

THE BENEFITS, RISKS, AND COSTS OF STRATOSPHERIC GEOENGINEERING

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Abstract

Injecting sulfate aerosol precursors into the stratosphere has been suggested as a means of geoengineering to cool the planet and reduce global warming. 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.

17 **1. Introduction**

18 Global warming will continue for decades due to anthropogenic emissions of greenhouse
19 gases and aerosols [*IPCC*, 2007a], with many negative consequences for society [*IPCC*, 2007b].
20 Although currently impossible, as there are no means of injecting aerosols or their precursors
21 into the stratosphere, the possibility of geoengineering the climate is now being discussed in
22 addition to the conventional potential responses of mitigation (reducing emissions) and
23 adaptation [*IPCC*, 2007c]. While originally suggested by *Budyko* [1974, 1977], *Dickinson*
24 [1996], and many others (see *Robock et al.* [2008] for a comprehensive list), *Crutzen* [2006] and
25 *Wigley* [2006] rekindled interest in stratospheric geoengineering using sulfate aerosols. This
26 proposal for “solar radiation management,” to reduce insolation with an anthropogenic
27 stratospheric aerosol cloud in the same manner as episodic explosive volcanic eruptions, will be
28 called “geoengineering” here, recognizing that others have a more inclusive definition of
29 geoengineering that can include tropospheric cloud modification, carbon capture and
30 sequestration, and other proposed techniques.

31 The decision to implement geoengineering will require a comparison of its benefits,
32 dangers, and costs to those of other responses to global warming. Here we present a brief review
33 of these factors for geoengineering. It should be noted that in the three years since *Crutzen*
34 [2006] and *Wigley* [2006] suggested that, in light of no progress toward mitigation,
35 geoengineering may be necessary to reduce the most severe impacts of global warming, there has
36 still been no global progress on mitigation. In fact, Mauna Loa data show that the rate of CO₂
37 increase in the atmosphere is actually rising. However, the change of U.S. administration in
38 2009 has completely changed the U.S. policy on global warming. In the past eight years, the
39 U.S. has stood in the way of international progress on this issue, but now President Obama is

40 planning to lead a global effort toward a mitigation agreement in Copenhagen in December
41 2009. If geoengineering is seen as a potential low-cost and easy “solution” to the problem, the
42 public backing toward a mitigation agreement, which will require some short-term dislocations,
43 may be eroded. This paper, therefore, is intended to serve as useful information for that process.

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

49 **2. Benefits**

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

62 Observations after large volcanic eruptions show that stratospheric sulfate aerosols
63 drastically change the partitioning of downward solar flux into direct and diffuse [Robock, 2000].
64 After the 1982 El Chichón eruption, observations at the Mauna Loa Observatory in Hawaii on
65 mornings with clear skies, at a solar zenith angle of 60° equivalent to two relative air masses,
66 showed a peak change of downward direct insolation, from 515 W m^{-2} to 340 W m^{-2} , while
67 diffuse radiation increased from 40 W m^{-2} to 180 W m^{-2} [Robock, 2000]. A similar effect was
68 observed after the 1991 Mt. Pinatubo eruption. While the change of net radiation after El
69 Chichón was a reduction of 35 W m^{-2} , this shift to an increase of the diffuse portion actually
70 produced an increase of the growth of terrestrial vegetation, and an increase in the terrestrial CO_2
71 sink. Gu *et al.* [1999, 2002, 2003], Roderick *et al.* [2001], and Farquhar and Roderick [2003]
72 suggested that increased diffuse radiation allows plant canopies to photosynthesize more
73 efficiently, increasing the CO_2 sink. Gu *et al.* [2003] actually measured this effect in trees
74 following the 1991 Pinatubo eruption. While some of the global increase in CO_2 sinks following
75 volcanic eruptions may have been due to the direct temperature effects of the eruptions, Mercado
76 *et al.* [2009] showed that the diffuse radiation effect produced an increase sink of about
77 1 Pg C a^{-1} for about one year following the Pinatubo eruption. The effect of a permanent
78 geoengineering aerosol cloud would depend on the optical depth of the cloud, and these observed
79 effects of episodic eruptions may not produce a permanent vegetative response as the vegetation
80 adjusts to this changed insolation. Nevertheless, this example shows that stratospheric
81 geoengineering may provide a substantial increased CO_2 sink to counter anthropogenic
82 emissions. This increase in plant productivity could also have a positive effect on agriculture.

83 **3. Risks**

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

92 Two of the reasons in the list have been strengthened by recent work. *Tilmes et al.*
93 [2008] used a climate model to show that indeed stratospheric geoengineering would produce
94 substantial ozone depletion, prolonging the end of the Antarctic ozone hole by several decades
95 and producing ozone holes in the Arctic in springs with a cold lower stratosphere. *Murphy*
96 [2009] used observations of direct solar energy generation in California after the 1991 Pinatubo
97 eruption and showed that generation went from 90% of peak capacity in non-volcanic conditions
98 to 70% in summer 1991 and to less than 60% in summer 1992.

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

103 **4. Costs**

104 *Robock* [2008a] suggested that the construction and operation of system to inject aerosol
105 precursors into the stratosphere might be very expensive. Here we analyze the costs of three

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

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

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

127 While volcanic eruptions inject mostly SO_2 into the stratosphere, the relevant quantity is
128 the amount of sulfur. If H_2S were injected instead, it would oxidize quickly to form SO_2 , which

129 would then react with water to form H_2SO_4 droplets. Because of the relative molecular weights,
130 only 2.66 Tg of H_2S (molecular weight 34 g mol^{-1}) would be required to produce the same
131 amount of sulfate aerosols as 5 Tg of SO_2 (molecular weight 64 g mol^{-1}). Since there are choices
132 for the desired sulfate aerosol precursor, our calculations will be in terms of stratospheric
133 injection of any gas. H_2S , however, is more corrosive than SO_2 [e.g., *Kleber et al.*, 2008] and is
134 very dangerous, so it would probably not be the gas of choice. Exposure to 50 ppm of H_2S can
135 be fatal [*Kilburn and Warshaw*, 1995]. H_2S was even used for a time as a chemical warfare
136 agent in World War I [*Croddy et al.*, 2001]. However, 100 ppm of SO_2 is also considered
137 “immediately dangerous to life and health” [ATSDR, 1998].

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

144 Our work is an update and expansion of the first quantitative estimates by *COSEPUP*
145 [1992]. While they listed “Stratospheric Bubbles; Place billions of aluminized, hydrogen-filled
146 balloons in the stratosphere to provide a reflective screen; Low Stratospheric Dust; Use aircraft
147 to maintain a cloud of dust in the low stratosphere to reflect sunlight; Low Stratospheric Soot;
148 Decrease efficiency of burning in engines of aircraft flying in the low stratosphere to maintain a
149 thin cloud of soot to intercept sunlight” among the possibilities for geoengineering, they did not
150 evaluate the costs of aircraft or stratospheric bubble systems.

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

161 In addition to these costs would be the cost of the production and transport to the
162 deployment point of the sulfur gas. *COSEPUP* [1992] estimated the price of SO₂ to be
163 \$50,000,000 per Tg in 1992 dollars, and H₂S would be much cheaper, as it is currently removed
164 from oil as a pollutant, so the price of the gases themselves would be a minor part of the total.
165 The current bulk price for liquid SO₂ is \$230/ton or \$230,000,000 per Tg [*Chemical Profiles*,
166 2009].

167 **4.1. Airplanes**

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

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

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

185 The military has already manufactured more planes than would be required for this
186 geoengineering scenario, potentially reducing the costs of this method. Since climate change is
187 an important national security issue [*Schwartz and Randall, 2003*], the military could be directed
188 to carry out this mission with existing aircraft at minimal additional cost. Furthermore, the KC-
189 135 fleet will be retired in the next few decades as a new generation of aerial tankers replaces it,
190 even if the military continues to need the in-flight refueling capability for other missions.

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

196 In addition to the issues of how to emit the gas as a function of space and time to produce
197 the desired aerosols, another concern is the maximum concentration of sulfate aerosols through
198 which airplanes can safely fly. In the past, noticeable damage has occurred to airplanes that fly
199 through plumes of volcanic ash containing SO₂. In June, 1982, after the eruption of Galunggung
200 volcano in Java, Indonesia, two passenger planes flew through a volcanic cloud. In one case the
201 windows were pitted, volcanic ash entered the engines and thrust was lost in all four engines. In
202 the other case, the same thing happened, with the plane descending 7.5 km before the engines
203 could be restarted [*Smithsonian Institution*, 1982]. While the concentration of sulfate in the
204 stratosphere would be less than in a plume like this, and there would be no ash, there could still
205 be sulfuric acid damage to airplanes. In the year after the 1991 Pinatubo eruption, airplanes
206 reported acid damage to windows and other parts. An engineering study would be needed to
207 ascertain whether regular flight into a stratospheric acid cloud would be safe, and how much
208 harm it would do to airplanes.

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

219 about \$3.7 million for the newer R model, based on an average of 300 flying hours per year
220 [*Curtin*, 2003].

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

228 **4.2. Artillery Shells**

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

238 **4.3. Stratospheric Balloons**

239 Requiring no fuel, weather balloons are launched on a daily basis to high levels of the
240 atmosphere. Balloons can be made out of either rubber or plastic, but plastic would be needed due
241 to the cold temperatures at the tropical tropopause or in the Arctic stratosphere, as rubber

242 balloons would break prematurely. Weather balloons are typically filled with helium, but
243 hydrogen (H_2) is less expensive and more buoyant than helium and can also be used safely to
244 inflate balloons.

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

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

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

265 0.141-.3/0-T from Aerostar International, with a maximum volume of 3990 m³, and available in
266 quantities of 10 or more for \$1,711 each. The balloons would burst at 25 mb.

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

$$270 \quad V = 3990 \text{ m}^3 \times \frac{25 \text{ mb}}{1000 \text{ mb}} \times \frac{293 \text{ K}}{230 \text{ K}} = 127 \text{ m}^3 \quad (1)$$

271 The mass of air displaced would be:

$$272 \quad m = \frac{pV}{RT} = \frac{1000 \text{ mb} \times 127 \text{ m}^3}{287 \frac{\text{J}}{\text{kg K}} \times 293 \text{ K}} = 151 \text{ kg} \quad (2)$$

273 To produce the required buoyancy, the balloon with its mixture of H₂ and H₂S would have a
274 mass $m' = m/1.2 = 125.9 \text{ kg}$. Normally a weather balloon is filled with He, allowing it to lift an
275 additional payload beneath it. In our case, the payload will be the H₂S inside the balloon. Since
276 each balloon has a mass of 11.4 kg, the total mass of the gases would be 114.5 kg. To produce
277 that mass in that volume would require a mixture of 37.65% H₂ and 62.35% H₂S by volume, for
278 a total mass of H₂S of 110.6 kg. To put 1 Tg of gas into the stratosphere per year would
279 therefore require 9 million balloons, or 36,000 per day (using 250 days per year). This would
280 cost \$15.5 billion per year just for the balloons. According to *COSEPUP* [1992], the additional
281 costs for infrastructure, personnel, and H₂ would be \$3,600,000,000 per year, or \$5.5 billion in
282 2008 dollars, for their balloon option, and as rough guess we adopt it for ours, too. So our
283 balloon option would cost \$21 billion per year in 2008 dollars.

284 The option above would also inject 0.04 Tg H₂ into the stratosphere each year. This is 2
285 to 3 orders of magnitude less than current natural and anthropogenic H₂ emissions [*Jacobson,*
286 2008], so would not be expected to have any detectable effects on atmospheric chemistry.

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

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

294 **4.4. Ideas of the Future**

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

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

306 We can imagine such a tower on the Equator with a hose to pump the gas to the
307 stratosphere. The weather on the Equator would present no strong wind issues, as tornadoes and
308 hurricanes cannot form there, but icing issues for the upper portion would need to be addressed.
309 If the gas were pushed up a hose, adiabatic expansion would cool it to temperatures colder than

310 the surrounding atmosphere, exacerbating icing problems. Because such a tower has never been
311 built, and many engineering issues would need to be considered, from the construction material
312 to the pumping needed, we cannot offer an estimate of the cost. However, only one tower would
313 be needed if the hoses were large enough to pump the required amount of gas. Weather issues,
314 such as strong winds, would preclude such a tower at high latitudes, even though it would not
315 need to be as tall. (A tethered balloon system would have all the same issues, but weather would
316 be even more of a factor.)

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

325 **5. Conclusions**

326 Using existing airplanes for geoengineering would cost several billion dollars per year,
327 depending on the amount, location, and type of sulfur gas injected into the stratosphere. As there
328 are currently 522 F-15C Eagles, 481 KC-135 Stratotankers, and 59 KC-10 Extenders, if a
329 fraction of them were dedicated to geoengineering, equipment costs would be minimal. Systems
330 using artillery or balloons would cost much more and would produce additional potential
331 problems of falling spent artillery shells or balloons, or H₂ injections into the stratosphere.
332 However, airplane systems would still need to address several issues before being practical,

333 including the effects of acid clouds on the airplanes, whether nozzles could be designed to
334 produce aerosol particles of the desired size distributions, and whether injection of sulfur gases
335 into an existing sulfuric acid cloud would just make existing droplets grow larger rather than
336 producing more small droplets. All the systems we evaluate would produce serious pollution
337 issues, in terms of additional CO₂, particles, and noise in the production, transportation, and
338 implementation of the technology at the location of the systems.

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

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

356 increased diffuse insolation and increased CO₂ ameliorate the effects of reduced soil moisture on
357 agricultural production?

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

370 As already pointed out by *Robock* [2008b], a well-funded national or international
371 research program, perhaps as part of the currently ongoing Intergovernmental Panel on Climate
372 Change Fifth Scientific Assessment, would be able to look at several other aspects of
373 geoengineering and provide valuable guidance to policymakers trying to decide how best to
374 address the problems of global warming. Such research should include theoretical calculations
375 as well as engineering studies. While small-scale experiments could examine nozzle properties
376 and initial formation of aerosols, they could not be used to test the climatic response of
377 stratospheric aerosols. Because of the natural variability of climate, either a large forcing or a
378 long-term (decadal) study with a small forcing would be necessary to detect a response above

379 climatic noise. Because volcanic eruptions occasionally do the experiment for us and climate
380 models have been validated by simulating volcanic eruptions, it would not be important to fully
381 test the climatic impact of stratospheric geoengineering in situ as part of a decision about
382 implementation. However, the evolution of aerosol properties, including size distribution, for an
383 established stratospheric aerosol cloud would need careful monitoring during any full-scale
384 implementation.

385

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

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

524 **Table 2.** Costs for different methods of injecting 1 Tg H₂S per year to the stratosphere.
525 Airplane data from *Air Combat Command* [2008], *Air Mobility Command* [2008a, 2008b]. Costs
526 in last two lines from *COSEPUP* [1992]. Conversion from 1992 and 1998 dollars to 2008
527 dollars (latest data available) using the Consumer Price Index [Williamson, 2008].

528

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

529

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

531



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



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)

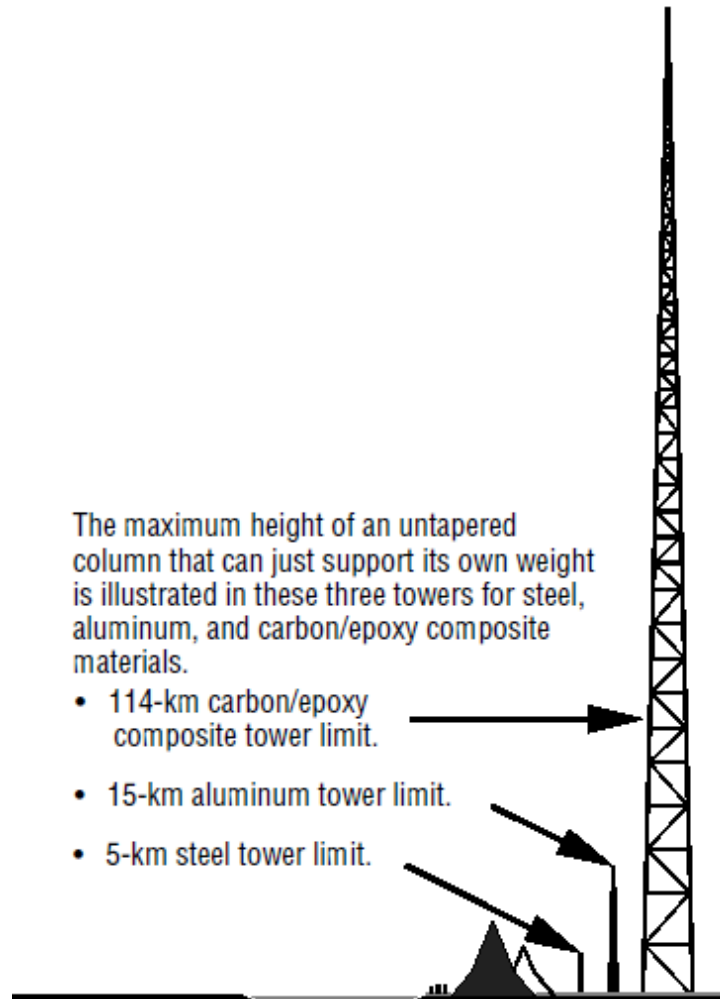


Figure 3. The maximum height of an untapered tower that can support its own weight, showing that one tower on the Equator could be used for stratospheric geoengineering. (From “Space Elevator Schematics” page at end of *Smitherman* [2000]).