The Stratospheric Shield

A practical, low-cost way to reverse catastrophic warming of the Arctic—or the entire planet

Introduction

Massive shifts are underway in the global energy system as humanity attempts to curtail the release of the gases responsible for greenhouse warming. Yet relatively little progress has been made so far in reducing global emissions of greenhouse gases; concentrations of carbon dioxide (CO_2), methane, and other contributors to the warming continue to increase in earth's atmosphere [Hoffmann 2009, Raupach et al. 2007]. At the same time, scientific projections of the possible future warming and associated changes to precipitation, heat waves, and major storms have generally grown more alarming[IPCC 2007].

A number of leading scientists have voiced concern that our best efforts to reduce emissions through conservation, improvements to energy efficiencies, and shifts to cleaner sources of energy may not be sufficiently fast to prevent intolerable climate change. They have proposed a variety of technologies—commonly called "geoengineering"—that could reverse global warming temporarily, buying time for the global economy to complete its move to a more sustainable energy system [Crutzen 2006, Cicerone 2006, Royal Society 2008].

These proposals have generated a lively and fruitful debate within the scientific community and the public at large about the cost and practicality of various geoengineering technologies, as well as possible unintended side effects of their use. Intellectual Ventures hopes to play a constructive role in this debate as a source of innovative technical ideas for solving some of these issues. We have funded research in this area—and are encouraging others to do so as well—because it would be irresponsible for the technical community to postpone such work until a climate emergency was actually underway. Intellectual Ventures does not advocate construction or deployment of geoengineering systems now, and we hope they will never be needed. But the prudent course is to begin studying options immediately. (See "Climate Science and Engineering at Intellectual Ventures" for further discussion about the role of geoengineering.)

A Global Cooling System

Scientists have proposed a wide variety of approaches for cooling part or all of the Earth [Blackstock et al. 2009]. One approach has received more attention than the others, however: the idea of increasing the amount of sulfur-bearing aerosols in the stratosphere and thereby decreasing slightly the amount of sunlight that reaches the earth [Kunzig 2009]. (The stratosphere is the weather-free portion of the atmosphere at altitudes between about 10 kilometers and 50 kilometers, or 33,000 to 165,000 feet.)

The attractiveness of this approach stems largely from the fact that it happens naturally during large volcanic eruptions, such as the eruption of Mount Pinatubo in the Philippines in 1991. Intensive scientific study of the Pinatubo eruption showed that sulfur dioxide aerosols injected high in the atmosphere cooled the planet by reflecting more incoming sunlight back into space [Robock 2002]. An even larger eruption in 1815 of Mount Tambora in Indonesia led to the second-coldest year in the northern hemisphere in four centuries, the "year without a summer" [Briffa et al. 1998].

Importantly, the cooling effect begins immediately, but is short-lived: unlike carbon dioxide emissions, which persist in the upper atmosphere, warming the earth for centuries [Matthews and Caldeira 2008], sulfur dioxide aerosols appear to remain in the stratosphere for only a year or two after injection before falling back to Earth [Caldeira and Wood 2008]. Any geoengineering system should ideally be not only quick-acting but also quickly reversible, so that the climate returns to its previous state soon after the system is turned off. This provides a measure of safety in case any damaging side effects appear when the system is deployed.

Also important is the fact that aerosols in the stratosphere tend to migrate toward the poles. Thus aerosols injected at the Arctic Circle would be expected to cool the Arctic but to have little or no effect on sunlight received by the temperate and tropical parts of the Earth. Aerosols injected into the atmosphere above Antarctica will similarly tend to disperse gradually toward the South Pole. To cover the entire planet, the spray would have to be released at a variety of latitudes, including sites near the equator.

The general poleward migration of high-altitude aerosols is useful for two reasons. First, it allows small-scale testing of a geoengineering system. A pilot project could be set up in northern Alaska or northern Europe, for example.

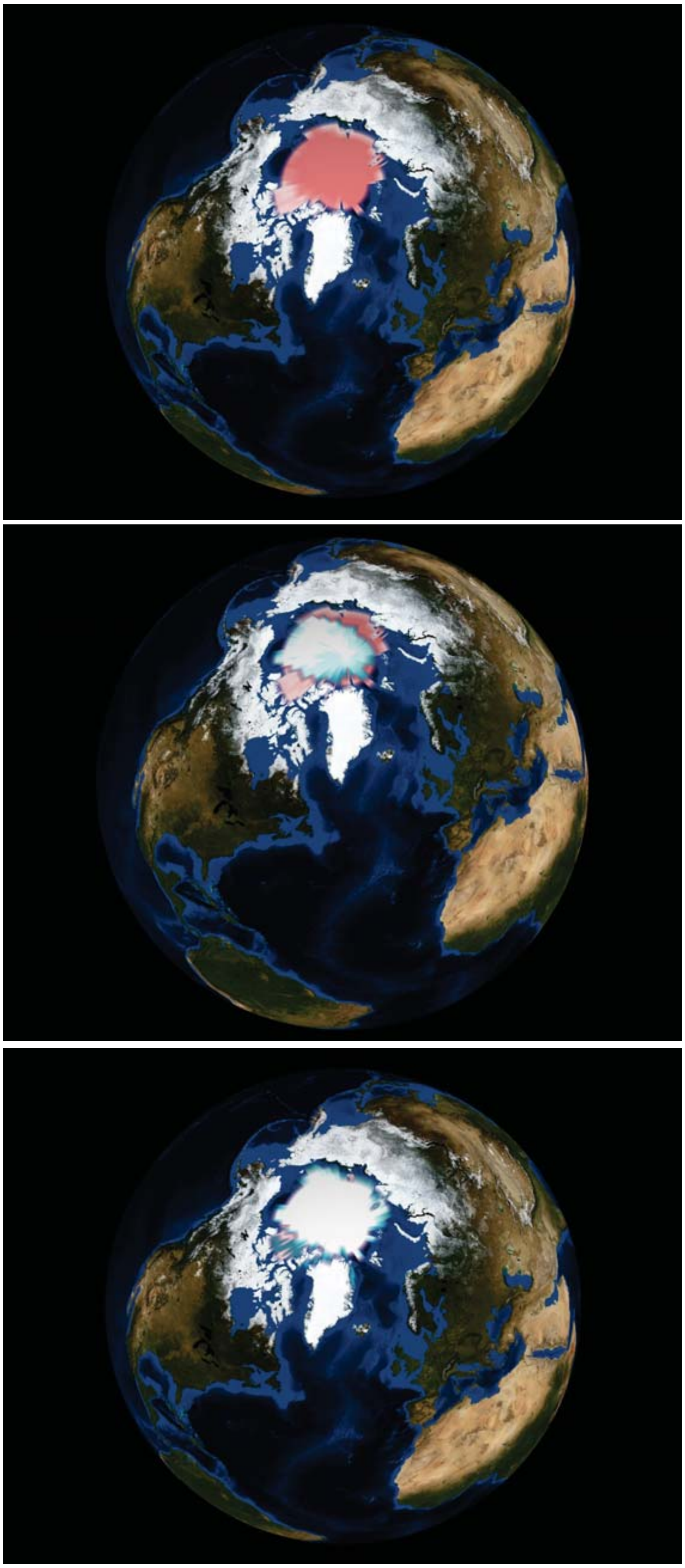
Second, the polar regions have so far experienced far greater warming than has the rest of the planet, and climate models project that this trend will continue [IPCC 2007]. If a climate emergency does occur that would warrant use of geoengineering, it seems probable that it will affect the Arctic or Antarctic ice caps first and more severely—indeed, an abrupt shift in climate may already be underway in the Arctic [Kerr 2007]. Systems that can concentrate their cooling effects to the northernmost or southernmost parts of the planet are thus more useful than those that only work uniformly on the entire Earth at once.

To estimate how much sunlight would need to be reflected to offset greenhouse warming of the Arctic or of the entire planet, scientists have turned to the same computer models that they use to project climate change scenarios [Caldeira and Wood 2008]. These models suggest that reducing incoming solar radiation by about 1.8% worldwide would offset the greenhouse warming caused by the doubling of CO_2 concentration from its level in preindustrial times. (The CO_2 concentration is currently about 1.4 times its preindustrial level and rising steadily. [Hoffman 2009])

Such a small change in solar radiation would almost certainly be imperceptible to our eyes. Because incoming sunlight would be more diffuse, scientists believe that stratospheric aerosols would increase plant growth, boosting agricultural productivity and increasing the rate at which carbon dioxide is absorbed out of the atmosphere [Robock et al. 2009]. More studies are needed to understand the magnitude of this effect and whether it could help to alleviate other consequences of high CO_2 levels, such as changes to the pH of the oceans.

Preliminary modeling studies suggest that two million to five million metric tons of sulfur dioxide aerosols (carrying one million to 2.5 million tons of sulfur), injected into the stratosphere each year, would reverse global warming due to a doubling of CO_2, if the aerosol particles are sufficiently small and well dispersed [Rasch et al. 2008]. Two million tons may sound like a lot, but it equates to roughly 2% of the SO_2 that now rises into the atmosphere each year, about half of it from manmade sources [Caldeira and Wood 2008], and far less than the 20 million tons of sulfur dioxide released over the course of a few days by the 1991 eruption of Mount Pinatubo [Robok et al. 2009]. Scientific studies published so far conclude that any increase in the acidity of rain and snow as several million additional tons a year of SO_2 precipitate out of the atmosphere would be minuscule and would not disrupt ecosystems [Kravitz et al. 2009].

A more limited geoengineering system designed to rescue



RESCUING ARCTIC SUMMER SEA ICE may be necessary—and possible—if CO_2 levels continue to rise, according to computer models of the global climate. The extent of ice cover on the Arctic Ocean at the end of September is shown at top for a world with preindustrial CO_2 levels (*pink*). The fraction covered by ice is much smaller if CO_2 levels double (*middle*). Models indicate that if a stratospheric aerosol shield reduced sunlight over latitudes north of 60°N by 10%, the ice cap would be restored to its former extent each summer (*bottom*).

CREDIT: Maps by Wayt Gibbs; data courtesy of Ken Caldeira, Carnegie Institute of Washington the Arctic ice cap and tundra from catastrophic warming (with much less cooling of the rest of the planet) would aim to attenuate the solar radiation hitting the Arctic and sub-Arctic latitudes of 60°N and higher by about 10%. Climate models indicate that this would lead to average temperatures in the region being about 2.8 °C (5 °F) lower than they would be without the system—enough to restore sea ice in the Arctic to its preindustrial extent. Snow depth might actually increase a bit over what it was before global warming began [Caldeira and Wood 2008].

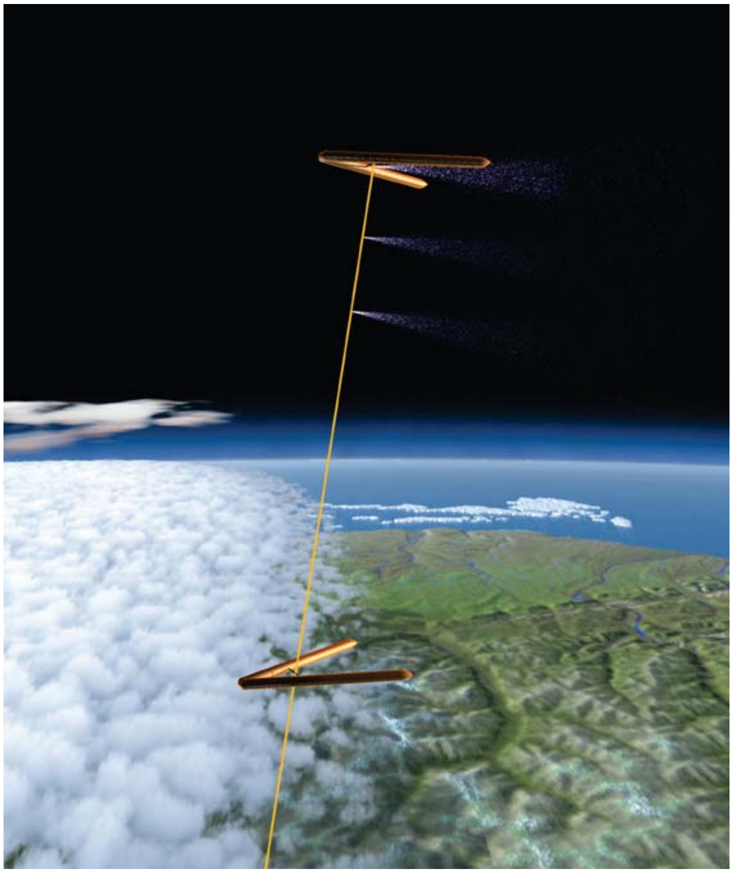
Because about 10% of the planet lies north of 60°N—which is roughly the latitude of Anchorage, Alaska or Oslo, Norway—a rough first-order estimate is that injection of as little as 200,000 metric tons a year of sulfur dioxide aerosol into the stratosphere above this region could offset warming within the Arctic. A phenomena peculiar to the polar atmosphere, the polar stratospheric vortex, adds uncertainty to this estimate, however. The vortex causes mixing between stratospheric air and the lower part of the atmosphere to occur more rapidly in the Arctic than at lower latitudes. As a result, aerosol particles injected into the stratosphere at latitudes above 60°N will probably fall back to Earth in less than a year, on average. To compensate for this effect—and because the aerosols serve no purpose during the dark polar winter—it would thus make sense to concentrate the injection period to just the spring, so that the cooling effect is at maximum strength during the summer melting season.

Cutting the Cost: A Hose is Better than Bombs

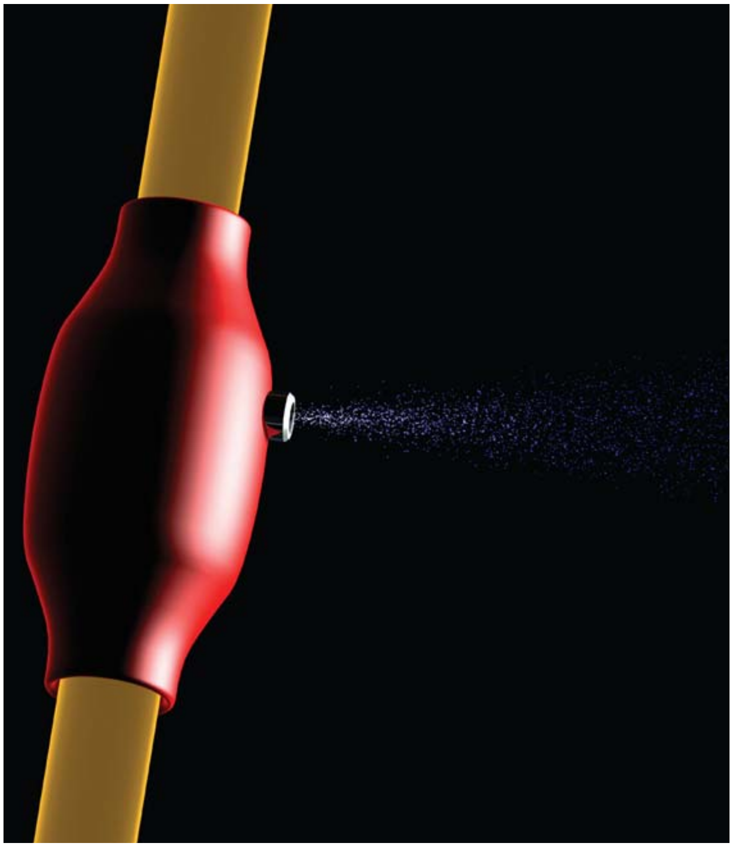
Lifting large masses of aerosols—or of anything, for that matter—up to the stratosphere poses a substantial engineering challenge. One of the principal criticisms of geoengineering proposals so far has been cost: published estimates of the construction costs of delivery systems of various kinds have run from $784 million to $6.6 billion, with estimated operating costs ranging from $225 million to $30 billion a year, depending on whether aircraft, artillery, or sulfur-filled exploding balloons were envisioned as vehicles for the aerosols [Robock et al. 2009].

In a series of invention sessions over the past several years, scientists and engineers at Intellectual Ventures have fleshed out ideas for a geoengineering system that could be far less expensive and more practical than others proposed to date. Called a Stratospheric Shield, or StratoShield for short, the system would deliver sulfur dioxide to an altitude of 30 kilometers in liquid form, through a very long hose supported by large, long-duration balloons. At the top of the hose, a series of atomizers would disperse the liquid into a fine mist of aerosol particles, each about 100 nanometers in diameter.

In the calculations we performed to validate this approach (described below), we focused on an installation capable of



HIGH-FLYING BLIMPS, based on existing protoypes, could support a hose no thicker than a fire hose (*above*) to carry sulfur dioxide as a clear liquid up to the stratosphere, where one or more nozzles (*below*) would atomize it into a fine mist of nanometer-scale aerosol particles. CREDIT: David Fierstein



pumping 100,000 metric tons a year (about 3.2 kilograms a second) of liquid sulfur dioxide up to the stratosphere, where it would be dispersed by atomizers into a fine mist. Several installations of this size—or one larger installation with several hoses—might be needed to save the Arctic from runaway warming, if they were operated only in the spring rather than year-round.

If at some point world leaders decided that a climate emergency warranted deployment of Stratospheric Shields on a global scale, a dozen or more installations of the size sketched out here could be set up around the world, with most of them at tropical and temperate latitudes, to erect an invisible reflective shield that could counteract greenhouse warming worldwide.

Our work so far, which represents substantial inventive activity but is still quite preliminary, suggests that the cost to construct a Stratospheric Shield with a pumping capacity of 100,000 tons a year would be roughly $24 million, including transportation and assembly. Annual operating costs would run approximately $10 million. The system would use only technologies and materials that already exist—although some improvements may be needed to existing atomizer technology in order to achieve wide sprays of nanometer-scale sulfur dioxide particles and to prevent the particles from coalescing into larger droplets.

Even if these cost estimates are off by a factor of 10 (and we think that is unlikely), this work appears to remove cost as an obstacle to cooling an overheated planet by technological means.

The Stratospheric Shield, and geoengineering in general, must still clear many other obstacles, however, before such systems can reasonably be considered for deployment. A concerted, well-funded, long-term research effort is needed to answer the many questions that remain. What effect would cooling by stratospheric aerosols have on shifts in precipitation, increasing acidification of the oceans, and other environmental changes driven by rising levels of CO_2? How would additional SO_2 in the stratosphere interact with the ozone layer? Are there compounds that would perform better than sulfur dioxide as reflectors, that would be even less expensive, or that would be lighter and thus easier to lift?

Now is the time for the science and engineering community to engage fully in the research needed to answer such questions. There currently is no business model for geoengineering that would encourage creative firms such as Intellectual Ventures to ramp up and maintain a serious research effort. But it is too important a topic to leave for the indefinite future.

In the following sections, we present more details on the Stratospheric Shield in the hope that it will inform and inspire others to refine the idea and to generate other inventions for coping with the defining problem of the 21st century.

References and Further Reading

J. J. Blackstock, D. S. Battisti, K. Caldeira, D. M. Eardley, J. I. Katz, D. W. Keith, A. A. N. Patrinos, D. P. Schrag, R. H. Socolow and S. E. Koonin, *Climate Engineering Responses to Climate Emergencies*, Novim, 2009.

K. R. Briffa, P. D. Jones, F. H. Schweingruber, and T. J. Osborn. Influence of volcanic eruptions on Northern Hemisphere summer temperature over 600 years. *Nature* **393**, pp. 450–455, 4 June 1998.

K. Caldeira and L. Wood. Global and Arctic climate engineering: numerical model studies. *Philosophical Transactions of the Royal Society A*, **366**, pp. 4039–4056, 2008.

R. J. Cicerone. Geoengineering: Encouraging research and overseeing implementation. *Climatic Change* **77**, pp. 221–226, 2006.

P. J. Crutzen. Albedo enhancement by stratospheric sulfur injections: a contribution to resolve a policy dilemma? *Climatic Change* **77**, pp. 211–220, 2006.

D. J. Hoffmann. The NOAA Annual Greenhouse Gas Index. NOAA, 2009.

Intellectual Ventures. Climate Science and Engineering at Intellectual Ventures. White paper, 2009.

IPCC. Climate Change 2007: The Physical Science Basis. Cambridge University Press, 2007.

R. A. Kerr. Is Battered Arctic Sea Ice Down for the Count? *Science* 318, pp. 33–34, 5 October 2007.

B. Kravitz, A. Robock, L. Oman, G. Stenchikov, and A. B. Marquardt. Sulfuric acid deposition from stratospheric geoengineering with sulfate aerosols. *Journal of Geophysical Research* **114**, D14109, 2009.

R. Kunzig. A Sunshade for Planet Earth. *Scientific American*, pp. 46–55, November 2008.

H.D. Matthews and K. Caldeira. Stabilizing climate requires near-zero emissions. *Geophysical Research Letters* **35**, L04705, 2008.

P. J. Rasch, S. Tilmes, R. P. Turco, A. Robock, L. Oman, C. C. Chen, G. L. Stenchikov, and R. R. Garcia. An overview of geoengineering of climate using stratospheric sulphate aerosols. *Philosophical Transactions of the Royal Society A* **366**, pp. 4007–4027, September 2008.

M. R. Raupach, G. Marland, P. Ciais, C. Le Quere, J. G. Canadell, G. Klepper, and C. B. Field. Global and regional drivers of accelerating CO2 emissions. *Proceedings of the National Academy of Sciences of the U.S.A.* **104**: 24, 2007.

A. Robock. The Climatic Aftermath. *Science* **295**, pp. 1242–1243, 15 February 2002.

A. Robock, A. Marquardt, B. Kravitz, and G. Stenchikov. Benefits, risks, and costs of stratospheric geoengineering. *Geophysical Research Letters* **36**, L19703, 2009.

The Royal Society of London. Special issue on geoengineering. *Philosophical Transactions of the Royal Society A* **366**, September 2008.

Pumping to the Stratosphere

To understand some of the important design parameters and engineering trade-offs for a Stratospheric Shield, we analyzed a system that could raise 100,000 tons of liquid a year from the ground to an elevation of 30 kilometers (100,000 feet). Delaying for a moment the question of how to support the hose, let's concentrate first on the fluid flow, which for the purposes of this exercise we assume will be constant.

Although 100,000 tons a year sounds like a lot of liquid, when pumped continuously through a hose, that amounts to just 3.2 kilograms per second and, at a liquid SO_2 density of 1.46 grams per cubic centimeter, a mere 34 gallons (150 liters) per minute. A garden hose with a ¾-inch inner diameter can deliver liquid that fast.

It takes quite a bit of energy to lift material into the stratosphere: about 30 trillion Joules of potential energy, in fact, to lift 100,000 tons to a height of 30 kilometers. If the work is spread out over the course of a year, however, that energy translates to a required power of just 1,000 kilowatts. Inefficiencies and other practical considerations will increase this amount, possibly by several times; nonetheless, the power levels are not daunting by industrial standards.

To pump 34 gallons a minute up a 30-kilometer-long hose, the system must overcome both the gravitational head and the flow resistance. The gravitational head, which is simply another way of talking about the potential energy considered previously, would amount to a pressure of 4,300 bar (62,000 p.s.i.) if the liquid has a constant density of 1.46 g/cm^3—not taking into account the small attenuation in the strength of gravity with increasing altitude.

The density of the SO_2 does not remain constant during its journey through the hose, however. That transit takes enough time that at any point in length of the hose, the temperature of the liquid inside the hose is not too far from the temperature of the air outside it, although friction from the flow will impart some heat to the fluid. Air temperature drops with altitude, and so will the temperature of the SO_2; the density of the liquid thus increases with altitude. The magnitude of the density change will vary depending on the site of the StratoShield as well as the season and time of day, but we can use the thermal profile of the Standard Atmosphere to estimate a typical value: between 1.40 g/cm^3 and 1.57 g/cm^3. This density range from bottom to top produces an overall gravitational head of 4,520 bar. There isn't much we can do about gravity except fight it with pumping power.

We have more control over the second kind of impediment, flow resistance. This pressure arises from drag forces imposed on the fluid by the walls of the pipe. By selecting the diameter of the hose and other design characteristics, we can choose whether the flow resistance pressure is much greater than the gravitational head or much less than it. A lower flow resistance might seem always preferable, but it comes at a price: a larger diameter hose, which means more mass for the balloons to support.

The weight of both the hose itself and the fluid it contains increase quickly as hose diameter expands. Consider two designs, one using a hose with a diameter of ⅝ inch (1.6 cm), the other a hose 1½ inches (3.8 cm) in diameter. The ⅝-inch hose has a cross-sectional area of 1.98 cm^2, which means that the flow velocity at the ground must be 11.4 m/s to achieve the required 34 gallons per minute delivery rate. (The flow velocity for this hose drops to 10.2 m/s at higher altitudes, due to cooling of the SO_2.)

To calculate the resulting flow resistance, we need to factor in the flow's Reynolds number and also the effect of pipe roughness. We'll assume a wall roughness of ½ mil (13 micron). The Reynolds number, like density, is a function of temperature and thus altitude. It changes along the hose by more than a factor of two—from 320,000 to 810,000—due to the temperature-induced gradients in density, viscosity, and velocity.

Fortunately, this variation in the Reynolds number has very little effect. The flow resistance remains essentially constant along the hose, ranging from 1,000 to 1,100 bar/km. The total flow-induced pressure head for the ⅝-inch hose is thus 30,800 bar, much larger than the 4,500 bar gravitational head. For a ⅝-inch hose, drag forces thus largely determine our pumping power.

In contrast, a 1½-inch hose can deliver the payload at a flow rate under 2 m/s, which generates a markedly smaller flow resistance of just 360 bar. The price for this huge reduction in pumping requirements is, of course, the need to generate more lift to support a heavier hose. The SO_2 alone in the ⅝-inch hose weighs 9.1 tons, whereas the liquid in the 1½-inch hose comes to a whopping 52.5 tons. The larger-bore hose will also weigh more than the thin hose, of course, but that difference is at least partially offset by the need to install more pumps (and electrical cable to run them) along the length of the thin hose. The choice of the optimum hose diameter thus requires a complex set of design trade-offs; one cannot simply peg the flow resistance to some percentage of the gravitational pressure head.

Option 1: A Big Pump on the Ground

Raising the fluid up the entire length of the hose with a single pump on the ground may seem impractical. A more feasible alternative, we thought, would be to distribute a series of small pumps at intervals along the hose. Each pump could then be of lower power, because it would only have to raise the liquid as far as the next pump. In effect, this does an end-run around gravity.

With further thought, however, we recognized that pumping from the ground, either using one large pump or a set of pumps in series, offers a number of advantages. Maintenance and replacement would be significantly easier, for example. Keeping the pumps on the ground would reduce the size of the balloons required and could eliminate the need to run electrical wiring up the hose.

Another important, but less obvious, advantage of pumping from the ground is that in such a system the pump can support the mass of the SO_2 liquid, through the pressure it delivers. Flow resistance will actually push up on the hose material and can be used to support part of its mass as well. These effects greatly reduce the lift necessary to raise the hose to altitude.

Unfortunately, however, a hose supported this way would be unstable to sideways wind forces, which can impose lateral momentum far greater than the upward momentum delivered by the flow of SO_2. Supporting most of the system weight with ground pressure is also ill-advised because of the possibility that a disruption of pump operation could cause the StratoShield to fall precipitously. A system pumped from the ground would thus probably need enough external support to handle wind forces and pump failures safely.

Support issues aside, an obvious drawback to pumping only from the ground is that the resulting pressures inside the hose must be extremely large. The hose wall must be thickened to withstand the high pressure, and the density of the SO_2 (which is a compressible fluid) will increase. The magnitude of this latter effect is not completely clear. Experimental data on the compressibility of liquid SO_2 extends only up to about 350 bar, which is not even a tenth of the gravitational head in the StratoShield. What data there are show that SO_2 has compressibility at 0 °C of 1.1 x 10^{-9}/Pa (1.1 x 10^{-4}/bar), a value about twice that of water. Using the existing data to fit an expression for the linear-secant modulus, we expect a 20% density increase at 4,500 bar and 0 °C.

TABLE 1. Hose Options for a Stratospheric Shield Pumped from the Ground

Hose diameter (cm)	Gravitational head (bar)	Flow resistance (bar)	Total pressure (bar)	SO_2 mass (metric tons)	Mass of fluid-filled hose (metric tons)
2.0	5,470	15,600	21,060	17.5	31.7
2.5	5,280	6,480	11,760	26.5	39.0
3.0	5,170	3,160	8,330	37.3	50.2
3.5	5,100	1,720	6,830	50.1	64.5
4.0	5,070	1,020	6,090	65.0	81.6
4.5	5,050	640	5,690	81.9	101.5

At the lower temperatures encountered throughout most of the hose, the SO_2 is stiffer. We estimate that the integrated pressure head, taking into account the pressure and temperature dependence of the compressibility, is about 5,000 bar. So, for a relatively fat hose, where the pressure is dominated by gravitational head, compressibility is not a major concern, even if we are pumping solely from a ground station. Compressibility becomes a much larger issue if the hose is narrow, due to the additive effect of flow resistance.

Hoses capable of containing pressures above 5,000 bar are already available commercially, so this does not seem to present a difficult technical challenge. High-pressure hoses are heavier, however. The question is whether the hose material and thickness required is compatible with a StratoShield system. Consider a hose made from a composite (possibly multilayered) material 10 mil (254 micron) thick with a mass of 400 g/m^2. A layer of high-strength Zylon fibers woven into the hose wall contain the high fluid pressure and are designed to reduce the operating stress from 800,000+ psi to a long-term creep-resistant value of 340,000 psi.

The hose mass required to confine a pressure of 5,000 bar scales with the mass of the fluid and the ratio of pressure to fiber strength. For most of the hose's length, the pressure-resistant mass dominates, requiring a hose mass of about 40% that of the SO_2. This penalty is highest at the base and decreases with height as the pressure requirement falls. The hose, in other words, need not be as strong and heavy at the top as it is

TABLE 2. Hose Options for a Stratospheric Shield with Airborne Pumps

Hose diameter (cm)	Gravitational head (bar)	Flow resistance (bar)	Total pressure (bar)	SO_2 mass (metric tons)	Mass of fluid-filled hose (metric tons)
2.0	4,520	18,810	23,330	14.5	15.4
2.5	4,520	7,550	12,070	22.6	23.8
3.0	4,520	3,610	8,130	32.6	34.0
3.5	4,520	1,940	6,460	44.3	46.0
4.0	4,520	1,140	5,660	57.9	59.9
4.5	4,520	720	5,240	73.3	75.6

at the bottom, if all the pumping is done on the ground.

For large diameter hoses, the pressure is dominated by the gravitational head, and the hose weight is dominated by the large diameter of the hose rather than the thickness of the wall. For narrow hoses, flow resistance increases the pressure, the compressibility of the fluid, and hence the weight penalty imposed by hose wall thickness. On the other hand, the overall mass can be lower for a narrow hose simply because it encloses a smaller volume.

Option 2: Smaller Pumps in the Air

Instead of relying solely on a big pump on the ground, we could place a series of pumps at intervals along the hose. Large pressures and fluid compressibility then cease to be concerns, and the hose can be lighter and have thinner walls. Each pump need deliver only modest pressure, and we could build extras into the chain so that the system can tolerate occasional pump failures. The total mass requiring support will be greater than what is shown in table 2, however, because it will include the additional weight of the pumps themselves as well as the electrical cables that power them.

The total pumping power required for the distributed approach is, of course, very similar to that for a ground-based pump, but there are small differences. The absence of compressibility reduces the gravitational head, but for low diameter hoses this effect is more than offset by the fact that denser fluid requires lower flow velocities and hence incurs less flow resistance.

Up, Up, and Away

Let us turn now to the question of how to raise the hose to the sky and hold it there. Others have suggested building enormous towers to support a hose, but this seems unnecessarily expensive and risky. A more practical way to support a hose to the sky is to harness atmospheric forces, either buoyancy or aerodynamic lift.

Balloons and blimps are well developed technologies, and are quite capable of lofting the hose weights presented in tables 1 and 2. As with pumping, we can choose among several strategies. One extreme is to lift only from the top of the hose, using a single long-duration balloon of 200 meters or more in diameter, flying at an altitude of about 30 kilometers. (A cluster of 100-meter-diameter balloons could work as well.) The hose material must then have sufficient tensile strength to support the entire system, or must be assisted by additional support cables. Because atmospheric density is low in the stratosphere, the balloon would have to be enormous to develop enough buoyancy.

At the opposite end of the range of strategies is an approach in which the hose itself is buoyant, so that every point along its length carries its own weight. (For a preliminary analysis of this option, see Blackstock *et al.* 2009.) In between these two extremes are intermediate strategies that use multiple balloons, each of which supports one segment of the hose. This approach allows the balloons to fly at lower altitudes and thus to be smaller (*see illustration on next page*). The hose itself need have minimal tensile strength, which translates to lighter weight.

One benchmark that is useful is considering these options is NASA's long-standing project to develop and demonstrate large, high-altitude balloons that are superpressurized with helium. A mission in December 2008 flew one such balloon that was 80 meters in diameter (200,000 m^3 volume) to an altitude of 33 kilometers. NASA plans to fly even larger balloons, of over 600,000 m^3 volume, in future missions.

The NASA balloons are not spherical, but rather are pumpkin-shaped for greater structural efficiency. The envelope has an isotensoid meridional profile and a multi-lobed, azimuthal shape. A thin-walled plastic material both contains the helium and transfers the internal gas pressure azimuthally to the meridional borders of each lobe. Global pressure loads are then handled by strong fibers running along each meridional cusp.

Table 3 shows the lifting capacity of such balloons as a function of their size and of altitude along the hose (*see page* 9). These figures show that a series of small balloons, each 20 to 30 meters in diameter and spaced roughly a kilometer from the next, should easily support typical hose weights of 1 to 2 ton/km along the lower half of the hose. Near the top of the hose, however, larger balloons of 60 to 70 meters in diameter would be needed (or alternatively more small balloons spaced closer together).

The distributed support strategy offers us considerable design freedom, because balloons need not be equal in size or set at equal intervals. Nor, given the tensile carrying capability of the hose, do lift and weight have to be balanced to close tolerances at each location. We could, for instance, elect to devote 0.2 ton/km of the hose mass to the strong Zylon fibers previously discussed; this strategy would yield a hose with a 30-ton carrying capacity, allowing very large offsets of lift to weight.

Blowing in the Wind

Given all these options, a support system would be straightforward to design—if only there were no wind. Unfortunately, winds at altitude are strong, often blow in different directions at different altitudes, and can change speed and direction rapidly. The need to deal with the static and dynamic forces imposed by wind will greatly influence the design of the hose's aerial support.

The existence of winds prevent the question of top-hung vs. distributed support from being the open-and-shut case it would otherwise be. The most efficient way structurally to help a long, thin object such as the hose resist sideways deflection by the wind is to draw it taut—exactly what a giant balloon at the top would do. Moreover, the strongest and most variable winds do not occur in the stratosphere, but at intermediate altitudes of around 10 kilometers (33,000 feet)—altitudes where one might distribute smaller support balloons. Lofting balloons in the windiest part of the atmosphere will expose the system to more wind stress.

Wind speeds generally increase in altitude, reaching values around 60 m/s at heights of 10 to 15 kilometers. When convolved with the atmospheric density profile, the dynamic pressures generated by the wind peak at roughly 1,000 Pa in the vicinity of 10 km altitude.

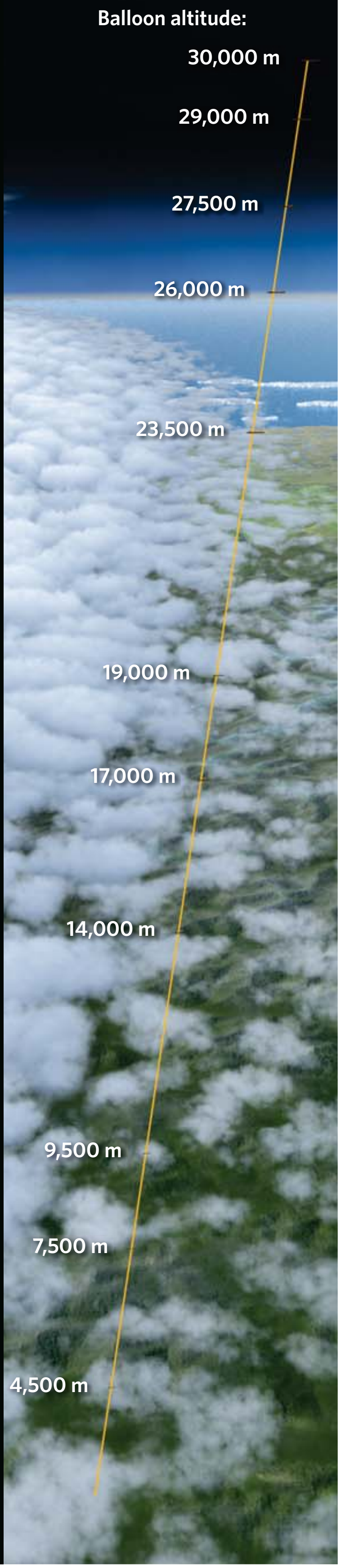
The wind pushes both the balloons and the hose itself. These should be thus designed to minimize drag and to present the smallest cross-section to the wind achievable (particularly for segments near 10 km altitude, where the wind forces are highest).

The balloons pose the greater challenge because of their larger lateral area: a single spherical balloon 35 meters in diameter presents about 1,000 m^2 of area to the wind, for example, which is about the same lateral area as the entire length of a hose 3 centimeters wide and 30 km long. Omitting balloons from the hose in the region around 10 km altitude would reduce the dynamic pressure on the system. But if the hose is denuded of balloons in its middle, the balloons at higher altitudes must be correspondingly larger.

To illustrate the trade-off, let's compare two designs for supporting a StratoShield that includes a hose 3 cm in diame-

Supporting a StratoShield with Multiple V-shaped Balloons

There are many possible ways to support a 30-kilometer-long hose to the stratosphere. Illustrated here is a series of 11 V-shaped blimps of three distinct sizes. The balloons are numbered from top to bottom.

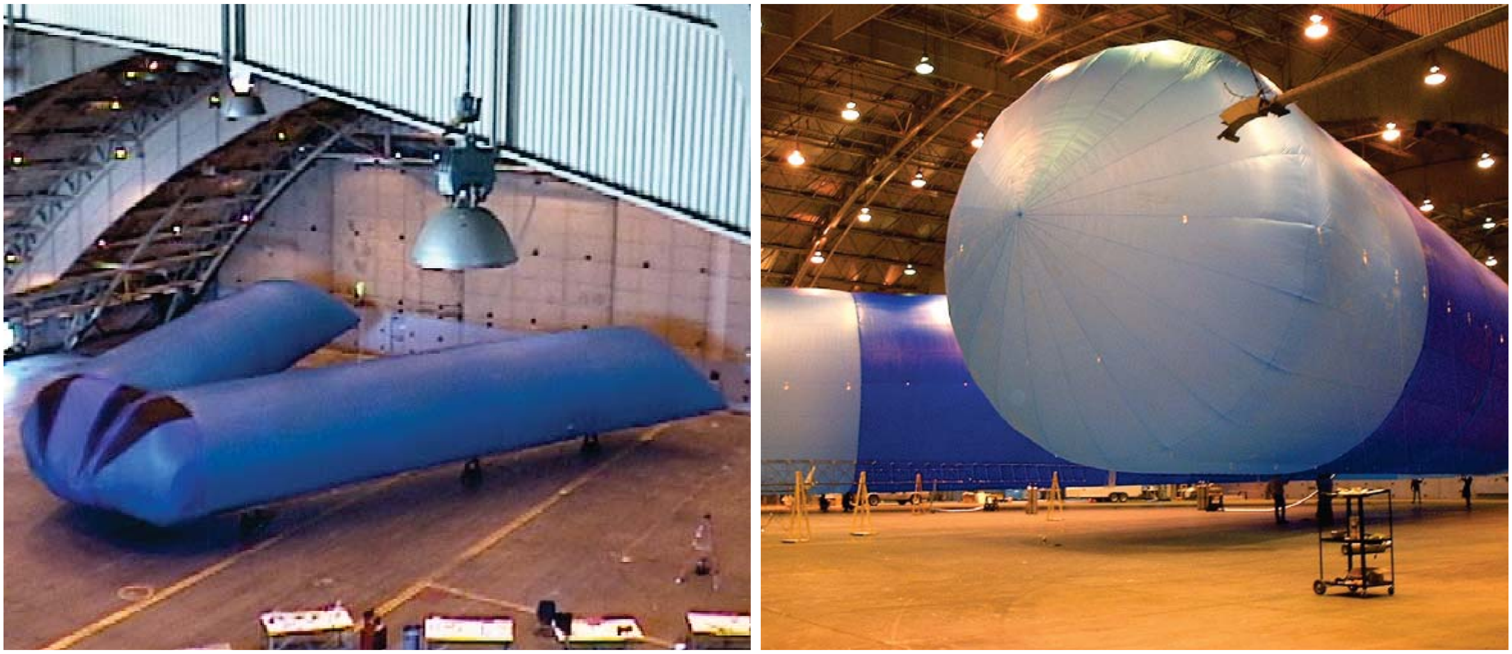


Balloons 1–5
Arm length: 330 m
X-sectional diameter: 22 m

Balloons 6–8
Arm length: 225 m
X-sectional diameter: 15 m

Balloons 9–11
Arm length: 150 m
X-sectional diameter: 10 m

For the entire set
Estimated wind drag: 170 kN
Estimated lift: 1,000 kN
Lift-to-drag ratio: 6:1
Est. slant angle: <10°



V-SHAPED BLIMPS large enough to be used in a StratoShield system have been constructed by JP Aerospace in Rancho Cordova, California.

CREDIT: Courtesy of JP Aerospace

ter, pumped solely from the ground. For safety, let's assume the balloons must support the full 50 tons of the lofted structure plus the SO_2 payload, not just the weight of the empty hose.

The first design balances lift and weight locally, as they vary along the hose, by placing balloons of appropriate size every half kilometer. The balloons range in diameter from 15 meters at the base to 56 meters at the top. Altogether, the balloons present an aggregate lateral area of 30,000 m^2 to the wind—30 times the area of the hose itself. When convolved with the dynamic wind pressure, the aggregate side force (for a drag coefficient of 1) is 3.3 MNwt, which is more than six times the weight of the hose.

TABLE 3. Lifting Capacity, in metric tons, of Pumpkin-shaped Balloons

	Diameter				
Altitude (km)	20 m	40 m	60 m	80 m	100 m
0	2.65	21.4	72.3	171.6	335.4
3	1.96	15.9	53.7	127.5	249.3
6	1.42	11.5	39.1	92.8	181.5
9	0.99	8.12	27.6	65.6	128.3
12	0.65	5.38	18.3	43.7	85.6
15	0.39	3.30	11.3	27.1	53.1
18	0.23	2.01	6.95	16.7	32.8
21	0.13	1.18	4.18	10.1	20.0
24	0.064	0.67	2.45	6.02	12.0
27	0.025	0.36	1.39	3.52	7.12
30	0.001	0.17	0.74	1.97	4.10

The second design balances lift and weight globally, by placing balloons only near the top of the hose, at a spacing of a half kilometer between the altitudes of 20 and 30 km. The balloons in this design are larger, ranging in diameter from 50 meters to 85 meters. Altogether, their aggregate lateral area is 45,000 m^2, 50% larger than in the first case. When convolved with the dynamic wind pressure, however, the aggregate side force (again for a unit drag coefficient) is only 2.5 MNwt, about one quarter lower than in the first design. The side force is still much greater than the weight of the hose, however. Clearly we must find some way to drastically reduce the wind load.

One redeeming feature of wind forces is that they can provide aerodynamic lift as well as drag. We could take advantage of this by using kites or other lifting airfoils to help support the hose. Although they wouldn't function all the time, they would provide lift at precisely the times it is most needed—when the wind is severe and pushing the hose sideways.

An even better solution may be to use buoyant lifting bodies, such as elongated balloons shaped like aerodynamic blimps rather than squat pumpkins. The balloons themselves can then combine the functions of static and dynamic lift.

This approach offers three major advantages. First, an elongated shape presents a much smaller frontal area to the wind for any given interior volume. Second, and even more important, is a reduction to the drag coefficient: for a typical blimp this is about 0.05, 1/20th that of a pumpkin-shaped balloon. Finally, blimps can be designed to generate aerodynamic lift that greatly exceeds the drag force. JP Aerospace has designed large V-shaped blimps that reportedly can generate 20 times as much lift force as the drag imposed by incident wind. The company has even constructed prototypes. Although a high ratio of lift to drag doesn't actually reduce the lateral force imposed by the wind, it would increase the hose tension, thereby reducing the deflection caused by the wind.

The one clear disadvantage of using blimp-like balloons is that they are less structurally efficient than pumpkin-shaped designs. That is, they have more wall mass per unit of buoyant lift, so they must be larger and made from more envelope material. These are affordable penalties, however, particularly since the gains in aerodynamic lift more than offset the losses in buoyancy.

We can similarly reduce the drag coefficient of the hose by giving it a streamlined shape or by surrounding it with a low-mass aerodynamic sheath. In either case, the wind will automatically twist the hose into the proper, drag-minimizing, orientation.

It seems clear that sensible use of well understood strategies for producing aerodynamic lift and reducing aerodynamic drag can enable a StratoShield system to tolerate wind forces with only modest (albeit highly dynamic) deflection of the hose.

Intead of a Hose, an Elevator?

An "elevator" is another alternative for lifting mass to the stratosphere. Like the hose, it would use one or more lighter-than-air structures tethered to the ground and a dispersal system at the top of the tether, nominally at 30 km altitude. The elevator, however, would carry the payload liquid in discrete tanks carried by vehicles ("climbers"), which crawl up the tether cable.

The main advantage that an elevator offers over a hose is the elimination of flow resistance. In principal, an elevator could transport liquids much more quickly than a hose of equivalent static capacity. It is certainly reasonable to imagine designing a vehicle that climbs a cable at tens of meters per second, in contrast to the few meters per second envisioned above for a 1½-inch (3.8-centimeter) hose.

We could consider many design options for a stratospheric elevator system. Motive power could be delivered mechanically by a continuous loop of moving cable (similar to a ski lift) or by a winch; or via electric traction, using external power from the cable or beamed from the ground; or by self-powered motors on the vehicles themselves.

The system could use just one large-capacity climber or several smaller vehicles. A single-car system is simpler. Increasing the number of cars keeps the load on the cable closer to constant, however, as well as more evenly distributed. Multiple vehicles could travel on a single cable if "sidings" were placed to allow up- and down-traveling vehicles to pass one another.

Other options include:

- vehicles that simply drop from the top of the cable and fall or glide back to Earth when empty;
- separate cables going up and coming down. A challenge with this approach would keeping cables from tangling or vehicles from colliding, unless the cables were very widely space at the ground.

The simplest option is probably to send a single self-powered climber up and down a single stationary cable. The most efficient option is likely a "conveyor belt" with an endless loop of cable carrying many small tanks. The latter would require a large amount of engineering development, however.

The first choice of power plant for a self-powered climber would be a turboshaft engine—or perhaps a lightweight, turbocharged piston engine—driving the vehicle mechanically. Unfortunately, the upper portion of the cable is, at 25 to 30 km, too high for existing air-breathing engine designs; the Perseus-B used a triple turbocharger to run at 18 km (62,000 ft.) altitude, the current record. (See www.aurora.aero for details.)

We have considered other options that might work for short-duration climbs with minimal pollution into the stratosphere, including:

- a monopropellant or bipropellant turbogenerator, e.g., using hydrogen peroxide plus a small amount of hydrocarbon fuel;
- an air-breathing turbogenerator that operates from sea level to 15–18 km, at which point high-specific-energy lithium batteries provide main propulsive power;
- high-efficiency electric motors driven exclusively by battery power.

A climber powered solely by batteries, if it is reasonably efficient, could climb to 30 km with about 50% payload fraction (~200 Wh/kg = 720 kJ/kg = 2.4 kg lifted to 30 km per 1 kg of battery). Outfitted with a lightweight motor to provide power for the first 15 km, it could have a payload fraction of about 70%. For long-term use of a battery-powered climber, however, batteries would have to endure many more than 1,000 charge-discharge cycles. If such options were not available, then a laser- or microwave-beamed power system, or a moving cable, would offer the next most attractive and cost-effective approaches.

A Cable to the Sky

Finally, let's consider what kind of cable would be required by a 30 km elevator. Zylon or similar cable of 1 cm^2 thickness offers a usable tensile strength (with safety margins) of 2 GPa and a load rating of 20,000 kg at a cable mass of 156 kg/km (so 4,700 kg for 30 km). It may be necessary to use multiple thinner cables interconnected by webbing to provide both protection from single-point breaks and additional traction area. Indeed, this is the "ribbon" configuration beloved of those who advocate development of space elevators.

If we assume a top station (tanks, tank swap mechanism, sprayer) that weighs one metric ton, then the total mass to be lifted is 15,700 kg. That is less than one third of the weight of a hose system pumped solely from the ground.

A slightly more sophisticated elevator system capable of maintaining climb speeds of 50 m/s—or one that includes a relay station at around 15 km altitude so that two climbers can travel at once—could substantially reduce the cycle time and thus the system mass. A 6,000 kg vehicle and 10,000 kg total system weight would be a reasonable goal.

An elevator could offer other advantages over a hose besides lower weight. It would be easier to unload the system quickly in the event of high winds aloft or low-altitude storms. Unloading a 30 km hose might require more than an hour, compared to about 15 minutes for an elevator. A related advantage is the ease with which the system could be unloaded at night in order to reduce load on the balloons and maintain constant altitude. An elevator system is also probably easier to prototype at small scale (e.g. 10,000 tons per year delivery rates), whereas flow resistance makes this difficult to do with a long hose.

References

J. J. Blackstock, D. S. Battisti, K. Caldeira, D. M. Eardley, J. I. Katz, D. W. Keith, A. A. N. Patrinos, D. P. Schrag, R. H. Socolow and S. E. Koonin, *Climate Engineering Responses to Climate Emergencies*, Novim, 2009.

The Stratospheric Shield

Frequently Asked Questions

CONTENTS

General

What is the StratoShield?

Where is the stratosphere?

How would the StratoShield put aerosols into the stratosphere?

Why are you building this now?

Why did you choose this idea to study?

How much aerosol would the StratoShield put into the stratosphere?

Why design a system that can only do a fraction of what is needed to stop global warming?

So what would this first-generation StratoShield accomplish?

What is the aerosol made of?

Balloons and Blimps

How much does the aerosol lofting system weigh?

Has anyone ever flown a high-altitude balloon capable of lifting that much mass?

How many blimps would there be?

How big would the blimps be?

Is it really possible to tether a blimp (or blimps!) to the ground from that altitude?

How thick would the tether need to be?

Wind

What happens when there's a wind?

How much lift could a blimp generate?

Won't those blimps and that cable act like a sail, putting too much side-load on the ground anchor? Won't they act like a kite, lifting the anchor out of the ground or breaking the cable at the ground?

What about dynamic loads? Won't peak loads (either at the ground due to stronger winds aloft or at any place along the cable due to creation of and then sudden eliminate of slack in the line) be greater than the system can handle?

Hoses and Pumping

Skyscrapers need special systems just to pump water up to their top, which is generally less than 1,000 feet. How are you going to pump a fluid up to 100,000 feet?

Given how long and high the hose is, what's to prevent it from freezing?

Maintaining Altitude

What happens when a balloon bursts or develops a leak?

How would you replenish the helium in a blimp that will be lost due to normal leakage?

Won't the cable or cables get tangled with each other and the blimps + pumps, or at least get damaged by collisions?

Logistics

Won't the cable present a navigational hazard for airplanes?

How much power does it take to pump that much matter all the way to the top?

Electrical Discharge

How will the system handle electrical discharge? Won't it be the world's largest lightning rod?

Alternative Approaches to Aerosol Injection

Why not just use airplanes to disperse the aerosols?

Why not just use artillery shells?

What are some of the other ideas for stratospheric aerosol enhancement?

Aren't there other ways of achieving the same effect?

Atmospheric Science

How will the aerosols be scattered across the entire stratosphere instead of just clumping in a narrow band where they're ejected?

What is the lifetime of the aerosols in the stratosphere?

Is radiation damage to the station components at higher altitudes a concern?

General

What is the StratoShield?

The StratoShield is one possible way to respond to a climate emergency in which greenhouse warming becomes intolerable. The StratoShield would reverse greenhouse warming by slightly reducing the amount of solar radiation that hits the Earth. The shield does this by increasing the amount of sulfur aerosols injected into the stratosphere by about 1%, a process that happens naturally whenever volcanoes erupt. The aerosols reflect incoming sunlight back into space. Although the change in sunlight would be imperceptible to human eyes—and probably beneficial for plants—it would have a substantial cooling effect for the part of the Earth under the shield.

Where is the stratosphere?

The stratosphere is a layer of the atmosphere between about 10 kilometers (33,000 feet) and 50 kilometers (165,000 feet) altitude. It lies above the troposphere, which is where most weather happens. The exact boundary between the troposphere and the stratosphere varies with latitiude.

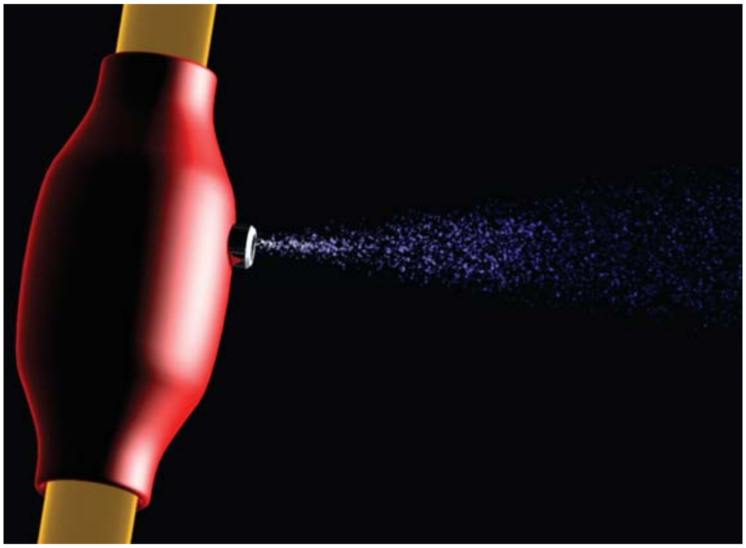
How would the StratoShield put aerosols into the stratosphere?

It would pump them up in liquid form through a very long hose, suspended by one or more balloons. Atomizers at the top of the hose would spray the clear liquid out into the air as a very fine mist, which wind currents would then spread around the circumference of the planet.

Why are you building this now?

We are not building or even planning to build the StratoShield. Intellectual Ventures is simply urging that research on geoengineering options, including stratospheric aerosol enhancement, begin in earnest now. We share with many others a concern that the massive scale of technological development, deployment, investment, and lifestyle changes required to bring greenhouse gas levels down to sustainable levels will take more time to implement than we have before the climate starts changing in intolerable ways.

If that happens, geoengineering options could buy humanity additional time to complete the shift to a cleaner energy system. The solution to the problem of climate change is new energy systems, not geoengineering. But we may find that we need geoengineering technologies as stop-gap responses if the transition to these cleaner energy systems takes too long, or if abrupt changes in climate occur unexpectedly.



Why did you choose this idea to study?

If the world decided that it had to use geoengineering as a stop-gap solution, the goal would be to deploy it quickly but also to phase it out relatively quickly. That leads us to prefer geoengineering approaches that are less expensive and that require little or no new technology, so are easier to deploy quickly. It also leads us to prefer approaches whose cooling effects are well understood and readily controlled, and which dissipate quickly once the system is turned down or turned off.

The StratoShield is an example of a geoengineering system that draws on existing technology and has deployment and annual operation costs amounting to millions of dollars, rather than billions. Although we have explored the general principles of how a system like this would operate, many technical details would have to be worked out. The detailed R&D is not something that IV currently contemplates doing, although if a responsible research program on geoengineering is launched, we may participate and collaborate with others in inventing and refining a variety of technical options.

In concert with technical development, a great deal of environmental science must be done to identify possible side effects. There may be work-arounds to avoid some side effects, but others could be show-stoppers. Much more intellectual effort needs to be applied to this area so that a body of scientific and engineering knowledge exists, should it ever be needed to address a climate emergency.

How much aerosol would the StratoShield put into the stratosphere?

The reference system we're studying would inject 100,000 metric tons of sulfur dioxide a year into the stratosphere, which at a constant flow rate works out to only about 34 gallons (130 liters) a minute. About 100 million tons of sulfur dioxide already rise into the stratosphere each year, about half from manmade sources (such as power plants) and half from natural processes (such as volcanoes). One StratoShield installation would thus increase annual aerosol input to the stratosphere by about one part in 1,000.

Scientific studies so far have concluded that a worldwide system (which would require a dozen or more StratoShield installations) would probably have to spread several million metric tons a year of sulfur dioxide throughout the stratosphere to reduce solar radiation hitting the entire planet by about 1.8% (4 W/m^2) globally. Climatologists believe that small reduction in sunlight would be adequate (if it occurred equally around the globe) to counter all of the warming caused by a doubling of CO_2 over preindustrial levels.

A StratoShield placing 100,000 metric tons of aerosol a year into the upper atmosphere would be expected to reduce incoming solar radiation by less than half a watt per square meter, averaged over the globe. More research is needed to confirm these estimates.

Why design a system that can only do a fraction of what is needed to stop global warming?

Global warming is an extremely complicated problem, and global cooling technologies should be approached gradually and with careful investigation of possible unwanted side effects. Small-scale testing will be a necessary part of this investigation.

A small scale StratoShield could also have more than a small impact. If deployed at an appropriate northern latitude, just a few installations of this size may be adequate (as a first generation system) to protect the Arctic by cooling Arctic waters enough to prevent catastrophic loss of sea ice, as well as by making most precipitation fall as snow instead of rain. Saving the Arctic ice cover could in turn halt positive feedback cycles that threaten to accelerate global warming.

If at some point an international consensus emerged that a temporary planetwide system was necessary, more and perhaps larger StratoShield installations could be deployed at a range of latitudes to generate the aerosol cover necessary.

So what would this first-generation StratoShield accomplish?

Three or four Stratoshield installations of the size we discuss here, if deployed at a latitude between 60°N and 70°N and operated only during the spring months, could help restore the shrinking ice cap in the Arctic Ocean to its full preindustrial extent. Maintaining sea ice is important in the fight against global warming, because ice has a very high albedo (it reflects sunlight back into space), whereas sea water has a very low albedo (it absorbs most of the incident sunlight). Because of this difference in albedo, once some of the sea ice melts, the resulting water absorbs much more sunlight, warming the adjacent water and causing more ice to melt, potentially resulting in a disastrous feedback cycle. In fact, the difference in albedo can lead to a difference of over 100 W/m^2, a much larger effect than the aerosol itself. Combating the loss of Arctic sea ice is therefore a major front in the fight against global warming.

What is the aerosol made of?

The aerosol would likely be made of sulfur dioxide (SO_2), a natural component of volcanic ash that is present in the air we all breathe every day. Another possibility is to use SO_3 instead. Engineered aerosols, not found naturally in the atmosphere, could be more efficient at reflecting certain parts of the solar spectrum, but their benefits over SO_2 might not be worth the cost of development and production—or the uncertainties about their environmental effects. Science has produced a good understanding of both the global sulfur cycle (which includes volcanic ash) and the safety of sulfur dioxide at the very low concentrations required for geoengineering. A good deal more research would be required to establish the safety and environmental life cycle of customized aerosol particles.

Why has Intellectual Ventures filed for patents on the StratoShield?

Patents are the primary way that I.V., as an invention company, communicates its technical ideas in detail to the global community of inventors and engineers. In the case of geoengineering, there are at least two additional reasons that inventors are well advised to file for patents. First, history shows that ideas are better cared for and more likely to be developed responsibly when someone owns them. Second and more important, a patent gives the inventor some measure of control over how—and whether—the invention is used. A geoengineering system would have effects that transcend borders and possibly generations. It should be deployed only if absolutely necessary, and even then only after a deliberate and inclusive international decision-making process. Patents usually remain in force for only 20 years after the time of application, but during that time they can give inventors some influence in preventing the premature use of their inventions.

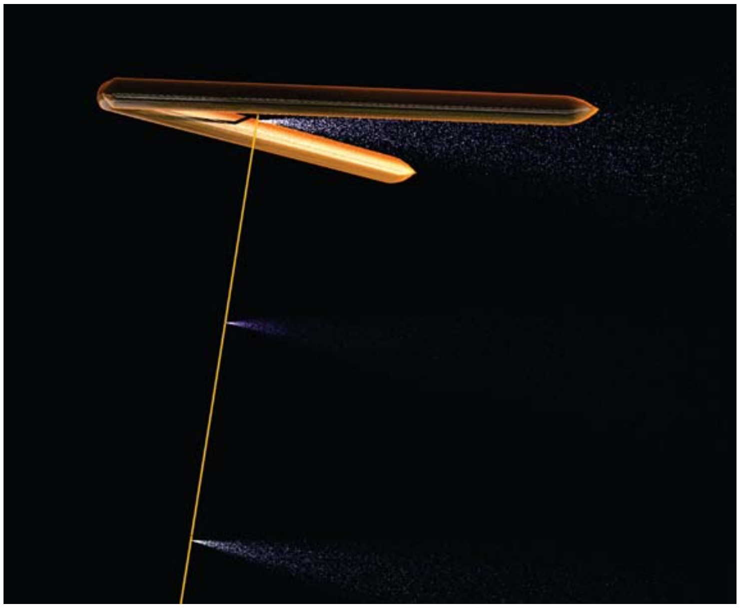
Balloons and Blimps

How much does the aerosol lofting system weigh?

The weight of the reference system is in the range of 30 tons to100 tons, depending on design choices such as the number of pumps, balloons, etc.

Has anyone ever flown a high-altitude balloon capable of lifting that much mass?

High-altitude balloons capable of lifting a few tons have been flown by NASA and others. A StratoShield could use multiple balloons (or blimps) to distribute the weight. Alternatively, existing blimp technology could be scaled up to a larger diameter if it was desirable to use fewer blimps, or perhaps even only one.



How many blimps would there be?

As our white paper discusses, the trade-offs between using more or fewer balloons are complicated, so more engineering studies need to be performed to decide on the best approach. A system with fewer (one to ten) blimps would use less helium, lowering costs. One with hundreds of blimps would have more redundancy in case of failure, which expands options for the materials used to make the balloons.

How big would the blimps be?

The size of the blimps depends on whether they are simple spherical balloons or more aerodynamically shaped blimps, as well as on how many there are. We are currently leaning towards a V-shaped blimp configuration, which provides low drag and a high lift-to-drag ratio. For a system using 20 blimps, the balloons might need to average about 30 meters in diameter (if they are spherical). Numerous trade-offs can be made among blimp size, number, spacing, and altitude. If there were only one single blimp at the very top, it would need to be over 200 meters in diameter.

Is it really possible to tether a blimp (or blimps!) to the ground from that altitude?

Tethered, high-altitude blimps are already being sold and operated. Aerostats, which are blimps directly tethered to a station on the ground, are sold by a few companies for communications, surveillance, and other purposes. They can carry significant weight (approximately a ton) at altitudes greater than four kilometers. More than 40 years ago, a V-shaped tethered blimp was flown to an altitude of 20 km.

How thick would the tether need to be?

The tether would have multiple components. At a minimum, it would need to have a hose for transferring the liquid aerosol up. It may also include a structural component (such as a steel cable) to hold the tension from the blimps. There is a trade-off between the pump pressure needed and the hose diameter, but a hose with the capacity of a large garden hose or a small fire hose should be sufficient. Depending on the design, tension loads could likely be handled by metal cable of less than a centimeter in diameter.

Wind

What happens when there's a wind?

At many altitudes, there will always be a wind, often very strong. Wind will deflect the entire system and thereby reduce the altitude at the top. If the hose were deflected entirely in one direction by 15 degrees, the release height would be lowered from 30 kilometers to 29 kilometers, still well into the stratosphere.

If the blimps are not spherical but rather have an aerodynamic shape, they will have lower drag and could even generate lift from the wind. The more lift we have available (either by making the blimps bigger or by harnessing aerodynamic lift), the less the cable will be deflected in a wind.

How much lift could a blimp generate?

It is easy to design blimp shapes whose lift force exceeds their wind drag. The V-shaped blimp we are examining should produce nearly 12 times as much lift as drag. Balloons of this sort would ensure that the hose would not deflect from the vertical much at all. A rough baseline design, using 11 blimps, would generate nearly 100 metric tons of lift and would limit deflection to 10 degrees.

Won't those blimps and that cable act like a sail, putting too much side-load on the ground anchor? Won't they act like a kite, lifting the anchor out of the ground or breaking the cable at the ground?

Although using multiple blimps would dramatically ease the technical specifications that the hose, cable, and blimps must meet, there is a downside to this approach: it can exacerbate the cumulative wind effects along the length of the cable. More aerodynamic designs (including V-shaped blimps) should be able to limit average sideways load at the anchor to 20 metric tons or less.

Any given cable segment will have some low, nominal tension at the bottom, to pull against whatever it is connected to (generally, a blimp). As you move up the cable, the tension increases since any point along the cable needs to support the weight of all of the cable below it. Therefore the maximum tension in any cable segment will be at its top, where it is connected to a blimp. The 100 metric tons of lift mentioned above for maximum winds would simply require an appropriately-sized cable and anchor.

What about dynamic loads? Won't peak loads (either at the ground due to stronger winds aloft or at any place along the cable due to creation of and then sudden eliminate of slack in the line) be greater than the system can handle?

One piece of research needed for the StratoShield is accurate information on wind speed, direction, and variability at all altitudes from the ground up to 30 kilometers. With that information, the blimps and cables can be sized to accommodate the maximum expected winds. The system can also be designed to minimize the possibility of slack in any of the cables.

Hoses and Pumping

Skyscrapers need special systems just to pump water up to their top, which is generally less than 1,000 feet. How are you going to pump a fluid up to 100,000 feet?

Standard residential pipes cannot handle high pressures—generally, they are rated to just 150 p.s.i. By using a specially designed hose and one or more pumps at high pressure, we can boost the fluid all the way to the top of the StratoShield. If the StratoShield used only a single pump, it would require more than 73,000 p.s.i. (nearly 5,000 times atmospheric pressure) to push aerosols all the way to 30 kilometers. This pressure can be reduced by instead using multiple pumps distributed along the length of the hose. If there were 40 pumps, for example, each one would need to generate about 2,000 p.s.i., which reinforced hose can easily handle.

There is a trade-off between a single pump at the anchor, requiring a very thick and heavy hose on the one hand, and many pumps distributed along the cables, increasing weight hanging from those cables on the other hand. In addition to the weight trade-offs between cable size and number of pumps, there is also the important consideration of reliability of the components. Much testing will need to be done in order to confidently understand the durability of the system.

Given how long and high the hose is, what's to prevent it from freezing?

The melting/freezing point of sulfur dioxide is -75 °C (-103 °F), so it is unlikely to freeze. Although the air at certain altitudes can occasionally get that cold, friction between the flowing SO_2 and the hose wall will provide enough heat to avoid freezing.

Maintaining Altitude

What happens when a balloon (blimp) bursts or develops a leak?

Each blimp would have excess lift so that the system as a whole can still operate with the loss of a single blimp. The top would lose altitude, but could still continue functioning in the stratosphere. If a blimp were damaged, the entire system would be reeled in and the damaged components replaced.

How would you replenish the helium in a blimp that will be lost due to normal leakage?

There are some ideas for using an extra hose to supply helium to the blimps. But it may be more practical to reel the system down to the Earth on a regular basis to change out blimps, service pumps, etc. The amount of particulate matter that needs to be sprayed into the stratosphere is determined on a time-averaged basis. Having a few days of down time every couple of months can easily be handled by sizing the system to pump at a slightly higher rate to compensate. High-altitude blimps can survive for 30-60 days on station, and research on improving the robustness of the outer blimp material (to protect it against UV damage) could extend this lifetime.

Won't the cable or cables get tangled with each other and the blimps + pumps, or at least get damaged by collisions?

The various cables (power for the pumps, the hose, the tensile rope, etc.) would likely be woven together to prevent exactly this problem. The system will be designed to minimize the ability of one component to bump into another, further minimizing any damage.

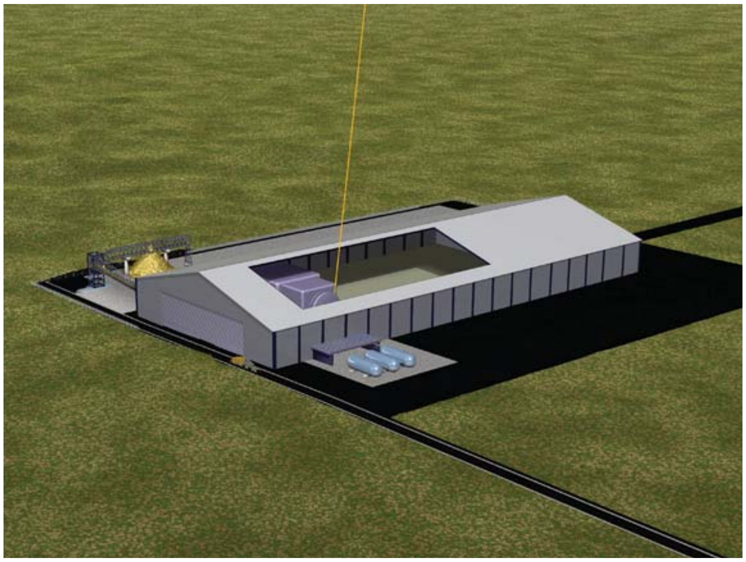
Logistics

Won't the cable present a navigational hazard for airplanes?

The blimps and hoses would use appropriate signaling technologies (e.g., flashing lights) to warn airplanes of their location. Additionally, a notice about the location and flight hazards of a StratoShield could be added for all local flights (a "Notice to Airmen" or NOTAM in the United States) so that pilots are aware of the general location to avoid.

How much power does it take to pump that much matter all the way to the top?

The reference system requires a few thousand kilowatts of power to lift the SO_2 to the release point. The exact answer will depend on energy efficiencies of various parts of the system.



Electrical Discharge

How will the system handle electrical discharge? Won't it be the world's largest lightning rod?

Segments between blimps would likely be insulated from each other, and the ground anchor would also be electrically insulated, to prevent grounding. Isolating segments from each other should also help reduce undesired current flows through the hose.

Although in principle power could be generated from electrical flows between layers of the atmosphere, the hardware currently available to do this would add unwanted mass and complexity. Further research into this type of power generation might turn up lightweight and efficient methods.

Alternative Approaches to Aerosol Injection

Why not just use airplanes to disperse the aerosols?

Others have proposed this approach, we also gave it serious consideration. We concluded that airplanes may not be the best solution., for a number of reasons. Some existing military aircraft do fly high enough to reach the stratosphere, and in principle could be retasked to deliver sulfur-bearing aerosols in the event of a climate emergency—which would after all constitute a threat to international security. Caclulations so far suggest the operating costs to use aircraft could be quite high, however, and if the required altitude for aerosol injection is beyond the bottom of the stratosphere (due to stratospheric wind patterns), the cost would go up dramatically.

A second concern with using military aircraft as delivery vehicles is the emissions of carbon dioxide and other greenhouse gases that they would produce, exacerbating the very problem they were deployed to solve. If fighter jets were used, 167 jets would each have to make three flights a day, 250 days a year to delivery the amount of aerosol required, according to one recent study [Robock *et al.* 2009]

A related, more promising idea is to adjust the fuel mixture in commercial airplanes to generate the needed aerosols in their exhaust (rather than flying a cargo hold full of aerosols). Unfortunately, this option would reduce their fuel efficiency and is not likely to be accepted by stakeholders in commercial airplane operations.

Why not just use artillery shells?

Firing artillery shells full of aerosols into the stratosphere is unlikely to gain acceptance for political, environmental, and financial reasons. Politically, we would expect there to be large opposition to the idea of using large cannons that would be shooting two large shells each per minute around the clock. Environmentally, the casings from each shell would presumably descend back to Earth, creating a localized problem with debris. Financially, firing shells is estimated to cost much more than other options.

What are some of the other ideas for stratospheric aerosol enhancement?

An idea, similar to the StratoShield, that our inventors have explored is the "chimney to the sky." The idea here is to create a double-walled, tubular balloon. The outer layer would be well insulated to keep the inner layer warm, enabling the entire structure to be lighter than air. The balloon would be attached at one end to the ground, with the other end floating in the stratosphere. The inner blimp would be kept warm by injecting hot SO_2, which would rise up the chimney to an exhaust port at the top. If needed, the top of the chimney could be partially supported by balloons.

I.V. inventors have begun prelimary calculations on what might be involved in constructing an "elevator" version of the StratoShield. This version would use a kind of elevator on which climbers would carry liquid sulfur dioxide to the stratosphere. The elevator would not require pumps or thick-walled hose, so it would have less weight to lift. It might also be able to deliver the payload more quickly.

Aren't there other ways of achieving the same effect?

There are many other ways of enhancing Earth's albedo to reduce average global insolation. I.V. has been collaborating with Professors John Latham and Stephen Salter on one very promising idea of theirs to increase marine cloud cover by spraying salty sea water into the air. The small droplets would serve to nucleate more clouds, which increases the albedo of that area. U.S. Secretary of Energy Steven Chu has advocated painting roofs white to increase their reflectivity. Our inventors have begun exploring ways to brighten ground cover such as asphalt by, for example, incorporating crushed glass into the mix.

Many of these ideas will no doubt prove ineffective or impractical for one reason or another when they are fully studied, but there does seem to be a wide array of options still to explore. It is an area ripe for invention.

How will the aerosols be scattered across the entire stratosphere instead of just clumping in a narrow band where they're ejected?

There are two scales of dispersal that are relevant here. One is the local density of aerosols (which will affect their clumping rate), and the other is the degree to which aerosols migrate to other latitudes.

Localized dispersal (at the ejection point) of aerosols is one area that will require more research and development. Ideas for enhancing dispersal include electrostatically charging the aerosols to encourage separation or coating them to reduce their ability to stick to each other.

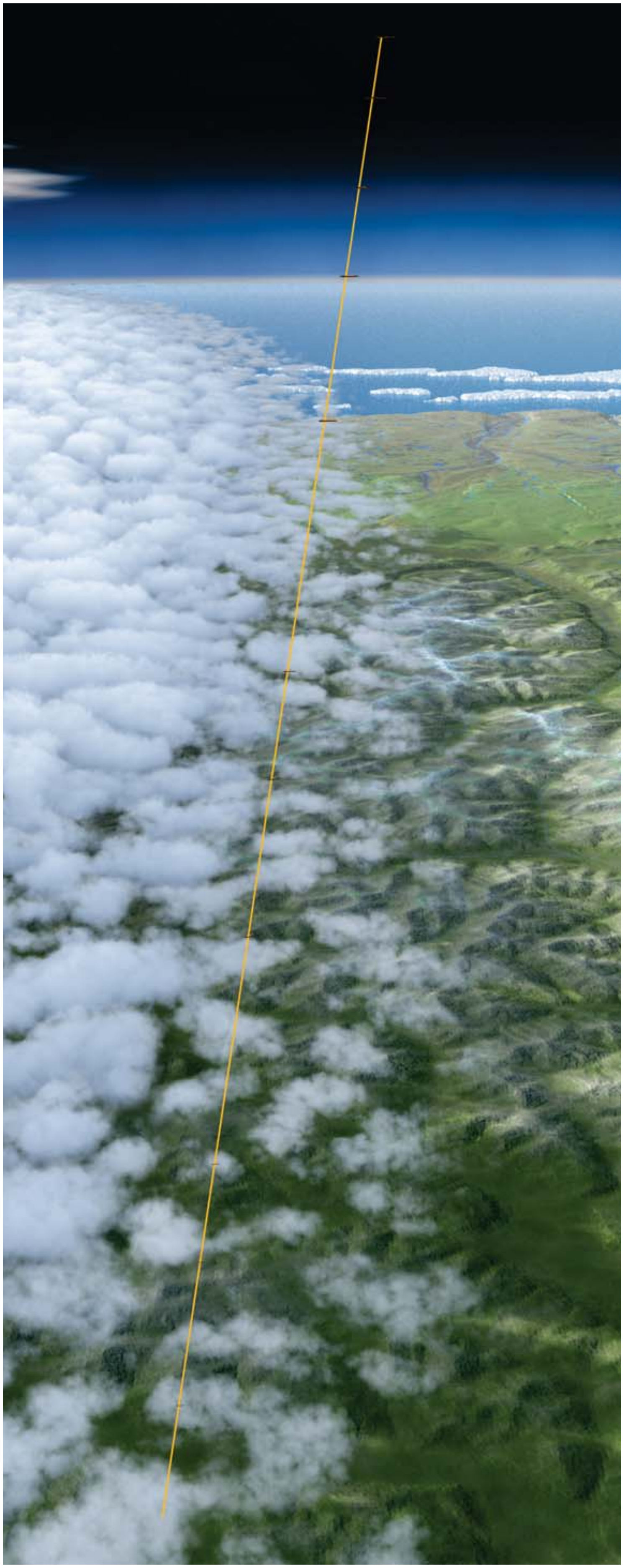
Current knowledge of stratospheric winds suggests that aerosols would mix at different altitudes and would migrate towards the poles. Aerosols injected at tropical and temperature latitudes would thus be expected to,spread both around the circumference of the planet and northward or southward toward the nearest pole.

What is the lifetime of the aerosols in the stratosphere?

The eruption of Mt. Pinatubo in 1991 gave us an opportunity to learn many things about using sulfur-based aerosols to cool the Earth. The aerosols it spewed into the stratosphere remained there for an average of 1-2 years before falling down through the troposphere.

Is radiation damage to the station components at higher altitudes a concern?

The blimp material may be coated to protect it from UV damage. Other radiation damage should be negligible for the relatively short duration that the StratoShield would be deployed.



References and Further Reading

J. J. Blackstock, D. S. Battisti, K. Caldeira, D. M. Eardley, J. I. Katz, D. W. Keith, A. A. N. Patrinos, D. P. Schrag, R. H. Socolow and S. E. Koonin, *Climate Engineering Responses to Climate Emergencies*, Novim, 2009.

Intellectual Ventures. Climate Science and Engineering at Intellectual Ventures. White paper, 2009.

A. Robock, A. Marquardt, B. Kravitz, and G. Stenchikov. Benefits, risks, and costs of stratospheric geoengineering. *Geophysical Research Letters* **36**, L19703, 2009.

The Royal Society of London. Special issue on geoengineering. *Philosophical Transactions of the Royal Society A* **366**, September 2008.