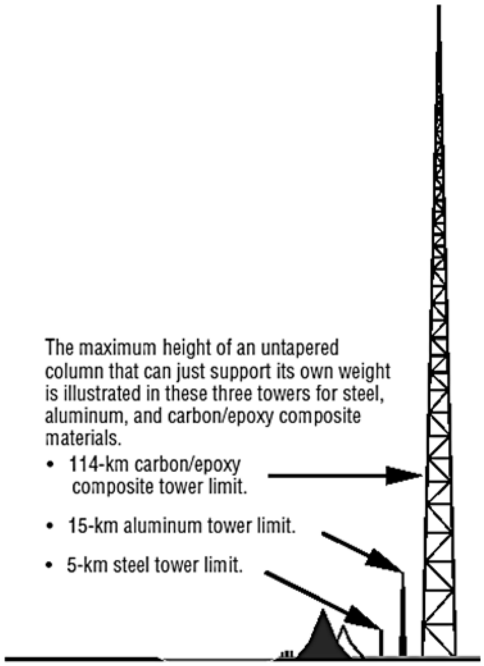

Figure 3. The maximum height of an untapered tower that can support its own weight, showing that one tower on the Equator could be used for stratospheric geoengineering. (From "Space Elevator Schematics" page at end of *Smitherman* [2000]).

but in the second case, when the balloons burst, the H_2S would be released into the stratosphere.

[29] *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.

[30] 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.

[31] 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:

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

The mass of air displaced would be:

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

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 $5.5 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.

[32] 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.

[33] 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."

[34] 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

[35] 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.

4.4.1. Tall Tower

[36] 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.

[37] 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. Only one tower would be needed if the hoses were large enough to pump the required amount of gas, but one or two additional backup systems would be needed if the planet were to depend on this to prevent climate emergencies. 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.)

4.4.2. Space Elevator

[38] 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

[39] 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 potential 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.

[40] 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."

[41] Table 1 gives a list of the potential benefits and problems with stratospheric geoengineering. But for society to make a decision as to whether to 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?

[42] 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.

[43] As already pointed out by *Robock* [2008b] and the *American Meteorological Society* [2009], 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.

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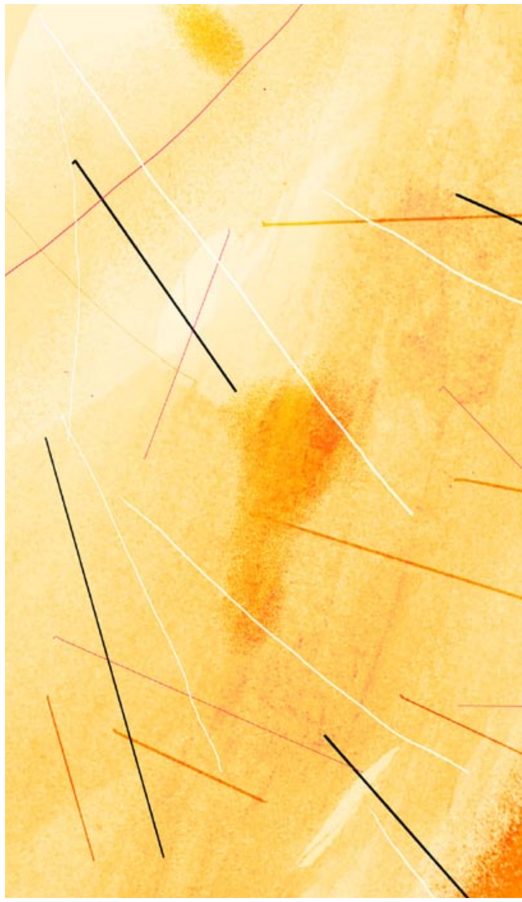
20 reasons why geoengineering may be a bad idea

Carbon dioxide emissions are rising so fast that some scientists are seriously considering putting Earth on life support as a last resort. But is this cure worse than the disease?

BY ALAN ROBOCK



JON HAN

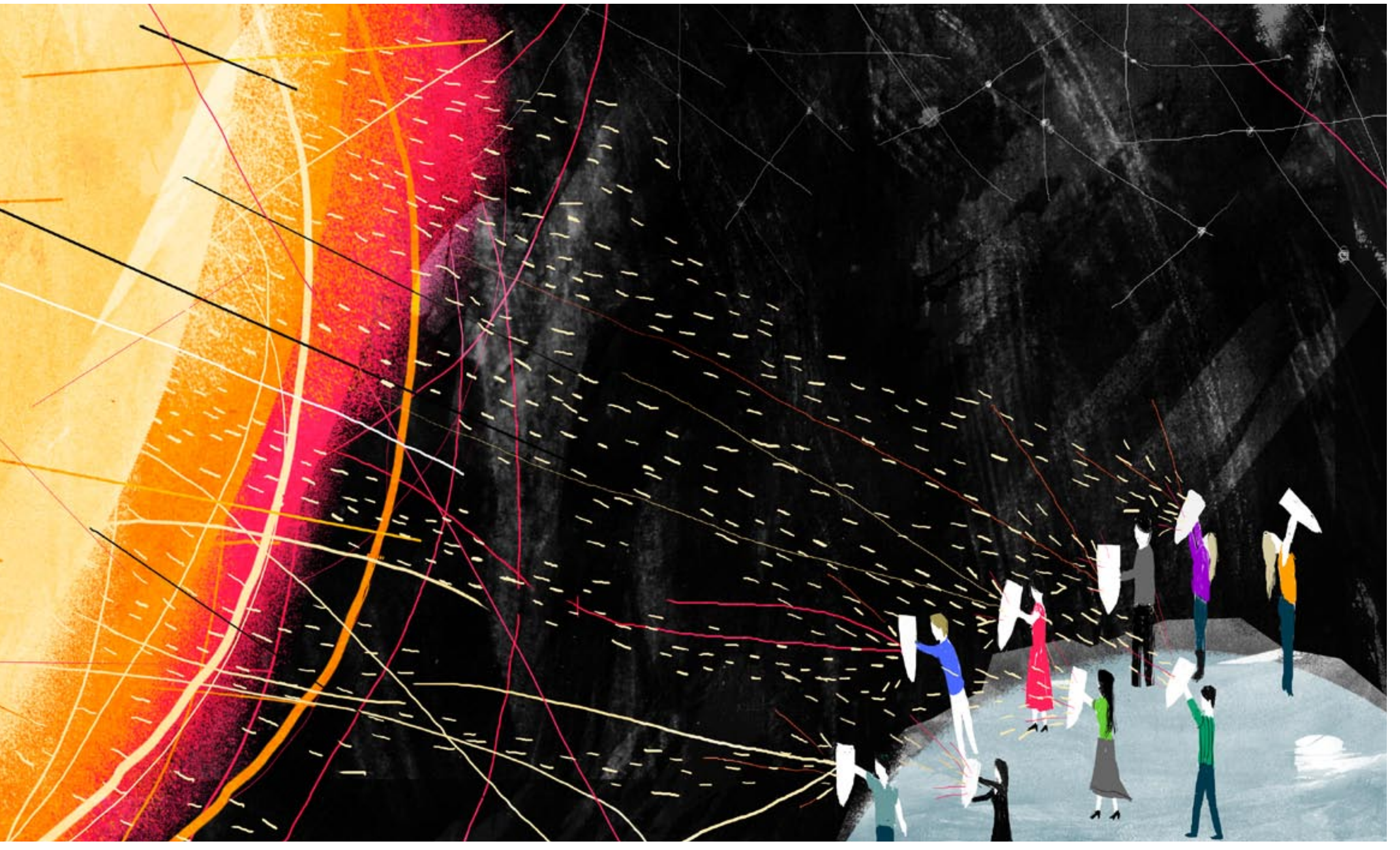
THE STATED OBJECTIVE OF THE 1992 U.N. Framework Convention on Climate Change is to stabilize greenhouse gas concentrations in the atmosphere "at a level that would prevent dangerous anthropogenic interference with the climate system." Though the framework convention did not define "dangerous," that level is now generally considered to be about 450 parts per million (ppm) of carbon dioxide in the atmosphere; the current concentration is about 385 ppm, up from 280 ppm before the Industrial Revolution.

In light of society's failure to act concertedly to deal with global warming in spite of the framework convention agreement, two prominent atmospheric scientists recently suggested that humans consider geoengineering—in this case, deliberate modification of the climate to achieve specific effects such as cooling—to address global warming. Nobel laureate Paul Crutzen, who is well regarded for his work on ozone damage and nuclear winter, spearheaded a special August 2006 issue of *Climatic Change* with a controversial editorial about injecting sulfate aerosols into the stratosphere as a means to block sunlight and cool Earth. Another respected climate scientist, Tom Wigley, followed up with a feasibility study in *Science* that advocated the same approach in combination with emissions reduction.[1]

The idea of geoengineering traces its genesis to military strategy during the early years of the Cold War, when scientists in the United States and the Soviet Union devoted considerable funds and research efforts to controlling the weather. Some early geoengineering theories involved damming the Strait of Gibraltar and the Bering Strait as a way to *warm* the Arctic, making Siberia more habitable.[2] Since scientists became aware of rising concentrations of atmospheric carbon dioxide, however, some have proposed artificially altering climate and weather patterns to reverse or mask the effects of global warming.

Some geoengineering schemes aim to remove carbon dioxide from the atmosphere, through natural or mechanical means. Ocean fertilization, where iron dust is dumped into the open ocean to trigger algal blooms; genetic modification of crops to increase biotic carbon uptake; carbon capture and storage techniques such as those proposed to outfit coal plants; and planting forests are such examples. Other schemes involve blocking or reflecting incoming solar radiation, for example by spraying seawater hundreds of meters into the air to seed the formation of stratocumulus clouds over the subtropical ocean.[3]

Two strategies to reduce incoming solar radiation—stratospheric aerosol injection as proposed by Crutzen and space-based sun shields (i.e., mirrors or shades placed in orbit between the sun and Earth)—are among the most widely discussed geoengineering schemes in scientific circles. While these schemes (if they could be built) would cool Earth, they might also have adverse consequences. Several papers in the August 2006 *Climatic Change* discussed some of these issues, but here I present a fairly comprehensive list of reasons why geoengineering might be a bad idea, first written down during a two-day NASA-



sponsored conference on Managing Solar Radiation (a rather audacious title) in November 2006.[4] These concerns address unknowns in climate system response; effects on human quality of life; and the political, ethical, and moral issues raised.

1. Effects on regional climate. Geoengineering proponents often suggest that volcanic eruptions are an innocuous natural analog for stratospheric injection of sulfate aerosols. The 1991 eruption of Mount Pinatubo on the Philippine island of Luzon, which injected 20 megatons of sulfur dioxide gas into the stratosphere, produced a sulfate aerosol cloud that is said to have caused global cooling for a couple of years without adverse effects. However, researchers at the National Center for Atmospheric Research showed in 2007 that the Pinatubo eruption caused large hydrological responses, including reduced precipitation, soil moisture, and river flow in many regions.[5] Simulations of the climate response to volcanic eruptions have also shown large impacts on regional climate, but whether these are good analogs for the geoengineering response requires further investigation.

Scientists have also seen volcanic eruptions in the tropics produce changes in atmospheric circulation, causing winter warming over continents in the Northern Hemisphere, as well as eruptions at high latitudes weaken the Asian and African monsoons, causing reduced precipitation.[6] In fact, the eight-month-long eruption of the Laki fissure in Iceland in 1783–1784 contributed to famine in Africa, India, and Japan.

If scientists and engineers were able to inject smaller amounts of stratospheric aerosols than result from volcanic eruptions, how would they affect summer wind and precipitation patterns? Could attempts to geoengineer isolated regions (say, the Arctic) be confined there? Scientists need to investigate these scenarios. At the fall 2007 American Geophysical Union meeting, researchers presented preliminary findings from several different climate models that simulated geoengineering schemes and found that they reduced precipitation over wide regions, condemning hundreds of millions of people to drought.

2. Continued ocean acidification. If humans adopted geoengineering as a solution to global warming, with no restriction on continued carbon emissions, the ocean would continue to become more acidic, because about half of all excess carbon dioxide in the atmosphere is removed by ocean uptake. The ocean is already 30 percent more acidic than it was before the Industrial Revolution, and continued acidification threatens the entire oceanic biological chain, from coral reefs right up to humans.[7]

3. Ozone depletion. Aerosol particles in the stratosphere serve as surfaces for chemical reactions that destroy ozone in the same way that water and nitric acid aerosols in polar stratospheric clouds produce the seasonal Antarctic ozone hole.[8] For the next four decades or so, when the concentration of anthropogenic ozone-depleting substances will still be large enough in the stratosphere

CAPITALIZING ON CARBON

Without market incentives, geoengineering schemes to reflect solar heat are still largely confined to creative thought and artists' renderings. But a few ambitious entrepreneurs have begun to experiment with privatizing climate mitigation through carbon sequestration. Here are a few companies in the market to offset your carbon footprint:

California-based technology startups Planktos and Climos are perhaps the most prominent groups offering to sell carbon offsets in exchange for performing ocean iron fertilization, which induces blooms of carbon-eating phytoplankton. Funding for Planktos dried up in early 2008 as scientists grew increasingly skeptical about the technique, but Climos has managed to press on, securing $3.5 million in funding from Braemar Energy Ventures as of February.

Also in the research and development phase is Sydney, Australia–based Ocean Nourishment Corporation, which similarly aims to induce oceanic photosynthesis, only it fertilizes with nitrogen-rich urea instead of iron. Atmocean, based in Santa Fe, New Mexico, takes a slightly different tack: It's developed a 200-meter deep, wave-powered pump that brings colder, more biota-rich water up to the surface where lifeforms such as tiny, tube-like salps sequester carbon as they feed on algae.

Related in mission if not in name, stationary carbon-capture technologies, which generally aren't considered geoengineering, are nonetheless equally inventive: Skyonic, a Texas-based startup, captures carbon dioxide at power plants (a relatively well-proven technology) and mixes it with sodium hydroxide to render high-grade baking soda. A pilot version of the system is operating at the Brown Stream Electric Station in Fairfield, Texas. To the west in Tucson, Arizona, Global Research Technologies, the only company in the world dedicated to carbon capture from ambient air, recently demonstrated a working "air extraction" prototype—a kind of carbon dioxide vacuum that stands upright and is about the size of a phone booth. Meanwhile, GreenFuel Technologies Corporation, in collaboration with Arizona Public Service Company, is recycling carbon dioxide emissions from power plants by using it to grow biofuel stock in the form of—what else?—algae. KIRSTEN JERCH

to produce this effect, additional aerosols from geoengineering would destroy even more ozone and increase damaging ultraviolet flux to Earth's surface.

4. Effects on plants. Sunlight scatters as it passes through stratospheric aerosols, reducing direct solar radiation and increasing diffuse radiation, with important biological consequences. Some studies, including one that measured this effect in trees following the Mount Pinatubo eruption, suggest that diffuse radiation allows plant canopies to photosynthesize more efficiently, thus increasing their capacity as a carbon sink.[9] At the same time, inserting aerosols or reflective disks into the atmosphere would reduce the total sunlight to reach Earth's surface. Scientists need to assess the impacts on crops and natural vegetation of reductions in total, diffuse, and direct solar radiation.

5. More acid deposition. If sulfate is injected regularly into the stratosphere, no matter where on Earth, acid deposition will increase as the material passes through the troposphere—the atmospheric layer closest to Earth's surface. In 1977, Russian climatologist Mikhail Budyko calculated that the additional acidity caused by sulfate injections would be negligibly greater than levels that resulted from air pollution.[10] But the relevant quantity is the *total* amount of acid that reaches the ground, including both wet (acid rain, snow, and fog) and dry deposition (acidic gases and particles). Any additional acid deposition would harm the ecosystem, and it will be important to understand the consequences of exceeding different biological thresholds. Furthermore, more acidic particles in the troposphere would affect public health. The effect may not be large compared to the impact of pollution in urban areas, but in pristine areas it could be significant.

6. Effects of cirrus clouds. As aerosol particles injected into the stratosphere fall to Earth, they may seed cirrus cloud formations in the troposphere.[11] Cirrus clouds affect Earth's radiative balance of incoming and outgoing heat, although the amplitude and even direction of the effects are not well understood. While evidence exists that some volcanic aerosols form cirrus clouds, the global effect has not been quantified.[12]

7. Whitening of the sky (but nice sunsets). Atmospheric aerosols close to the size of the wavelength of light produce a white, cloudy appearance to the sky. They also contribute to colorful sunsets, similar to those that occur after volcanic eruptions. The red and yellow sky in *The Scream* by Edvard Munch was inspired by the brilliant sunsets he witnessed over Oslo in 1883, following the eruption of Krakatau in Indonesia.[13] Both the disappearance of blue skies and the appearance of red sunsets could have strong psychological impacts on humanity.

8. Less sun for solar power. Scientists estimate that as little as a 1.8 percent reduction in incoming solar radiation would compensate for a doubling of atmospheric carbon dioxide. Even this small reduction would significantly affect the radiation available for solar power systems—one of the prime alternate methods of generating clean energy—as the response of different solar power systems to total available sunlight is not linear. This is especially true for some of the most efficiently designed systems that reflect or focus direct solar radiation on one location for direct heating.[14] Following the Mount Pinatubo eruption and the 1982 eruption of El Chichón in Mexico, scientists observed a direct solar radiation decrease of 25–35 percent.[15]

9. Environmental impacts of implementation. Any system that could inject aerosols into the stratosphere, i.e., commercial jetliners with sulfur mixed into their fuel, 16-inch naval rifles firing 1-ton shells of dust vertically into the air, or hoses suspended from stratospheric balloons, would cause enormous environmental damage. The same could be said for systems that would deploy sun shields. University of Arizona astronomer Roger P. Angel has proposed putting a fleet of 2-foot-wide reflective disks in a stable orbit between Earth and the sun that would bend sunlight away from Earth.[16] But to get the needed *trillions* of disks into space, engineers would need 20 electromagnetic launchers to fire missiles with stacks of 800,000 disks every five minutes for twenty years. What would be the atmospheric effects of the resulting sound and gravity waves? Who would want to live nearby?

10. Rapid warming if deployment stops. A technological, societal, or political crisis could halt a project of stratospheric aerosol injection in mid-deployment. Such an abrupt shift would result in rapid climate warming, which would produce much more stress on society and ecosystems than gradual global warming.[17]

11. There's no going back. We don't know how quickly scientists and engineers could shut down a geoengineering system—or stem its effects—in the event of excessive climate cooling from large volcanic eruptions or other causes. Once we put aerosols into the atmosphere, we cannot remove them.

12. Human error. Complex mechanical systems never work perfectly. Humans can make mistakes in the design, manufacturing, and operation of such systems. (Think of Chernobyl, the *Exxon Valdez*, airplane crashes, and friendly fire on the battlefield.) Should we stake the future of Earth on a much more complicated arrangement than these, built by the lowest bidder?

13. Undermining emissions mitigation. If humans perceive an easy technological fix to global warming that allows for "business as usual," gathering the national (particularly in the United States and China) and international will to change consumption patterns and energy infrastructure will be even more difficult.[18] This is the oldest and most persistent argument against geoengineering.

14. Cost. Advocates casually claim that it would not be too expensive to implement geoengineering solutions, but there have been no definitive cost studies, and estimates of large-scale government projects are almost always too low. (Boston's "Big Dig" to reroute an interstate highway under the coastal city, one of humankind's greatest engineering feats, is only one example that was years overdue and billions over budget.) Angel estimates that his scheme to launch reflective disks into orbit would cost "a few trillion dollars." British economist Nicholas Stern's calculation of the cost of climate change as a percentage of global GDP (roughly $9 trillion) is in the same ballpark; Angel's estimate is also orders of magnitude greater than current global investment in renewable energy technology. Wouldn't it be a safer and wiser investment for society to instead put that money in solar power, wind power, energy efficiency, and carbon sequestration?

15. Commercial control of technology. Who would end up controlling geoengineering systems? Governments? Private companies holding patents on proprietary technology? And whose benefit would they have at heart? These systems could pose issues analogous to those raised by pharmaceutical companies and energy conglomerates whose products ostensibly serve the public, but who often value shareholder profits over the public good.

16. Military use of the technology. The United States has a long history of trying to modify weather for military purposes, including inducing rain during the Vietnam War to swamp North Vietnamese supply lines and disrupt antiwar protests by Buddhist monks.[19] Eighty-five countries, including the United States, have signed the U.N. Convention on the Prohibition of Military or Any Other Hostile Use of Environmental Modification Techniques (ENMOD), but could techniques developed to control global climate forever be limited to peaceful uses?

17. Conflicts with current treaties. The terms of ENMOD explicitly prohibit "military or any other hostile use of environmental modification techniques having widespread, long-lasting or severe effects as the means of destruction, damage, or injury to any other State Party." Any geoengineering scheme that adversely affects regional climate, for example, producing warming or drought, would therefore violate ENMOD.

18. Control of the thermostat. Even if scientists could predict the behavior and environmental effects of a given geoengineering project, and political leaders could muster the public support and funding to implement it, how would the world agree on the optimal climate? What if Russia wants it a couple of degrees warmer, and India a couple of degrees cooler? Should global climate be reset to preindustrial temperature or kept constant at today's reading? Would it be possible to tailor the climate of each region of the planet independently without affecting the others? If we proceed with geoengineering, will we provoke future climate wars?

19. Questions of moral authority. Ongoing global warming is the result of inadvertent climate modification. Humans emit carbon dioxide and other greenhouse gases to heat and cool their homes; to grow, transport, and cook their food; to run their factories; and to travel—not intentionally, but as a by-product of fossil fuel combustion. But now that humans are aware of their effect on climate, do they have a moral right to continue emitting greenhouse gases? Similarly, since scientists know that stratospheric aerosol injection, for example, might impact the ecosphere, do humans have a right to plow ahead regardless? There's no global agency to require an environmental impact statement for geoengineering. So, how should humans judge how much climate control they may try?

20. Unexpected consequences. Scientists cannot possibly account for all of the complex climate interactions or predict all of the impacts of geoengineering. Climate models are improving, but scientists are discovering that climate is changing more rapidly than they predicted, for example, the surprising and unprecedented extent to which Arctic sea ice melted during the summer of 2007. Scientists may never have enough confidence that their theories will predict how well geoengineering systems can work. With so much at stake, there is reason to worry about what we don't know.

The reasons why geoengineering may be a bad idea are manifold, though a moderate investment in *theoretical* geoengineering research might help scientists to determine whether or not it *is* a bad idea. Still, it's a slippery slope: I wouldn't advocate actual small-scale stratospheric experiments unless comprehensive climate modeling results could first show that we could avoid at least all of the potential consequences we *know* about. Due to the inherent natural variability of the climate system, this task is not trivial. After that there are still the unknowns, such as the long-term effects of short-term experiments—stratospheric aerosols have an atmospheric lifetime of a couple years.

Solving global warming is not a difficult technical problem. As Stephen Pacala and Robert Socolow detail with their popular wedge model, a combination of several specific actions can stabilize the world's greenhouse gas emissions—although I disagree with their proposal to use nuclear power as one of their "wedges."[20] Instead, the crux of addressing global warming is political. The U.S. government gives multibillion-dollar subsidies to the coal, oil, gas, and nuclear industries, and gives little support to alternative energy sources like solar and wind power that could contribute to a solution. Similarly, the federal government is squashing attempts by states to mandate emissions reductions. If global warming is a political problem more than it is a technical problem, it follows that we don't need geoengineering to solve it.

The U.N. Framework Convention on Climate Change defines "dangerous anthropogenic interference" as *inadvertent* climate effects. However, states must also carefully consider geoengineering in their pledge to prevent dangerous anthropogenic interference with the climate system. ■

FOR NOTES, PLEASE SEE P. 59.

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AN ETHICAL ASSESSMENT OF GEOENGINEERING

While there are many questions about the feasibility, cost, and effectiveness of geoengineering plans, my colleague Alan Robock has been the most systematic and persistent of a number of scientists in raising ethical quandaries about the enterprise. But just how serious are these ethical quandaries?

Most science poses risks of unintended consequences, and lots of science raises issues of commercial and military control. At issue here is whether there is any reason to believe *ex ante* that these are special or unusually large risks. Merely asserting them does not ground an objection *per se*.

Not all of Robock's concerns involve ethics, but of those that do, some involve issues of procedural justice (such as who decides) while others involve matters of distributive justice (such as uneven benefit and harm). To simplify things, let's assume that injecting aerosols into the stratosphere successfully cooled Earth without any untoward effects and with evenly distributed benefits. One might still object that there are issues of procedural justice involved—who decides and who controls. But such concerns don't get much traction when everyone benefits.

Let's pull back from this idealization to imagine an outcome that involves untoward consequences and an uneven distribution of benefits. We deal with consequences by balancing them against the benefits of our interventions. The issue is whether or not we can obtain reliable estimates of both risks and benefits without full-scale implementation of the planned intervention. We already know from modeling that the impact of any such intervention will be uneven, but again, without knowing what the distribution of benefit and harm would be, it's hard to estimate how much this matters. Let's differentiate two circumstances under which going ahead with the intervention might be judged: One is where everyone benefits, while the other is a circumstance in which something less is the case. A conservative conclusion would be to say that beyond modeling and controlled, low-level tests (if the modeling justifies it), we shouldn't sanction any large-scale interventions unless they are in everyone's interest. A slightly eased condition, proposed by the philosopher Dale Jamieson, would be that at least nobody is worse off. That may not be as farfetched a condition as one might think, since, in the end, we are considering this intervention as a means to balance a risk we all face—global warming.

But suppose there are isolated livelihoods that only suffer negative effects of geoengineering. Then numbers begin to matter. In the case that a geoengineering scheme were to harm the few, we should have the foresight to be able to compensate, even if doing so requires something as drastic as relocating populations. I don't mean to oversimplify a complicated issue, but objection to any negative consequences whatsoever isn't a strong enough argument to end discussion.

More trenchant is the worry that the mere possibility of geoengineering would undermine other efforts to decrease our carbon output. Such moral hazard is a familiar worry, and we don't let it stop us in other areas: Antilock braking systems and airbags may cause some to drive more recklessly, but few would let that argument outweigh the overwhelming benefits of such safety features.

As Robock correctly asserts, the crux of addressing global warming may be a political—not a scientific—problem, but it doesn't follow that we may not need geoengineering to solve it. If it is a political problem, it is a *global* political problem, and getting global agreement to curb greenhouse gases is easier said than done.

With geoengineering, in principle, one nation or agent could act, but a challenge arises if the intervention is certain to have uneven impacts among nations. At this early stage, there is no cost associated with improving our ability to quantify and describe what those inequalities would look like. Once we have those answers in hand, then we can engage in serious ethical consideration over whether or not to act. MARTIN BUNZL

Martin Bunzl is a professor of philosophy at Rutgers University.

NOTES

20 reasons why geoengineering may be a bad idea

CONTINUED FROM P. 18

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Climate change and security

CONTINUED FROM P. 24

1. Climate Change 2007: Summary for Policy Makers. Contribution of Working Group II to the Fourth Assessment Report of the

COMMENTARY

Geoengineering: The good, the MAD, and the sensible

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After the collapse of international climate policy in Copenhagen in December 2009, the tale of geoengineering, promising end-of-the-chimney fixes for anthropogenic global warming, has become increasingly popular (1). This is essentially a tale of two fairies (2): the rather wicked one conjures up solar radiation management (SRM), and the tolerably good one delivers CO_2 removal through schemes like industrial "air capture" (IAC). Unfortunately, a study by House et al. (3) pours lots of cold water on the hot IAC stuff. Most notably, the authors maintain that the total systems costs of IAC (factoring in all pertinent processes, materials, and structures) might well be on the order of $1,000 (US$) per ton CO_2 extracted from the atmosphere. This is tantamount to forecasting a financial tsunami: for making a tangible contribution to global warming [and ocean acidification (4)] reduction, several Gt CO_2 should be "scrubbed" every year in the last third of the 21st century (see below), thus generating a multitrillion-dollar IAC bill.

House et al. arrive at their important cost estimate by blending existing bits of scientific and technical information into a convincing common-sense analysis. The take-home message is that the energetic and economic challenges of IAC systems design and implementation have probably been underestimated by previous studies promoting that climate-fix option (5–7). The House et al. argument rests on five cognitive pillars, namely (*i*) an evaluation of the pertinent Sherwood-plot approach to dilute streams (8); (*ii*) a realistic thermodynamic efficiency assessment of the processes involved in IAC; (*iii*) a rough quantification of the power costs for IAC, which can achieve significant carbon negativity only by tapping nonfossil energy sources; (*iv*) an analogy assessment of the work required for chemical removal of trace gases from mixed streams, exploiting rich empirical data available for SO_2 and NO_x handling; and (*v*) a careful discussion of the design options for large-scale IAC installations, reconciling competing physical and chemical constraints.

The last aspect is related to the gigantic volumes of air that need to be processed swiftly through the scrubber plants, where the ambient CO_2 contacts appropriate solvents or sorbents. This, in turn, confirms an intuitive skepticism about IAC schemes prevalent among experts with formal training in statistical physics: you need to work hard to beat entropy growth within a given subspace of the universe. So it seems rather odd to first burn fossil fuels (where the ambient carbon was captured, reduced, and concentrated by biogeochemical processes over hundred millions of years), then let the oxidized carbon mix and migrate across the entire atmosphere, and finally distill the CO_2 again molecule by molecule using sophisticated technology. There is no free energy lunch…

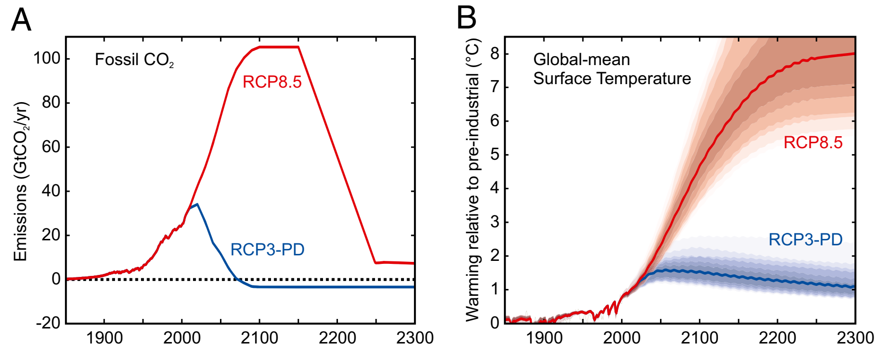

Fig. 1. Thrust Reversal or Reacceleration? Comparison of an emissions scenario compatible with the 2 °C objective (RCP3-PD, blue) and a more-business-than-usual scenario (RCP8.5, red). (*A*) Respective fossil CO_2 release. Note that the annual CO_2 emissions drop to −3.4 Gt by 2100 in the strong mitigation case. (*B*) Resulting likelihood fans for global mean temperature rise. With kind permission from Springer Science + Business Media: Climate Change, The RCP greenhouse gas concentrations and their extensions from 1765 to 2300, 109 (2011) 233, Malte Meinshausen, Figure 6.

This is a most inconvenient truth for climate protection. Fig. 1 highlights the crucial choice that humankind has to make about its collective radiative forcing (9): if CO_2 emissions shrink according to an aggressive worldwide mitigation strategy ("Thrust Reversal"), then there is a good chance of keeping planetary mean surface temperature increase below the 2 °C guardrail (10, 11) as adopted by more than 190 nations in 2010 (12). Note, however, that this strategy not only foresees a complete phase-out of CO_2 emissions by 2070, but also the establishment of *negative* fluxes of CO_2 afterward.

The extreme alternative ("Reacceleration") is the total shirking of climate responsibility by a world economy fixated on material growth: the plentiful fossil energy resources still in the ground (such as tar sands, shale oil and gas, and—most importantly—coal) are tapped despite the inexorably soaring production costs (13), atmospheric CO_2 concentration approaches the 2,000-ppm level, and global mean temperature rises by up to 8 °C by 2300. Never mind where the civilization jet will eventually crash.

Very few people who accept the insights of state-of-the-art climate science find the Reacceleration scenario and its dire consequences acceptable. However, it is not unlikely that the myopic market forces will drive the extraction process further and further. Therefore, the last best hope may reside in an environmental fix engineered independently of energy systems transformations, namely radiation management that cools down the planet (or, at least, large parts of it). An ample literature on SRM is already available (see especially refs. 14 and 15), in which numerous schemes of varying sophistication (such as placing mirrors in outer space, deploying reflecting aerosols or metal flakes in the atmosphere, manipulating cloud cover, enhancing land albedo, or simply painting roofs white) are explored.

Some of those ideas actually originated in the scientific circles surrounding John von Neumann and Edward Teller in the 1950s (16). These two masterminds openly advocated weather-manipulation ways of winning the Cold War against the Soviet Union. A contemporary giant of science, the Nobel laureate Paul Crutzen, has rekindled the SRM debate in 2006 through an essay on stratospheric sulfur injection (17). However, he has consistently argued then and ever since that such a climate-engineering scheme would be implemented out of despair only, that is, if the

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See companion article on page 20428.

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establishment of any "conventional" climate-protection measure (like a worldwide cap-and-trade system for greenhouse gas emissions) failed. Crutzen, Carlo Rubbia (a Nobel laureate in physics and an eminent energy expert), the climate scientist Alan Robock, and I were members of a recent Pontifical Academy of Sciences panel (18) that also discussed the portfolio of potential SRM schemes. Convincing arguments were raised that radiation manipulation may be a rather bad political idea (see, e.g., ref. 19), whereas research in this field might generate important scientific insights transcending the elusive climate-fix realm (see, e.g., refs. 20 and 21).

On closer inspection, SRM exhibits MAD traits. The latter acronym stands for "mutual assured destruction," that is, the ominous doctrine of the arms race frenzy. If the climate can be influenced rather inexpensively by sending aerosol rockets to the stratosphere, then who decides when and where the buttons are pushed? Certain countries like Russia might actually welcome some warming of their territories. So would they shoot down, say, Indian or Chinese geoengineering missiles launched for stabilizing the Asian monsoon pattern or other tipping elements in the Earth system (22)? One step further up the escalation ladder, the supposed beneficiaries of climate change might deliberately increase their greenhouse gas emissions for overcompensating SRM, and so on. Additionally, the crucial point that temporal failure of artificial insolation reduction would most probably wreak havoc has been made repeatedly (23).

Although a committee recently convened by the Bipartisan Policy Center Panel in Washington, DC seems prepared to relativize some negative aspects of SRM and to call for a substantial research and development program (24), the dilemma of geoengineering does not evaporate: the (moderately) good schemes involving ambient CO_2 capture are not affordable (according to the House et al. assessment summarized above), and the (moderately) affordable schemes involving radiation manipulation are no good, so what are we going to do? The answer seems obvious and utterly sensible, namely intentionally aborting *unintended* geoengineering as resulting from careless fossil fuel use. Following are five arguments in favor of climate mitigation by industrial transformation (25).

First, you need to approach zero before you can go negative. So the decisive phase of the Thrust Reversal scenario of Fig. 1 consists of a resolute phasing-out of CO_2 in the next 5 or so decades. In a consecutive phase, net carbon extraction from the atmosphere should happen. Fortunately, CO_2 capture from concentrated biomass flue gas (26) may do this job more cost-efficiently ($150–400 per ton) than the IAC schemes proposed so far. A precondition for this, however, is the development of appropriate carbon capture and storage (CCS) schemes, which may be needed anyway as a climate-protection bridge between fossil and sustainable energy.

Second, we do know a lot already about energy-efficiency measures (27) and renewable energy systems and infrastructures (13). Technological breakthroughs that are bound to happen with enhanced research and development for IAC will equally likely become available in the former realms through a process of induced innovation (28).

Third, emission reductions will not cost the Earth. According to recent multimodel assessments, mitigation in line with the 2 °C objective would be accompanied by 1–3% aggregated losses of world gross domestic product until the end of the century (13).

Fourth, there are multiple cobenefits of climate protection by systemic decarbonization. Outdoor pollution (such as acid rain) originating from fossil fuel use keeps on destroying invaluable ecosystem services all over the world; indoor air pollution from primitive household fires fed by biomass or coal has just been linked to nearly 2 million deaths per annum (29).

Last, efficiency and renewables will achieve something that geoengineering approaches do not even care to consider: laying the foundations for a sustainable global energy supply system that (*i*) can virtually exist forever, and (*ii*) offers more equitable opportunities for the developing world than the fossil–nuclear complex.

In essence, humankind should avoid betting on the fabrication of a silver bullet for shooting climate change. Our world does not need SRM or IAC in the first place, but rather a novel way of going MAD: "mutual assured decarbonization."

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ATMOSPHERIC SCIENCE

Whither Geoengineering?

Costs, benefits, and harms associated with geoengineering must be assessed before it is used to mitigate climate change.

Alan Robock

According to the Intergovernmental Panel on Climate Change (IPCC) (*1*), global warming will soon have severe consequences for our planet. The IPCC also estimates (*2*) that mitigation would only cost ~0.1% of the global gross national product per year for the next 30 years, a price far smaller than the damage that would occur. As a potential route to mitigation, the old idea of "geoengineering" has gotten much attention in the last 2 years (*3*, *4*). On page 1201 of this issue, Tilmes *et al*. (*5*) quantify the effects of one geoengineering approach—the introduction of additional aerosols into Earth's stratosphere, akin to a volcanic eruption—on high-latitude stratospheric ozone concentrations.

A polar stratospheric cloud over McMurdo, Antarctica, on 24 August 2004. These clouds cause ozone depletion every spring because of anthropogenic chlorine in the stratosphere. The ozone hole is expected to disappear by the middle of this century, but with geoengineering, the Antarctic ozone hole would continue to form for another 30 to 70 years.

Geoengineering involves trying to reduce the amount of sunlight reaching Earth's surface to compensate for the additional long-wave infrared radiation from greenhouse gases, thereby reducing or reversing global warming (*6*). Even if it works, there are problems with this approach (*7*). If perceived to be a possible remedy for global warming, it would reduce societal pressure to reduce greenhouse gas emissions. It could reduce overall precipitation, particularly Asian and African summer monsoon rainfall, threatening the food supply of billions. It would allow continued ocean acidification, because some of the carbon dioxide humans put into the atmosphere continues to accumulate in the ocean. Weather modification could be used as a weapon (*8*), thus violating the 1977 U.N. Convention on the Prohibition of Military or Any Other Hostile Use of Environmental Modification Techniques. There would be rapid warming if geoengineering stopped suddenly. If geoengineering worked, whose hand would be on the thermostat? How could the world agree on an optimal climate?

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Nevertheless, for some schemes, the benefits may outweigh the problems, especially if used on a temporary basis. To date, only some schemes have been investigated in detail. Furthermore, proponents of geoengineering, especially the fossil fuel industry, will continue to push for its use.

Sunshades in orbit around Earth (*9*) or cloud seeding to brighten them (*10*) have been proposed, but most geoengineering ideas focus on emulating explosive volcanic eruptions by injecting SO_2 or H_2S into the stratosphere, producing a sulfuric acid cloud to scatter solar radiation back to space and cool the planet. Deciding whether this is a good idea or not requires detailed analysis of the costs, benefits, and harm to the planet that such a strategy would entail, and comparison to the same metrics for mitigation and sequestration. Given the need for rapid mitigation, these ideas need rapid and thorough investigation.

It has been suggested (*3*, *4*) that the cooling of the global climate for a couple years after large volcanic eruptions—like the 1991 Mount Pinatubo eruption—serves as an innocuous model for what humans could do by creating a permanent stratospheric aerosol layer. However, volcanic eruptions actually serve as a warning about geoengineering: They produce drought (*11*), hazy skies, much less direct solar radiation for use as solar power, and ozone depletion (*12*).

We now have an ozone hole over Antarctica every spring because the polar stratospheric clouds that form there (see the figure) serve as surfaces for heterogeneous chemistry that releases chlorine, which then catalytically destroys ozone. Polar stratospheric clouds only form when the temperature falls below ~195 K, but additional sulfate aerosols provided by geoengineering or volcanic eruptions alter these temperature restrictions and provide more surface area for the chemistry, allowing more chlorine to be activated and more ozone to be destroyed.

Advocates of geoengineering suggest that this ozone problem would not be important, because the stratospheric concentration of chlorine is slowly decreasing as a result of global environmental agreements (*13*). However, Tilmes *et al.* show that even with the projected chlorine declines, ozone depletion (and increased ultraviolet flux) would be prolonged for decades by geoengineering of the stratospheric sulfate layer. In their model, the effects would occur every spring in the Southern Hemisphere and in most springs in the warmer Northern Hemisphere. The presence of sulfate aerosols would raise the temperature needed for chlorine activation over 200 K, expanding both vertically and horizontally the regions of polar ozone depletion.

A U.S. Department of Energy white paper (*14*) in October 2001 recommended a $13 million/year national geoengineering research effort, but the paper was never released. According to the paper, "any effort to deliberately moderate or ameliorate threats that may arise or become more likely as a result of climate change should be undertaken only in extraordinary circumstances.... In view of the risk of significant consequences to society and the environment from either inaction or

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poorly understood actions, research should be initiated now to examine possible options to moderate adverse climate threats; to ensure that these options are effective, affordable, reversible and sustainable."

It is not too late to make up for lost time, but further delay must be avoided. A research program, more generously funded than that proposed in 2001, supported by the U.S. federal government with international cooperation, will allow us to compare the efficacy, costs, and consequences of the various options of responding to global warming—mitigation, sequestration, geoengineering, or doing nothing—so that an informed public can agree on the best courses of action.

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ASTRONOMY

A Blast from the Past

Echoes of light, reflections from nearby gas and dust clouds, can be used to reconstruct past astronomical events.

Andrew C. Fabian

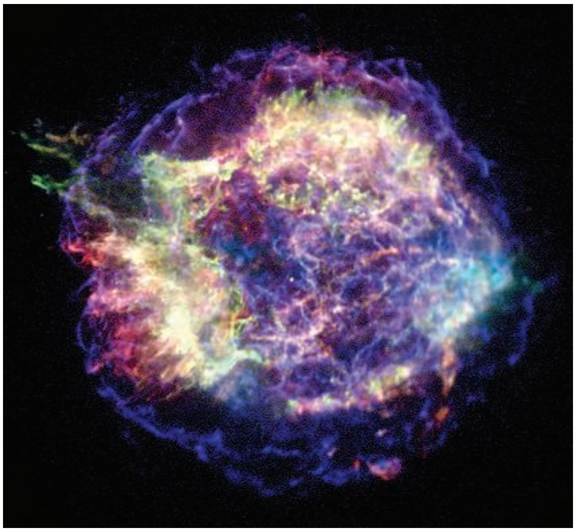
Have you ever wanted to view an event that happened many years ago? Most of the light from that event is still traveling through space and can, in principle, be reflected back to us to reconstruct the event. This is, of course, completely impractical for events that occur on a human scale, but when a star explodes as a supernova, so much light is emitted that it may be possible to see a delayed reflection from surrounding dust clouds. On page 1195 of this issue, Krause *et al*. (*1*) report their observations of a light echo for the outburst of Cassiopeia A (Cas A), which is the most recent nearby supernova known to have occurred in our Galaxy.

The remnant of Cas A was first discovered in 1947 and identified optically in 1950. From its observed expansion, it can be deduced that the explosion itself would have occurred around 1680, as viewed from Earth. A recent x-ray image of the remnant is shown in the figure.

More recently, infrared images made with the Spitzer Space Telescope revealed moving light echoes around Cas A 4 years ago (*2*). These echoes were monitored last year with the Calar Alto optical telescope in Spain, and a spectrum of a particularly bright patch was taken by the Subaru telescope in Hawaii. The echo spectrum clearly shows light from the supernova. When a star of 10 to 20 solar masses explodes, an energy equivalent to about 1% of the mass of the Sun is turned into kinetic energy of the stellar envelope, which then expands into space at velocities of 10,000 km/s or more. The spectrum shows emission and absorption lines Doppler-broadened by such large velocities. The presence of hydrogen lines in the spectrum places it in the category of a type II supernova, which results from collapse of the core of a massive star when it runs out of fuel, as was long suspected from the properties of the still-expanding remnant. The spectrum is remarkably similar to that of supernova 1993J (SN 1993J), a type IIb supernova seen (in 1993) in the nearby galaxy M81.

Light echoes also have recently been seen from SN 1993J (*3*), and from other supernovae in our satellite galaxy, the Large Magellanic Cloud (*4*), including the famous SN 1987A (*5*), which is the only supernova to have been seen with the naked eye since the invention of the telescope more than 400 years ago. Van den Bergh (*6*) in 1966 had tried to look for an echo around Cas A. However, we now know that it was much too faint to be seen with the photographic plates available at that time.

The light echo spectrum from Cas A is notable primarily because Cas A is a type IIb supernova and its remnant has been so well studied due to its proximity and youth. We can assume (*7*) that Cas A was a red giant before it exploded, and that it probably had a binary companion at some stage. The progenitor of SN 1993J was predicted to have been a member of a binary, and a massive star consistent with a companion remains at the site (*8*). There is no such stellar companion remaining at the position of Cas A, so it possibly spiraled into the progenitor some time before the explosion. A faint nonvariable pointlike x-ray source has been found (*9*) close to the center of the remnant and is probably a neutron star.



Supernova remnant. An image of the Cas A remnant taken by the Chandra X-ray Observatory (CXC).

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The Geoengineering Option: A Last Resort Against Global Warming?

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The Geoengineering Option

A Last Resort Against Global Warming?

David G. Victor, M. Granger Morgan, Jay Apt, John Steinbruner, and Katharine Ricke

EACH YEAR, the effects of climate change are coming into sharper focus. Barely a month goes by without some fresh bad news: ice sheets and glaciers are melting faster than expected, sea levels are rising more rapidly than ever in recorded history, plants are blooming earlier in the spring, water supplies and habitats are in danger, birds are being forced to find new migratory patterns.

The odds that the global climate will reach a dangerous tipping point are increasing. Over the course of the twenty-first century, key ocean currents, such as the Gulf Stream, could shift radically, and thawing permafrost could release huge amounts of additional greenhouse gases into the atmosphere. Such scenarios, although still remote, would dramatically accelerate and compound the consequences of global warming. Scientists are taking these doomsday scenarios seriously because the steady accumulation of warming gases in the atmosphere

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is forcing change in the climate system at rates so rapid that the outcomes are extremely difficult to predict.

Eliminating all the risks of climate change is impossible because carbon dioxide emissions, the chief human contribution to global warming, are unlike conventional air pollutants, which stay in the atmosphere for only hours or days. Once carbon dioxide enters the atmosphere, much of it remains for over a hundred years. Emissions from anywhere on the planet contribute to the global problem, and once headed in the wrong direction, the climate system is slow to respond to attempts at reversal. As with a bathtub that has a large faucet and a small drain, the only practical way to lower the level is by dramatically cutting the inflow. Holding global warming steady at its current rate would require a worldwide 60–80 percent cut in emissions, and it would still take decades for the atmospheric concentration of carbon dioxide to stabilize.

Most human emissions of carbon dioxide come from burning fossil fuels, and most governments have been reluctant to force the radical changes necessary to reduce those emissions. Economic growth tends to trump vague and elusive global aspirations. The United States has yet to impose even a cap on its emissions, let alone a reduction. The European Union has adopted an emissions-trading scheme that, although promising in theory, has not yet had much real effect because carbon prices are still too low to cause any significant change in behavior. Even Norway, which in 1991 became one of the first nations to impose a stiff tax on emissions, has seen a net increase in its carbon dioxide emissions. Japan, too, has professed its commitment to taming global warming. Nevertheless, Tokyo is struggling to square the need for economic growth with continued dependence on an energy system powered mainly by conventional fossil fuels. And China's emissions recently surpassed those of the United States, thanks to coal-fueled industrialization and a staggering pace of economic growth. The global economic crisis is stanching emissions a bit, but it will not come close to shutting off the faucet.

The world's slow progress in cutting carbon dioxide emissions and the looming danger that the climate could take a sudden turn for the worse require policymakers to take a closer look at emergency strategies for curbing the effects of global warming. These strategies, often called "geoengineering," envision deploying systems on a planetary scale, such as launching reflective particles into the atmosphere or positioning sunshades to cool the earth. These strategies could cool the planet, but they would not stop the buildup of carbon dioxide or lessen all its harmful impacts. For this reason, geoengineering has been widely shunned by those committed to reducing emissions.

Serious research on geoengineering is still in its infancy, and it has not received the attention it deserves from politicians. The time has come to take it seriously. Geoengineering could provide a useful defense for the planet—an emergency shield that could be deployed if surprisingly nasty climatic shifts put vital ecosystems and billions of people at risk. Actually raising the shield, however, would be a political choice. One nation's emergency can be another's opportunity, and it is unlikely that all countries will have similar assessments of how to balance the ills of unchecked climate change with the risk that geoengineering could do more harm than good. Governments should immediately begin to undertake serious research on geoengineering and help create international norms governing its use.

THE RAINMAKERS

GEOENGINEERING IS not a new idea. In 1965, when President Lyndon Johnson received the first-ever U.S. presidential briefing on the dangers of climate change, the only remedy prescribed to counter the effects of global warming was geoengineering. That advice reflected the scientific culture of the time, which imagined that engineering could fix almost any problem.

By the late 1940s, both the United States and the Soviet Union had begun exploring strategies for modifying the weather to gain battlefield advantage. Many schemes focused on "seeding" clouds with substances that would coax them to drop more rain. Despite offering no clear advantage to the military, "weather makers" were routinely employed (rarely with much effect) to squeeze more rain from clouds for thirsty crops. Starting in 1962, U.S. government researchers for Project Stormfury tried to make tropical hurricanes less intense through cloud seeding, but with no clear success. Military experts also dreamed of using nuclear explosions and other interventions to create a more advantageous climate. These applications were frightening enough that in 1976 the United Nations adopted the Convention on the Prohibition of Military or Any Other Hostile Use of Environmental Modification Techniques to bar such projects. By the 1970s, after a string of failures, the idea of weather modification for war and farming had largely faded away.

Today's proposals for geoengineering are more likely to have an impact because the interventions needed for global-scale geoengineering are much less subtle than those that sought to influence local weather patterns. The earth's climate is largely driven by the fine balance between the light energy with which the sun bathes the earth and the heat that the earth radiates back to space. On average, about 70 percent of the earth's incoming sunlight is absorbed by the atmosphere and the planet's surface; the remainder is reflected back into space. Increasing the reflectivity of the planet (known as the albedo) by about one percentage point could have an effect on the climate system large enough to offset the gross increase in warming that is likely over the next century as a result of a doubling of the amount of carbon dioxide in the atmosphere. Making such tweaks is much more straightforward than causing rain or fog at a particular location in the ways that the weather makers of the late 1940s and 1950s dreamed of doing.

In fact, every few decades, volcanoes validate the theory that it is possible to engineer the climate. When Mount Pinatubo, in the Philippines, erupted in 1991, it ejected plumes of sulfate and other fine particles into the atmosphere, which reflected a bit more sunlight and cooled the planet by about 0.5 degrees Celsius over the course of a year. Larger eruptions, such as the 1883 eruption of Krakatau, in Indonesia, have caused even greater cooling that lasted longer. Unlike efforts to control emissions of greenhouse gases, which will take many years to yield a noticeable effect, volcano-like strategies for cooling the planet would work relatively promptly.

Another lesson from volcanoes is that a geoengineering system would require frequent maintenance, since most particles lofted into the stratosphere would disappear after a year or two. Once a geoengineering project were under way, there would be strong incentives to continue it, since failure to keep the shield in place could allow particularly harmful changes in the earth's climate, such as warming so speedy that ecosystems would collapse because they had no time to adjust. By carefully measuring the climatic effects of the next major volcanic eruption with satellites and aircraft, geoengineers could design a number of climate-cooling technologies.

ALBEDO ENHANCERS

TODAY, THE term "geoengineering" refers to a variety of strategies designed to cool the climate. Some, for example, would slowly remove carbon dioxide from the atmosphere, either by manipulating the biosphere (such as by fertilizing the ocean with nutrients that would allow plankton to grow faster and thus absorb more carbon) or by directly scrubbing the air with devices that resemble big cooling towers. However, from what is known today, increasing the earth's albedo offers the most promising method for rapidly cooling the planet.

Most schemes that would alter the earth's albedo envision putting reflective particles into the upper atmosphere, much as volcanoes do already. Such schemes offer quick impacts with relatively little effort. For example, just one kilogram of sulfur well placed in the stratosphere would roughly offset the warming effect of several hundred thousand kilograms of carbon dioxide. Other schemes include seeding bright reflective clouds by blowing seawater or other substances into the lower atmosphere. Substantial reductions of global warming are also possible to achieve by converting dark places that absorb lots of sunlight to lighter shades—for example, by replacing dark forests with more reflective grasslands. (Engineered plants might be designed for the task.)

More ambitious projects could include launching a huge cloud of thin refracting discs into a special space orbit that parks the discs between the sun and the earth in order to bend just a bit of sunlight away before it hits the planet.

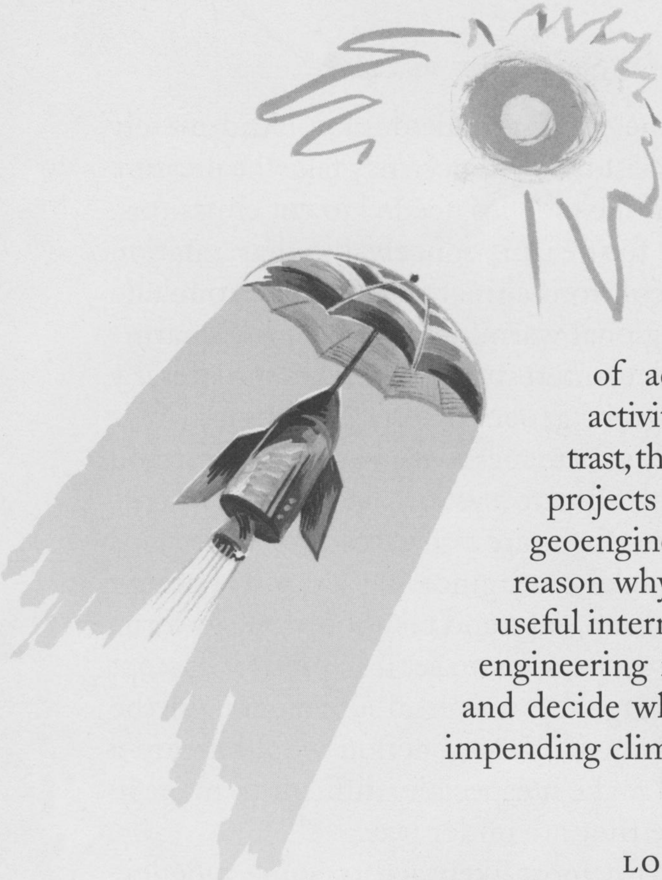
So far, launching reflective materials into the upper stratosphere seems to be the easiest and most cost-effective option. This could be accomplished by using high-flying aircraft, naval guns, or giant balloons. The appropriate materials could include sulfate aerosols (which would be created by releasing sulfur dioxide gas), aluminum oxide dust, or even self-levitating and self-orienting designer particles engineered to migrate to the Polar Regions and remain in place for long periods. If it can be done, concentrating sunshades over the poles would be a particularly interesting option, since those latitudes appear to be the most sensitive to global warming. Most cost estimates for such geoengineering strategies are preliminary and unreliable. However, there is general agreement that the strategies are cheap; the total expense of the most cost-effective options would amount to perhaps as little as a few billion dollars, just one percent (or less) of the cost of dramatically cutting emissions.

Every few decades, volcanoes validate the theory that it is possible to engineer the climate.

Cooling the planet through geoengineering will not, however, fix all of the problems related to climate change. Offsetting warming by reflecting more sunlight back into space will not stop the rising concentration of carbon dioxide in the atmosphere. Sooner or later, much of that carbon dioxide ends up in the oceans, where it forms carbonic acid. Ocean acidification is a catastrophe for marine ecosystems, for the 100 million people who depend on coral reefs for their livelihoods, and for the many more who depend on them for coastal protection from storms and for biological support of the greater ocean food web. Over the last century, the oceans have become markedly more acidic, and current projections suggest that without a serious effort to control emissions, the concentration of carbon dioxide will be so high by the end of the century that many organisms that make shells will disappear and most coral reef ecosystems will collapse, devastating the marine fishing industry. Recent studies have also suggested that ocean acidification will increase the size and depth of "dead zones," areas of the sea that are so oxygen depleted that larger marine life, such as squid, are unable to breathe properly.

Altering the albedo of the earth would also affect atmospheric circulation, rainfall, and other aspects of the hydrologic cycle. In the six to 18 months following the eruption of Mount Pinatubo, rainfall and river flows dropped, particularly in the tropics. Understanding these dangers better would help convince government leaders in rainfall-sensitive regions, such as parts of China and India (along with North Africa, the Middle East, and the desert regions of the southwestern United States), not to prematurely deploy poorly designed geoengineering schemes that could wreak havoc on agricultural productivity. Indeed, some climate models already suggest that negative outcomes—decreased precipitation over land (especially in the tropics) and increased precipitation over the oceans—would accompany a geoengineering scheme that sought to lower average temperatures by raising the planet's albedo. Such changes could increase the risk of major droughts in some regions and have a major impact on agriculture and the supply of fresh water. Complementary policies—such as investing in better water-management schemes—may be needed.

The highly uncertain but possibly disastrous side effects of geoengineering interventions are difficult to compare to the dangers of unchecked global climate change. Chances are that if countries begin deploying geoengineering systems, it will be because calamitous climate change is near at hand. Yet the assignment



of blame after a geoengineering disaster would be very different from the current debates over who is responsible for climate change, which is the result of centuries of accumulated emissions from activities across the world. By contrast, the side effects of geoengineering projects could be readily pinned on the geoengineers themselves. That is one reason why nations must begin building useful international norms to govern geoengineering in order to assess its dangers and decide when to act in the event of an impending climatic disaster.

LONE RANGERS

AN EFFECTIVE foreign policy strategy for managing geoengineering is difficult to formulate because the technology involved turns the normal debate over climate change on its head. The best way to reduce the danger of global warming is, of course, to cut emissions of carbon dioxide and other greenhouse gases. But success in that venture will require all the major emitting countries, with their divergent interests, to cooperate for several decades in a sustained effort to develop and deploy completely new energy systems with much lower emissions. Incentives to defect and avoid the high cost of emissions controls will be strong.

By contrast, geoengineering is an option at the disposal of any reasonably advanced nation. A single country could deploy geoengineering systems from its own territory without consulting the rest of the planet. Geoengineers keen to alter their own country's climate might not assess or even care about the dangers their actions could create for climates, ecosystems, and economies elsewhere. A unilateral geoengineering project could impose costs on other countries, such as changes in precipitation patterns and river flows or adverse impacts on agriculture, marine fishing, and tourism. And merely knowing that geoengineering exists as an option may take the pressure off governments to implement the policies needed to cut emissions.

At some point in the near future, it is conceivable that a nation that has not done enough to confront climate change will conclude that global warming has become so harmful to its interests that it should unilaterally engage in geoengineering. Although it is hardly wise to mess with a poorly understood global climate system using instruments whose effects are also unknown, politicians must take geoengineering seriously because it is cheap, easy, and takes only one government with sufficient hubris or desperation to set it in motion. Except in the most dire climatic emergency, universal agreement on the best approach is highly unlikely. Unilateral action would create a crisis of legitimacy that could make it especially difficult to manage geoengineering schemes once they are under way.

Fiddling with the climate to fix the climate strikes most people as a shockingly bad idea.

Although governments are the most likely actors, some geoengineering options are cheap enough to be deployed by wealthy and capable individuals or corporations. Although it may sound like the stuff of a future James Bond movie, private-sector geoengineers might very well attempt to deploy affordable geoengineering schemes on their own. And even if governments manage to keep freelance geoengineers in check, the private sector could emerge as a potent force by becoming an interest group that pushes for deployment or drives the direction of geoengineering research and assessment. Already, private companies are running experiments on ocean fertilization in the hope of sequestering carbon dioxide and earning credits that they could trade in carbon markets. Private developers of technology for albedo modification could obstruct an open and transparent research environment as they jockey for position in the potentially lucrative market for testing and deploying geoengineering systems. To prevent such scenarios and to establish the rules that should govern the use of geoengineering technology for the good of the entire planet, a cooperative, international research agenda is vital.

FROM SCIENCE FICTION TO FACTS

DESPITE YEARS of speculation and vague talk, peer-reviewed research on geoengineering is remarkably scarce. Nearly the entire community of geoengineering scientists could fit comfortably in a single university seminar room, and the entire scientific literature on the subject could be read during the course of a transatlantic flight. Geoengineering continues to be considered a fringe topic.

Many scientists have been reluctant to raise the issue for fear that it might create a moral hazard: encouraging governments to deploy geoengineering rather than invest in cutting emissions. Indeed, geoengineering ventures will be viewed with particular suspicion if the nations funding geoengineering research are not also investing in dramatically reducing their emissions of carbon dioxide and other greenhouse gases. Many scientists also rightly fear that grants for geoengineering research would be subtracted from the existing funds for urgently needed climate-science research and carbon-abatement technologies. But there is a pressing need for a better understanding of geoengineering, rooted in theoretical studies and empirical field measurements. The subject also requires the talents of engineers, few of whom have joined the small group of scientists studying these techniques.

The scientific academies in the leading industrialized and emerging countries—which often control the purse strings for major research grants—must orchestrate a serious and transparent international research effort funded by their governments. Although some work is already under way, a more comprehensive understanding of geoengineering options and of risk-assessment procedures would make countries less trigger-happy and more inclined to consider deploying geoengineering systems in concert rather than on their own. (The International Council for Science, which has a long and successful history of coordinating scientific assessments of technical topics, could also lend a helping hand.) Eventually, a dedicated international entity overseen by the leading academies, provided with a large budget, and suffused with the norms of transparency and peer review will be necessary.

In time, international institutions such as the Intergovernmental Panel on Climate Change could be expected to synthesize the findings from the published research. The IPCC, which shared the Nobel Peace Prize in 2007 for its pivotal role in building a consensus around climate science, has not considered geoengineering so far because the topic is politically radioactive and there is a dearth of peer-reviewed research on it. The IPCC's fifth assessment report on climate change, which is being planned right now, should promise to take a closer look at geoengineering. Attention from the IPCC and the world's major scientific academies would help encourage new research.

A broad and solid foundation of research would help on three fronts. First, it would transform the discussion about geoengineering from an abstract debate into one focused on real risk assessment. Second, a research program that was backed by the world's top scientific academies could secure funding and political cover for essential but controversial experiments. (Field trials of engineered aerosols, for example, could spark protests comparable to those that accompanied trials of genetically modified crops.) Such experiments will be seen as more acceptable if they are designed and overseen by the world's leading scientists and evaluated in a fully transparent fashion. Third, and what is crucial, a better understanding of the dangers of geoengineering would help nations craft the norms that should govern the testing and possible deployment of newly developed technologies. Scientists could be influential in creating these norms, just as nuclear scientists framed the options on nuclear testing and influenced pivotal governments during the Cold War.

The option of geoengineering exists. It would be dangerous for scientists and policymakers to ignore it.

If countries were actually to contemplate the deployment of geoengineering technologies, there would inevitably be questions raised about what triggers would compel the use of these systems. Today, nobody knows which climatic triggers are most important for geoengineering because research on the harmful effects of climate change has not been coupled tightly enough with research on whether and how geoengineering might offset those effects.

Although the international scientific community should take the lead in developing a research agenda, social scientists, international lawyers, and foreign policy experts will also have to play a role. Eventually, there will have to be international laws to ensure that globally credible and legitimate rules govern the deployment of geoengineering systems. But effective legal norms cannot be imperiously declared. They must be carefully developed by informed consensus in order to avoid encouraging the rogue forms of geoengineering they are intended to prevent.

Those who worry that such research will cause governments to abandon their efforts to control emissions, including much of the environmental community, are prone to seek a categorical prohibition against geoengineering. But a taboo would interfere with much-needed scientific research on an option that might be better for humanity and the world's ecosystems than allowing unchecked climate change or reckless unilateral geoengineering. Formal prohibition is unlikely to stop determined rogues, but a smart and scientifically sanctioned research program could gather data essential to understanding the risks of geoengineering strategies and to establishing responsible criteria for their testing and deployment.

BRAVE NEW WORLD

FIDDLING WITH the climate to fix the climate strikes most people as a shockingly bad idea. Many worry that research on geoengineering will make governments less willing to regulate emissions. It is more likely, however, that serious study will reveal the many dangerous side effects of geoengineering, exposing it as a true option of last resort. But because the option exists, and might be used, it would be dangerous for scientists and policymakers to ignore it. Assessing and managing the risks of geoengineering may not require radically different approaches from those used for other seemingly risky endeavors, such as genetic engineering (research on which was paused in the 1970s as scientists worked out useful regulatory systems), the construction and use of high-energy particle accelerators (which a few physicists suggest could create black holes that might swallow the earth), and the development of nanotechnology (which some worry could unleash self-replicating nanomachines that could reduce the world to "gray goo"). The option of eliminating risk altogether does not exist. Countries have kept smallpox samples on hand, along with samples of many other diseases, such as the Ebola and Marburg viruses, despite the danger of their inadvertent release. All of these are potentially dangerous endeavors that governments, with scientific support, have been able to manage for the greater good.

Humans have already engaged in a dangerous geophysical experiment by pumping massive amounts of carbon dioxide and other greenhouse gases into the atmosphere. The best and safest strategy for reversing climate change is to halt this buildup of greenhouse gases, but this solution will take time, and it involves myriad practical and political difficulties. Meanwhile, the dangers are mounting. In a few decades, the option of geoengineering could look less ugly for some countries than unchecked changes in the climate. Nor is it impossible that later in the century the planet will experience a climatic disaster that puts ecosystems and human prosperity at risk. It is time to take geoengineering out of the closet—to better control the risk of unilateral action and also to know the costs and consequences of its use so that the nations of the world can collectively decide whether to raise the shield if they think the planet needs it.