**Stratospheric Sulfate Aerosols (Geoengineering)**

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The ability of **stratospheric sulfate aerosols** to create a [global dimming](http://en.wikipedia.org/wiki/Global_dimming) effect has made them a possible candidate for use in [climate engineering](http://en.wikipedia.org/wiki/Climate_engineering) projects to limit the effect and impact of [climate change](http://en.wikipedia.org/wiki/Climate_change) due to rising levels of [greenhouse gases](http://en.wikipedia.org/wiki/Greenhouse_gases). Delivery of precursor sulfide gases such as [sulfuric acid](http://en.wikipedia.org/wiki/Sulfuric_acid), [hydrogen sulfide](http://en.wikipedia.org/wiki/Hydrogen_sulfide) (H2S) or [sulfur dioxide](http://en.wikipedia.org/wiki/Sulfur_dioxide) (SO2) by [artillery](http://en.wikipedia.org/wiki/Artillery), aircraft and [balloons](http://en.wikipedia.org/wiki/Balloons) has been proposed.

Tom Wigley calculated the impact of injecting sulfate particles, or aerosols, every one to four years into the stratosphere in amounts equal to those lofted by the volcanic eruption of [Mount Pinatubo](http://en.wikipedia.org/wiki/Mount_Pinatubo) in 1991, but did not address the many technical and political challenges involved in potential climate engineering efforts. If found to be economically, environmentally and technologically viable, such injections could provide a "grace period" of up to 20 years before major cutbacks in greenhouse gas emissions would be required, he concludes.

Direct delivery of precursors is proposed by [Paul Crutzen](http://en.wikipedia.org/wiki/Paul_Crutzen). This would typically be achieved using sulfide gases such as [dimethyl sulfide](http://en.wikipedia.org/wiki/Dimethyl_sulfide), [sulfur dioxide](http://en.wikipedia.org/wiki/Sulfur_dioxide) (SO2), [carbonyl sulfide](http://en.wikipedia.org/wiki/Carbonyl_sulfide), or [hydrogen sulfide](http://en.wikipedia.org/wiki/Hydrogen_sulfide) (H2S). These compounds would be delivered using artillery, aircraft (such as the high-flying [F-15C](http://en.wikipedia.org/wiki/McDonnell_Douglas_F-15_Eagle)) or balloons, and result in the formation of compounds with the sulfate [anion](http://en.wikipedia.org/wiki/Anion) SO42-.

According to estimates by the [Council on Foreign Relations](http://en.wikipedia.org/wiki/Council_on_Foreign_Relations), "one kilogram of well-placed sulfur in the stratosphere would roughly offset the warming effect of several hundred thousand kilograms of carbon dioxide."

**Aerosol formation**

Primary aerosol formation, also known as homogeneous aerosol formation results when gaseous SO2 combines with water to form [aqueous](http://en.wikipedia.org/wiki/Aqueous) [sulfuric acid](http://en.wikipedia.org/wiki/Sulfuric_acid) (H2SO4). This acidic liquid solution is in the form of a [vapor](http://en.wikipedia.org/wiki/Vapor) and [condenses](http://en.wikipedia.org/wiki/Condenses) onto particles of solid matter, either [meteoritic](http://en.wikipedia.org/wiki/Meteor) in origin or from dust carried from the surface to the stratosphere. Secondary or heterogeneous [aerosol](http://en.wikipedia.org/wiki/Aerosol) formation occurs when H2SO4 vapor condenses onto existing aerosol particles. Existing aerosol particles or [droplets](http://en.wikipedia.org/wiki/Droplets) also run into each other, creating larger particles or droplets in a process known as [coagulation](http://en.wikipedia.org/wiki/Coagulation). Warmer atmospheric temperatures also lead to larger particles. These larger particles would be less effective at scattering [sunlight](http://en.wikipedia.org/wiki/Sunlight) because the peak light scattering is achieved by particles with a diameter of 0.3 μm.

**Arguments for the technique**

The arguments in favor of this approach are:

* **Natural process**: Stratospheric sulfur aerosols are created by existing atmospheric processes (especially [volcanoes](http://en.wikipedia.org/wiki/Volcanoes)), the behavior of which has been studied observationally. This contrasts with other, more speculative climate engineering schemes which do not have natural analogs (e.g. [space sunshade](http://en.wikipedia.org/wiki/Space_sunshade)).
* **Speed of action**: [Solar radiation management](http://en.wikipedia.org/wiki/Solar_radiation_management) works quickly, in contrast to [carbon sequestration](http://en.wikipedia.org/wiki/Carbon_sequestration) projects such as [carbon dioxide air capture](http://en.wikipedia.org/wiki/Carbon_dioxide_air_capture) which would take longer to have an effect, as the latter relies on removing large amounts of [carbon dioxide](http://en.wikipedia.org/wiki/Carbon_dioxide) before they become effective; however, gaps in understanding of these processes exist (e.g. the effect on stratospheric climate and on rainfall patterns) and further research is needed
* **Technological feasibility**: In contrast to other climate engineering schemes, such as space sunshade, the technology required is pre-existing: [chemical manufacturing](http://en.wikipedia.org/wiki/Chemical_manufacturing), [artillery shells](http://en.wikipedia.org/wiki/Artillery_shells), [fighter aircraft](http://en.wikipedia.org/wiki/Fighter_aircraft), [weather balloons](http://en.wikipedia.org/wiki/Weather_balloons), etc.
* **Cost**: The low-tech nature of this approach has led commentators to suggest it will cost less than many other interventions. Costs cannot be derived in a wholly objective fashion, as pricing can only be roughly estimated at an early stage. However, an assessment reported in [New Scientist](http://en.wikipedia.org/wiki/New_Scientist) suggests it would be cheap relative to cutting emissions. According to [Paul Crutzen](http://en.wikipedia.org/wiki/Paul_Crutzen) annual cost of enough stratospheric sulfur injections to counteract effects of doubling CO2 concentrations would be $25–50 billion a year. This is over 100 times cheaper than producing the same temperature change by reducing CO2 emissions.
* **Efficacy**: Most climate engineering schemes can only provide a limited intervention in the climate—one cannot reduce the temperature by more than a certain amount with each technique. New research by Lenton and Vaughan suggests that this technique may have a high radiative 'forcing potential'.
* **Tipping points**: Application of this technique may prevent [climate tipping elements](http://en.wikipedia.org/wiki/Tipping_point_%28climatology%29), such as the loss of the Arctic summer sea ice, Arctic methane hydrate release, loss of the [Greenland ice sheet](http://en.wikipedia.org/wiki/Greenland_ice_sheet)

**Efficacy problems**

All climate engineering schemes have potential efficacy problems, due to the difficulty of modelling their impact and the inherently complex nature of the global [climate system](http://en.wikipedia.org/wiki/Climate_system). Nevertheless, certain efficacy issues are specific to the use of this particular technique.

* **Lifespan of aerosols**: Tropospheric sulfur aerosols are short lived. Delivery of particles into the lower stratosphere in the arctic will typically ensure that they remain aloft only for a few weeks or months, as air in this region is predominantly descending. To ensure endurance, higher-altitude delivery is needed, ensuring a typical endurance of several years by enabling injection into the rising leg of the [Brewer-Dobson circulation](http://en.wikipedia.org/wiki/Brewer-Dobson_circulation) above the tropical [tropopause](http://en.wikipedia.org/wiki/Tropopause). Further, sizing of particles is crucial to their endurance.
* **Aerosol delivery**: Even discounting the challenges of lifting, there are still significant challenges in designing a delivery system that is capable of delivering the precursor gases in the right manner to encourage effective aerosol formation. For example, it has been suggested that artillery shells would result in inadequate distribution, and thus result in large particles, which quickly rain out. The size of aerosol particles is also crucial, and efforts must be made to ensure optimal delivery.
* **Distribution**: It is logistically difficult to deliver aerosols evenly around the globe. Challenges therefore exist in creating a network of delivery points sufficient to allow viable climate engineering from a limited number of launching sites.

**Possible side effects**

[Climate engineering](http://en.wikipedia.org/wiki/Climate_engineering) in general is a controversial technique, and carries problems and risks. However, certain problems are specific to, or more pronounced with this particular technique.

* **Drought**, particularly [monsoon](http://en.wikipedia.org/wiki/Monsoon) failure in Asia and Africa is a major risk.
* [**Ozone depletion**](http://en.wikipedia.org/wiki/Ozone_depletion) is a potential side effect of sulfur aerosols; and these concerns have been supported by modelling.
* **Tarnishing of the sky**: Aerosols will noticeably affect the appearance of the sky, resulting in a potential "whitening" effect, and altered sunsets.
* [**Tropopause**](http://en.wikipedia.org/wiki/Tropopause) **warming** and the humidification of the stratosphere.
* **Effect on** [**clouds**](http://en.wikipedia.org/wiki/Clouds): Cloud formation may be affected, notably [cirrus clouds](http://en.wikipedia.org/wiki/Cirrus_cloud) and [polar stratospheric clouds](http://en.wikipedia.org/wiki/Polar_stratospheric_clouds).
* **Effect on** [**ecosystems**](http://en.wikipedia.org/wiki/Ecosystem): The diffusion of sunlight may affect plant growth. but more importantly increase the rate of ocean acidification by the deposition of hydrogen ions from the acidic rain
* **Effect on** [**solar energy**](http://en.wikipedia.org/wiki/Solar_energy): Incident sunlight will be lower, which may affect solar power systems both directly and disproportionately, especially in the case that such systems rely on direct radiation.
* **Deposition effects**: Although predicted to be insignificant, there is nevertheless a risk of direct environmental damage from falling particles.
* **Uneven effects**: Aerosols are reflective, making them more effective during the day. Greenhouse gases block outbound radiation at all times of day. Further the effects will not give a homogeneous effect across the regions of the world.
* **Stratospheric temperature change**: Aerosols can also absorb some radiation from the Sun, the Earth and the surrounding atmosphere. This changes the surrounding air temperature and could potentially impact on the stratospheric circulation, which in turn may impact the surface circulation.

Further, the delivery methods may cause significant problems, notably [climate change](http://en.wikipedia.org/wiki/Climate_change) and possible [ozone depletion](http://en.wikipedia.org/wiki/Ozone_depletion) in the case of aircraft, and [litter](http://en.wikipedia.org/wiki/Litter) in the case of untethered balloons.

**Delivery methods**

Various techniques have been proposed for delivering the aerosol precursor gases (H2S and SO2). The required altitude to enter the stratosphere is the height of the [tropopause](http://en.wikipedia.org/wiki/Tropopause), which varies from 11 km (6.8 miles/36,000 feet) at the poles to 17 km (11 miles/58,000 feet) at the equator.

* **Aircraft** such as the F15-C variant of the [F-15 Eagle](http://en.wikipedia.org/wiki/F-15_Eagle) have the necessary [flight ceiling](http://en.wikipedia.org/wiki/Flight_ceiling), but limited payload. Military tanker aircraft such as the [KC-135 Stratotanker](http://en.wikipedia.org/wiki/KC-135_Stratotanker) and [KC-10 Extender](http://en.wikipedia.org/wiki/KC-10_Extender) also have the necessary ceiling and have greater payload.
* Modified [**Artillery**](http://en.wikipedia.org/wiki/Artillery) might have the necessary capability, but requires a polluting and expensive [gunpowder](http://en.wikipedia.org/wiki/Smokeless_powder) charge to loft the payload. [Railgun](http://en.wikipedia.org/wiki/Railgun) artillery could be a non-polluting alternative.
* [**High-altitude balloons**](http://en.wikipedia.org/wiki/High-altitude_balloon) can be used to lift precursor gases, in tanks, bladders or in the balloons' envelope. Balloons can also be used to lift pipes and hoses, but no [moored balloon](http://en.wikipedia.org/wiki/Moored_balloon) has ever been deployed to the necessary altitude.

**Material options**

Precursor gases such as [sulfur dioxide](http://en.wikipedia.org/wiki/Sulfur_dioxide) and [hydrogen sulfide](http://en.wikipedia.org/wiki/Hydrogen_sulfide) have been considered. Use of gaseous [sulfuric acid](http://en.wikipedia.org/wiki/Sulfuric_acid) appears to reduce the problem of aerosol growth.

**Injection regime**

The latitude and distribution of injection loci has been discussed by various authors. Whilst a near-equatorial injection regime will allow particles to enter the rising leg of the [Brewer-Dobson circulation](http://en.wikipedia.org/wiki/Brewer-Dobson_circulation), several studies have concluded that a broader, and higher-latitude, injection regime will reduce injection mass flow rates and/or yield climatic benefits. Concentration of precursor injection in a single longitude appears to be beneficial, with condensation onto existing particles reduced, giving better control of the size distribution of aerosols resulting. The long residence time of [CO2] in the atmosphere may require a millennium-timescale commitment to SRM.

**See also**

* [Weather Modification Operations and Research Board](http://en.wikipedia.org/wiki/Weather_Modification_Operations_and_Research_Board)