Climate Engineering with Stratospheric Aerosols and Associated Engineering Parameters

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Abstract

Climate engineering with stratospheric aerosols, an idea inspired by large volcanic eruptions, could cool the Earth's surface, thereby ameliorating some of the predicted dangerous impacts of anthropogenic climate change. However, the effectiveness of climate engineering achieving a particular climate goal, as well as the resulting side effects, depends upon certain aerosol parameters and how theses aerosols are deployed in the stratosphere. Through the examples of sulfate and black carbon aerosols, this paper explores the space of "engineering" parameters for stratospheric climate engineering: aerosol composition, aerosol size, and spatial and temporal variations in deployment. The effects of climate engineering are sensitive to these parameters, suggesting a particle could be found or designed to achieve desired climate outcomes. This opens the possibility for discussion of societal goals for climate engineering which could account for the multitude of values of different stakeholders.

1. Introduction

Large volcanic eruptions cause surface cooling by creating a layer of stratospheric sulfate aerosols which scatter incoming solar radiation. The 1991 eruption of Mount Pinatubo, which injected approximately 20 Tg of sulfur dioxide into the stratosphere, caused global cooling by 0.5°C for a year after the eruption [*Soden et al.*, 2002]. Eruptions like these have inspired a commonly studied method of climate engineering:

deliberately creating a layer of stratospheric aerosols to cool the planet [*Budyko*, 1974].

In addition to surface cooling, large tropical eruptions induce patterns of winter warming over Northern Hemisphere continents, which is a dynamical response of the atmospheric circulation to stratospheric heating by the aerosols [*Shindell et al.*, 2001; *Stenchikov et al.*, 1998]. The summer monsoon over India and East Asia is weakened due to a weaker temperature gradient between the Indian Ocean and the Asian continent and reduced evaporative flux from the Indian Ocean [*Boos and Kuang*, 2001; *Manabe and Terpstra*, 1974; *Oman et al.*, 2006]. An increase in available photochemical surfaces provided by the aerosols catalyzes ozone loss [*Kinnison et al.*, 1994].

High latitude eruptions have somewhat different climate effects. Patterns of winter warming are not seen, but weakening of the Indian summer monsoon is more prominent [*Oman et al.*, 2006]. The aerosols have a shorter atmospheric lifetime (~8 months *e*-folding lifetime versus ~12 months for tropical eruptions), as transporting the aerosols from the tropics to the poles and mid-latitude storm tracks, where they are removed, accounts for much of the lifetime of stratospheric aerosols injected into the tropics. The time of year of the eruption plays a critical role in determining climate impacts, as aerosols injected in the winter at high latitudes will have reduced radiative effects due to reduced amounts of sunlight and will also be removed from the stratosphere more quickly [*Kravitz and Robock*, 2011].

Climate engineering with stratospheric sulfate aerosols has been studied repeatedly with climate models. Simulations in which globally averaged temperature is returned to a reference state show the tropics are slightly overcooled, and high latitudes, particularly the Arctic, remain warmer than in the reference case [*Govindasamy and Caldeira*, 2000; *Kravitz et al.*, 2012b]. Unlike for large tropical volcanic eruptions,

Northern Hemisphere continents do not show winter warming patterns for climate engineering with stratospheric sulfate aerosols [*Robock et al.*, 2008]. This method of climate engineering cools the surface more than the rest of the troposphere, which stabilizes the lower atmosphere and weakens the hydrologic cycle [*Bala et al.*, 2008]. Studies have not yet revealed whether summer monsoon weakening is a robust feature of climate model response to stratospheric sulfate aerosol climate engineering.

These simulated climate effects are dependent upon the method of climate engineering chosen, namely stratospheric sulfate aerosols that are similar to the aerosols from the Mt. Pinatubo eruption. These aerosols have particular compositions (approximately 75% sulfuric acid and 25% water) and sizes (aerosol effective radius of ~0.5 μm) [*Rasch et al.*, 2008]. They are also assumed to be injected above the equator, distributed through an altitude of 16-25 km. If any of these parameters is changed, the radiative and climate effects would likely change as well.

This paper will discuss some of the options for changing aerosol "engineering" parameters, specifically aerosol composition and aerosol size, as well as the location and time of year of the injection of these aerosols. While discussion will largely be limited to illustrative examples involving sulfate and black carbon aerosols, particles that are designed to optimize particular radiative and climatic outcomes will also be discussed. Finally, once the parameter space has been outlined, implications of these various potential choices will be addressed.

2. Engineering Parameters

2.1. Composition

Sulfate aerosols scatter nearly 100% of visible and ultraviolet light, whereas black

carbon aerosols are excellent absorbers. Although both types of aerosols will prevent some amount of solar radiation from reaching the surface if placed in the stratosphere, black carbon will cause significant stratospheric heating. 1 Tg of black carbon aerosols (0.08 μm radius) in the lower stratosphere has been simulated to cause over 20°C of stratospheric heating [*Kravitz et al.*, 2012a]. Conversely, the eruption of Pinatubo created 29 times the aerosol loading and produced 2-3°C of stratospheric heating [*Stenchikov et al.*, 2002]. Stratospheric heating would increase Arctic zonal winds, forcing a positive mode of the Arctic oscillation. The reactions governing catalytic ozone loss are temperature dependent, so stratospheric heating would also cause stratospheric ozone loss [*Groves et al.*, 1978]. Arctic ozone loss would be promoted, but evaporation of polar stratospheric clouds in the Antarctic would slow Antarctic ozone loss. The addition of photochemical surfaces to the stratosphere would also promote ozone loss for both sulfate and black carbon aerosols; stratospheric climate engineering with 2 Tg S yr^{-1} would delay recovery of the Antarctic ozone hole by 30-70 years [*Tilmes et al.*, 2008].

Black carbon aerosols (typical radius 0.08 μm) cause more cooling per unit mass than volcanic sulfate aerosols. Stratospheric injection of 1 Tg yr^{-1} black carbon aerosols has been simulated to cause 0.4°C of surface cooling [*Kravitz et al.*, 2012a]. 0.6°C of cooling was reported for climate engineering with stratospheric sulfate aerosols with an injection rate of 5 Tg sulfur dioxide per year [*Robock et al.*, 2008].

Stratospheric aerosols will fall into the troposphere within a few years. The amount of additional rain acidity resulting from climate engineering with 5 Tg sulfur dioxide per year would likely be insufficient to cause damage to most ecosystems [*Kravitz et al.*, 2009]. Conversely, black carbon is toxic and causes respiratory impairment [*Baan et al.*, 2006]. Moreover, if black carbon lands on snow or bright

surfaces, it lowers the albedo of those surfaces, and the planet retains more solar radiation, exacerbating global warming [*Vogelmann et al.*, 1988].

2.2. Size

Sulfate aerosols are most efficient at scattering when they are small (~0.1 μm radius). As the particles grow larger, their infrared effect becomes greater; above ~2 μm in radius, infrared effects overwhelm the scattering effects, and they become net absorbing particles. Larger particles have a greater fall speed and thus a lower atmospheric lifetime. Simulations have shown that increasing the size of black carbon particles by 50% reduced surface cooling by more than a factor of 2 [*Kravitz et al.*, 2012a].

Depending upon aerosol composition, particle size may be somewhat predetermined. Sulfate aerosols tend to coagulate, and sulfur dioxide can condense onto existing particles. Both factors tend to increase particle size. Some studies which do not account for microphysics show 0.6°C of cooling could be attained with injection rates of 5 Tg SO_2 per year [*Robock et al.*, 2008]. Including aerosol microphysics in simulations increases the amount of SO_2 needed to be greater than 50 Tg per year [*English et al.*, 2011; *Heckendorn et al.*, 2009; *Pierce et al.*, 2010]. One proposal to overcome microphysical limitations is direct condensation of sulfuric acid vapor to produce a monodisperse distribution of small sulfate aerosols, but this idea is currently untested [*Pierce et al.*, 2010]. Black carbon aerosols tend not to coagulate in ways that alter their radiative properties and are generally smaller. Also, in the stratosphere, they could be heated by the sun and self-loft [*Pueschel et al.*, 2000; *Rohatscheck*, 1996].

2.3. Spatial/Temporal Distribution

Longitude of injection of stratospheric aerosols is largely irrelevant, as the general circulation of the atmosphere will evenly distribute the aerosols across all longitudes within a matter of weeks. Conversely, the radiative and climatic impacts of climate engineering are quite sensitive to latitude and altitude of the particles. Surface cooling from stratospheric aerosol climate engineering tends to increase with stratospheric altitude of the aerosols, in part due to longer atmospheric lifetime [*Ban-Weiss et al.*, 2012; *Kravitz et al.*, 2012a].

Varying solar radiation reductions by latitude and season results in moderate improvements (<6%) in global temperature and precipitation residuals (climate engineering minus reference case) compared to a uniform solar reduction, but targeting regions with the highest residuals results in improvements in these regions by up to 30% [*MacMartin et al.*, 2012]. Aerosols injected extratropically tend to remain in the hemisphere of injection, and stratospheric sulfate aerosol climate engineering in only one hemisphere can shift the Intertropical Convergence Zone, a band of equatorial precipitation, potentially causing Sahelian greening or drying [J. M. Haywood and A. Jones, personal communication, 31 March 2012].

3. Designed Particles

Changing these "engineering" parameters for sulfate and black carbon can, to some degree, tune the climate effects of stratospheric aerosol climate engineering, but some side effects are unavoidable. For example, despite being excellent scatterers, sulfate aerosols mostly scatter light forward, whereas cooling is achieved by scattering sunlight back to space. Black carbon absorbs solar radiation, keeping the energy in the atmosphere. The optimal sulfate aerosol size might not be achievable due to

coagulation.

These concerns suggest that desired aerosol parameters can be chosen by using designed particles. An example is a perfectly scattering particle that photophoretically levitates at 50 km in altitude [*Keith*, 2010]. Although the climate effects of this proposed particle are unknown, as are the side effects on stratospheric chemistry and atmospheric circulation, this idea suggests particles could be created to take advantage of certain properties and to ameliorate some side effects or shortcomings.

4. Conclusions

The goal of mapping the space of these "engineering" parameters and their resulting climate effects is to eventually be able to address the question of what society might want climate engineering to do. For example, if societal goals are primarily to preserve Arctic sea ice, climate engineering could be done with stratospheric sulfate aerosols injected into the Arctic during spring. If the primary goal is cooling the planet while avoiding any increase in rain acidity, perhaps black carbon would be preferred over sulfate. If the primary goal and side effects of climate engineering can be chosen, the foundation has been laid for discussions on determining climate goals.

Such a discussion will not have clear answers, as goals do not depend solely on climatology. There are multiple stakeholders with myriad values which encompass scientific, social, political, legal, ethical, and personal dimensions. Currently, there is no clear method of addressing and synthesizing these issues on a global scale. Moreover, assuming a method of conducting climate engineering could be chosen, society will need to decide how much climate engineering will be done.

The choice of "engineering" parameters has not been fully explored, and there are

many uncertainties in the predicted impacts of climate engineering. Filling this space will require concerted effort and is well beyond the scope of this paper. The purpose here is to illustrate a potential research agenda that could be useful in choosing goals of climate engineering.

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