

THE PRACTICALITY OF GEOENGINEERING

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Abstract

1
2 Injecting sulfate aerosol precursors into the stratosphere has been suggested as a means of
3 geoengineering to cool the planet and reduce global warming. Here we evaluate the practicality
4 of this means of geoengineering by examining the costs of using airplanes, balloons, or artillery
5 to place hydrogen sulfide (H₂S) into the lower stratosphere, in either the tropics or the Arctic.
6 Existing U.S. military fighter and tanker planes could be retrofitted, and the annual costs would
7 be several billion dollars. Using artillery or balloons to loft the gas would be much more
8 expensive. We do not have enough information to evaluate more exotic techniques, such as
9 pumping the gas up through a hose attached to a tower or balloon system. While the cost of
10 injecting aerosol precursors would not be a limiting factor, there are many other potential
11 problems with geoengineering, and they need to be evaluated and compared to the potential
12 benefits before a decision to proceed with geoengineering can be made.

13 **Introduction**

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

21 Geoengineering today is impossible, as there are no means of injecting aerosols or their
22 precursors into the stratosphere. *Robock* [2008] suggested that the construction and operation of
23 such a system might be very expensive. Here we analyze the costs of three suggested methods of
24 placing the aerosol precursors into the stratosphere, airplanes, artillery shells, and stratospheric
25 balloons (Figure 1, Table 1). Because such systems do not currently exist, the estimates
26 presented here are rough but provide quantitative starting points for further discussions of the
27 practicality of geoengineering.

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

33 The 1991 Mt. Pinatubo eruption injected 20 Tg SO₂ into the tropical lower stratosphere
34 [*Bluth et al.*, 1992], which formed sulfate aerosols and cooled the climate for about two years.
35 As discussed by *Robock et al.* [2008], the equivalent of one Pinatubo every 4-8 years would be

36 required to stop global warming or even reduce global temperature in spite of continued
37 greenhouse gas emissions. While volcanic eruptions inject mostly SO₂ into the stratosphere, the
38 relevant quantity is the amount of sulfur. If H₂S were injected instead, it would oxidize quickly
39 to form SO₂, which would then react with water to form H₂SO₄ droplets. Because of the relative
40 molecular weights, only 2.66 Tg of H₂S (molecular weight 34 g mol⁻¹) would be required to
41 produce the same amount of sulfate aerosols as 5 Tg of SO₂ (molecular weight 64 g mol⁻¹).
42 Since there are choices for the desired sulfate aerosol precursor, our calculations will be in terms
43 of stratospheric injection of H₂S. Using H₂S, which is rather corrosive and dangerous, could
44 potentially exacerbate the inherent difficulties of this problem, but we do not address that issue
45 here. For actual implementation, a specific gas would need to be chosen, and the results
46 presented would be scaled appropriately. For example, if SO₂ were to be injected rather than
47 H₂S, approximately twice as many resources as the values given here would be needed.

48 If the decision were ever made to actually conduct geoengineering, the amount of gas to
49 loft, the timing and location of injections, and how to produce aerosols, would have to be
50 considered, and these are issues we address in other work [*Rasch et al.*, 2008]. Here we just
51 examine the question of the cost of lofting 1 Tg of H₂S per year into the stratosphere. Other
52 more speculative geoengineering suggestions, such as engineered aerosols [e.g., *Teller et al.*,
53 1997], are not considered here.

54 Our work is an update and expansion of the first quantitative estimates by *COSEPUP*
55 [1992]. While they listed “Stratospheric Bubbles; Place billions of aluminized, hydrogen-filled
56 balloons in the stratosphere to provide a reflective screen; Low Stratospheric Dust; Use aircraft
57 to maintain a cloud of dust in the low stratosphere to reflect sunlight; Low Stratospheric Soot;
58 Decrease efficiency of burning in engines of aircraft flying in the low stratosphere to maintain a

59 thin cloud of soot to intercept sunlight” among the possibilities for geoengineering, they did not
60 evaluate the costs of aircraft or stratospheric bubble systems.

61 Rather than cooling the entire planet, it has been suggested that we only try to modify the
62 Arctic to prevent a sea ice-free Arctic summer and to preserve the ice sheets in Greenland while
63 mitigation is implemented [*Lane et al.*, 2007]. Along these lines, *Robock et al.* [2008] tested a
64 scenario of annual injection of 3 Tg of SO₂ at 68°N in addition to tropical injection scenarios.
65 One important difference between tropical and Arctic injections is the height of the tropopause,
66 which is about 16 km in the tropics but only about 8 km in the Arctic. These different heights
67 affect the capability of different injection schemes to reach the lower stratosphere, and we
68 consider both cases here.

69 In addition to these costs would be the cost of the production and transport to the
70 deployment point of the sulfur gas. COSEPUP [1992] estimated the price of SO₂ to be
71 \$50,000,000 per Tg in 1992 dollars, and H₂S would be much cheaper, as it is currently removed
72 from oil as a pollutant, so the price of the gases themselves would be a minor part of the total.

73 **Airplanes**

74 Small jet fighter planes, like the F-15C Eagle (Figure 2a), are capable of flying into the
75 lower stratosphere in the tropics, while in the Arctic, larger planes, such as the KC-135
76 Stratotanker or KC-10 Extender (Figure 2b), are capable of reaching the required altitude.
77 Options for dispersing gases from planes include the addition of sulfur to the fuel, which would
78 release the aerosol through the exhaust system of the plane, or the attachment of a nozzle to
79 release the sulfur from its own tank within the plane, which would be the better option. Putting
80 sulfur in the fuel would have the problem that if the sulfur concentration were too high in the
81 fuel, it would be corrosive and affect combustion. Also, it would be necessary to have separate

82 fuel tanks for use in the stratosphere and in the troposphere, to avoid sulfate aerosol pollution in
83 the troposphere.

84 The military has already manufactured more planes than would be required for this
85 geoengineering scenario, potentially reducing the costs of this method. Since climate change is
86 an important national security issue [*Schwartz and Randall, 2003*], the military could be directed
87 to carry out this mission with existing aircraft at minimal additional cost. Furthermore, the KC-
88 135 fleet will be retired in the next few decades as a new generation of aerial tankers replaces it,
89 even if the military continues to need the in-flight refueling capability for other missions.

90 Unlike the small jet fighter planes, the KC-135 and KC-10 are used to refuel planes mid-
91 flight and already have a nozzle installed. In the tropics, one option might be for the tanker to fly
92 to the upper troposphere, and then fighter planes would ferry the sulfur gas up into the
93 stratosphere (Figure 2b). It may also be possible to have a tanker tow a glider with a hose to loft
94 the exit nozzle into the stratosphere. Certainly aircraft systems could be designed and built to
95 inject gases into the stratosphere, but here we evaluate existing aircraft.

96 In addition to the issues of how to emit the gas as a function of space and time to produce
97 the desired aerosols, another concern is the maximum concentration of sulfate aerosols through
98 which airplanes can safely fly. In the past, noticeable damage has occurred to airplanes that fly
99 through plumes of volcanic ash containing SO₂. In June, 1982, after the eruption of Galunggung
100 volcano in Java, Indonesia, two passenger planes flew through a volcanic cloud. In one case the
101 windows were pitted, volcanic ash entered the engines and thrust was lost in all four engines. In
102 the other case, the same thing happened, with the plane descending 7.5 km before the engines
103 could be restarted [*Smithsonian Institution, 1982*]. While the concentration of sulfate in the
104 stratosphere would be less than in a plume like this, and there would be no ash, in the year after

105 the 1991 Pinatubo eruption, airplanes reported acid damage to windows and other parts. An
106 engineering study would be needed to ascertain whether regular flight into a stratospheric acid
107 cloud would be safe, and how much harm it would do to airplanes.

108 The calculations for airplanes are summarized in Table 1. We assume that the sulfur gas
109 will be carried in the cargo space of the airplane, completely separate from the fuel tank. The
110 cost of each plane comes from *Air Combat Command* [2008] for the F-15C (\$29.9 million), *Air*
111 *Mobility Command* [2008a] for the KC-10 (\$88.4 million), and *Air Mobility Command* [2008b]
112 for the KC-135 (\$39.6 million), in 1998 dollars, and is then converted to 2007 dollars (latest data
113 available) by multiplying by a factor of 1.27 using the Consumer Price Index [*Williamson,*
114 2008]. If existing aircraft were converted to geoengineering use, the cost would be much less
115 and would only be for retrofitting of the airplanes to carry H₂S and installation of the proper
116 nozzles. The annual cost per aircraft for personnel, fuel, maintenance, modifications, and spare
117 parts for the older E model of the KC-135 is \$4.6 million, while it is about \$3.7 million for the
118 newer R model, based on an average of 300 flying hours per year [*Curtin, 2003*].

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

126 **Artillery Shells**

127 *COSEPUP* [1992] made calculations using 16-inch (41-cm) naval rifles, assuming that
128 aluminum oxide (Al_2O_3) dust would be injected into the stratosphere. They envisaged 40 10-
129 barrel stations operating 250 days per year with each gun barrel replaced every 1500 shots. To
130 place 5 Tg of material into the stratosphere, they estimated the annual costs, including
131 ammunition, gun barrels, stations, and personnel, as \$100 billion (1992 dollars), with the cost of
132 the Al_2O_3 only \$2.5 million of the total. So the cost for 1 Tg would be \$30 billion (2007 dollars).
133 It is amusing that they conclude, with a total lack of irony, “The rifles could be deployed at sea
134 or in empty areas (e.g., military reservations) where the noise of the shots and the fallback of
135 expended shells could be managed.”

136 **Stratospheric Balloons**

137 Requiring no fuel, weather balloons are launched on a daily basis to high levels of the
138 atmosphere. Balloons can be made out of either rubber or plastic, but plastic would be needed due
139 to the cold temperatures at the tropical tropopause or in the Arctic stratosphere, as rubber
140 balloons would break prematurely. Weather balloons are typically filled with helium. Hydrogen
141 (H_2), which is less expensive than helium, can also be used to inflate balloons but is not normally
142 used due to its flammability, as demonstrated in the Hindenburg disaster.

143 Balloons could be used in several ways for geoengineering. As suggested by L. Wood
144 (personal communication, 2008), a balloon could float in the stratosphere, suspending a hose to
145 pump gas upwards. Such a system has never been demonstrated and should probably be
146 included in the next section of this paper on exotic future ideas. Another idea is to use
147 aluminized long-duration balloons floating as reflectors [*Teller et al.*, 1997], but again, such a
148 system depends on future technology development. Here we discuss two options based on

149 current technology: lofting a payload under a balloon or mixing H₂ and H₂S inside a balloon. In
150 the first case, the additional mass of the balloon and its gas would be a weight penalty, but in the
151 second case, when the balloons burst, the H₂S would be released into the stratosphere.

152 *COSEPUP* [1992] discussed a system to loft a payload under large H₂ balloons, smaller
153 multi-balloon systems, and hot air balloons. To inject 1 Tg of H₂S into the stratosphere with H₂
154 balloons, the cost including balloons, dust, dust dispenser equipment, hydrogen, stations, and
155 personnel, was estimated to be \$20 million, which would be \$30 million in 2007 dollars. Hot air
156 balloon systems would cost 4 to 10 times that of using H₂ balloons.

157 We examined another idea, of mixing H₂ and H₂S inside a balloon, and then just
158 releasing the balloons to rise themselves and burst in the stratosphere, releasing the gases. The
159 H₂S would then oxidize to form sulfate aerosols, but we have not examined the chemical effects
160 of the H₂. Since H₂S has a molecular weight of 34 g/mol, as compared to 29 g/mol for air, by
161 mixing it with H₂, balloons can be made buoyant. The standard buoyancy of weather balloons as
162 compared to air is 20%. The largest standard weather balloon available is model number SF4-
163 0.141-.3/0-T from Aerostar International, with a maximum volume of 3990 m³, and available in
164 quantities of 10 or more for \$1,711 each. The balloons would burst at 25 mb.

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

168
$$V = 3990 \text{ m}^3 \times \frac{25 \text{ mb}}{1000 \text{ mb}} \times \frac{293 \text{ K}}{230 \text{ K}} = 127 \text{ m}^3 \quad (1)$$

169 The mass of air displaced would be:

170
$$m = \frac{pV}{RT} = \frac{1000 \text{ mb} \times 127 \text{ m}^3}{287 \frac{\text{J}}{\text{kg K}} \times 293 \text{ K}} = 151 \text{ kg} \quad (2)$$

171 To produce the required buoyancy, the balloon with its mixture of H₂ and H₂S would have a
172 mass $m' = m/1.2 = 125.9$ kg. Normally a weather balloon is filled with He, allowing it to lift an
173 additional payload beneath it. In our case, the payload will be the H₂S inside the balloon. Since
174 each balloon has a mass of 11.4 kg, the total mass of the gases would be 114.5 kg. To produce
175 that mass in that volume would require a mixture of 37.65% H₂ and 62.35% H₂S by volume, for
176 a total mass of H₂S of 110.6 kg. To put 1 Tg of gas into the stratosphere per year would
177 therefore require 9 million balloons, or 36,000 per day (using 250 days per year). This would
178 cost \$15.5 billion per year just for the balloons. According to *COSEPUP* [1992], the additional
179 costs for infrastructure, personnel, and H₂ would be \$3,600,000,000 per year, or \$5.3 billion in
180 2007 dollars, for their balloon option, and as rough guess we adopt it for ours, too. So our
181 balloon option would also cost \$21 billion per year in 2007 dollars.

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

185 **Ideas of the Future**

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

189 **Tall Tower.** The tallest structure in the world today is the KTHI-TV transmission tower
190 in Fargo, North Dakota, at 629 m high [*Smitherman*, 2000]. However, as *Smitherman* [2000]
191 explains, the heights of this tower and current tall buildings are not limited by materials or
192 construction constraints, but only because there has been no need. Currently, an untapered
193 column made of aluminum that can just support its own weight could be built to a height of 15

194 km. One made of carbon/epoxy composite materials could be built to 114 km. If the tower were
195 tapered (with a larger base), had a fractal truss system, were stabilized with guy wires, like the
196 KTHI-TV tower, or included balloons for buoyancy, it could be built much higher.

197 We can imagine such a tower on the Equator with a hose to pump the gas to the
198 stratosphere. The weather on the Equator would present no strong wind issues, as tornadoes and
199 hurricanes cannot form there, but icing issues near the top would need to be addressed. Because
200 such a tower has never been built, and many engineering issues would need to be considered,
201 from the construction material to the pumping needed, we cannot offer an estimate of the cost.
202 However, only one tower would be needed if the hose was large enough to pump the required
203 amount of gas. Weather issues, such as strong winds, would preclude such a tower at high
204 latitudes, even though it would not need to be as tall.

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

213 **Conclusions**

214 Using existing airplanes for geoengineering would cost several billion dollars per year,
215 depending on the amount, location, and type of sulfur gas injected into the stratosphere. As there
216 are currently 522 F-15C Eagles, 481 KC-135 Stratotankers, and 59 KC-10 Extenders, if a

217 fraction of them were dedicated to geoengineering, equipment costs would be minimal. Systems
218 using artillery or balloons would cost much more and would produce additional problems of
219 falling spent artillery shells or balloons, or massive H₂ injections into the stratosphere. However,
220 airplane systems would still need to address several issues before being practical, including the
221 effects of acid clouds on the airplanes and whether nozzles could be designed to produce aerosol
222 particles of the desired size distributions. All the systems we evaluate would produce serious
223 pollution issues, in terms of additional CO₂, particles, and noise in the production, transportation,
224 and implementation of the technology at the location of the systems.

225 Several billion dollars per year is a lot of money, but compared to the international gross
226 national product, this amount would not be a limiting factor in the decision of whether to proceed
227 with geoengineering. Rather, other concerns, including reduction of Asian monsoon rainfall,
228 ozone depletion, reduction of solar power, psychological effects of no more blue skies, and
229 political and ethical issues [*Robock*, 2008], will need to be compared to the potential advantages
230 before society can make this decision. As *COSEPUP* [1992] already understood, “The
231 feasibility and possible side-effects of these geoengineering options are poorly understood.
232 Their possible effects on the climate system and its chemistry need considerably more study and
233 research. They should not be implemented without careful assessment of their direct and indirect
234 consequences.”

235

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286 **Table 1.** Costs for different methods of injecting 1 Tg H₂S per year to the stratosphere.
287 Airplane data from *Air Combat Command* [2008], *Air Mobility Command* [2008a, 2008b]. Costs
288 in last two lines from *COSEPUP* [1992]. Conversion from 1992 and 1998 dollars to 2007
289 dollars (latest data available) using the Consumer Price Index [Williamson, 2008].

290

Method	Payload (tons)	Ceiling (km)	# of Units	Purchase Price (2007 dollars)	Annual Cost
F-15C Eagle	8	20	167 with 3 flights/day	\$6,363,000,000	\$4,175,000,000*
KC-135 Tanker	91	15	15 with 3 flights/day	\$755,000,000	\$375,000,000
KC-10 Extender	160	13	9 with 3 flights/day	\$1,080,000,000	\$225,000,000*
Naval Rifles	0.5		8,000 shots per day	included in annual cost	\$30,000,000,000
Stratospheric Balloons	4		37,000 per day	included in annual cost	\$21,000,000,000-\$30,000,000,000

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

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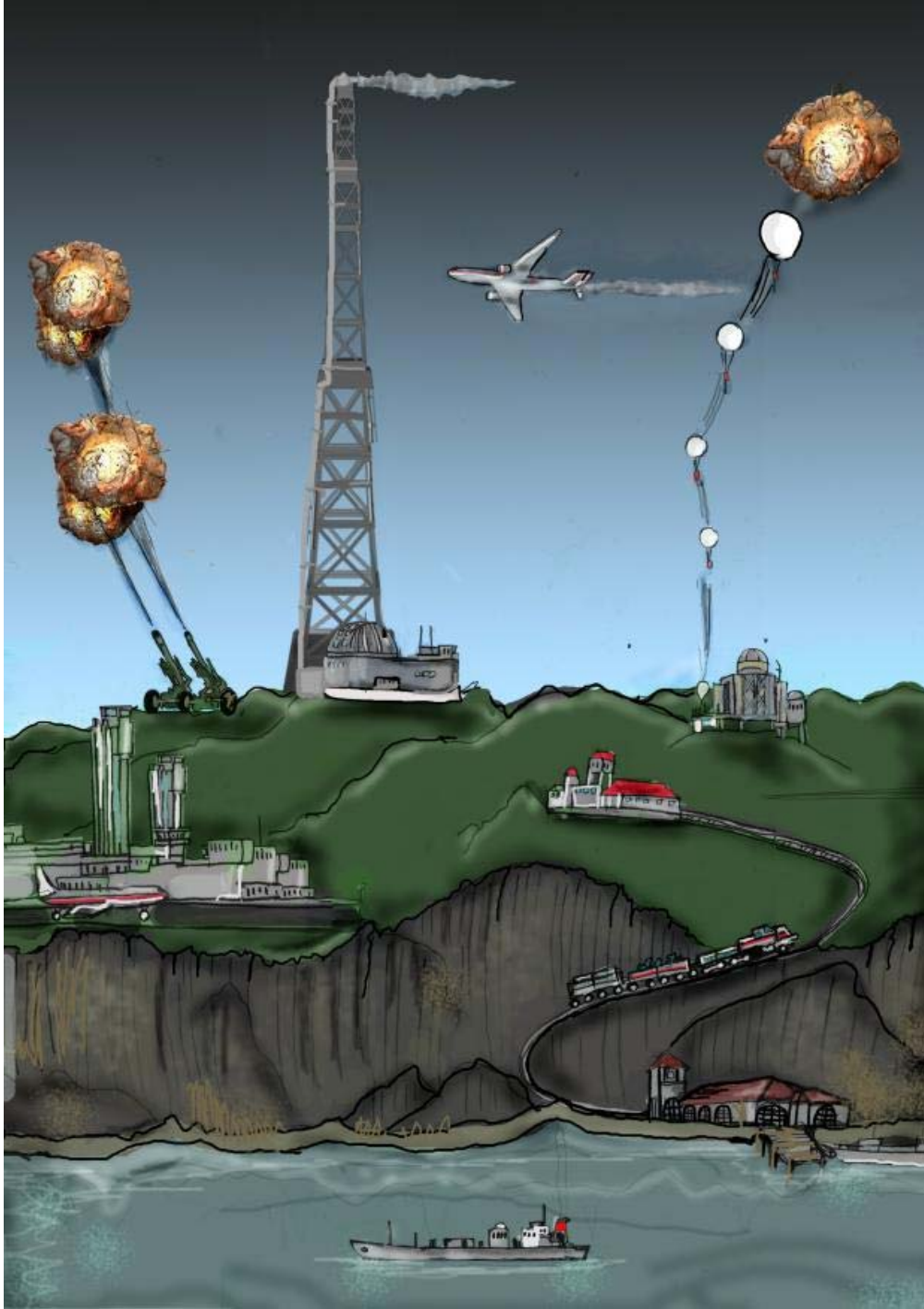


Figure 1. Proposed methods of stratospheric aerosol injection. A mountain top location would require less energy for lofting to stratosphere. Drawing by Brian West.



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)