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Crutzen +10: Reflecting upon 10 years of geoengineering research

# Geoengineering with stratospheric aerosols: What do we not know after a decade of research?

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**Key Points:**

- Research should be strategic to inform possible future decisions about deployment of an intervention
- Uncertainties include both "scientific" and "design" (or engineering) questions
- Geoengineering research should aim both to reduce and manage uncertainties

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**Abstract** Any well-informed future decision on whether and how to deploy solar geoengineering requires balancing the impacts (both intended and unintended) of intervening in the climate against the impacts of not doing so. Despite tremendous progress in the last decade, the current state of knowledge remains insufficient to support an assessment of this balance, even for stratospheric aerosol geoengineering (SAG), arguably the best understood (practical) geoengineering method. We articulate key unknowns associated with SAG, including both climate-science and design questions, as an essential step toward developing a future strategic research program that could address outstanding uncertainties.

## 1. Introduction

Substantial progress has been made towards understanding solar geoengineering, and stratospheric aerosol geoengineering (SAG) in particular, in the 10 years since *Crutzen's* [2006] article. We build on this research to focus on what is not known about this approach, and opportunities for additional research, rather than what is known [which has been covered, e.g., by *Caldeira et al.*, 2013; *Robock*, 2014; *National Academy of Sciences*, 2015; *Irvine et al.*, 2016]. Articulating important unknowns is an essential step toward developing a strategic research program that would support future decisions surrounding geoengineering deployment by addressing key uncertainties: reducing them where possible, understanding limits on how well they can be resolved, quantifying the consequences of remaining uncertainty, and developing strategies to manage irreducible uncertainties.

A decision to deploy a geoengineering intervention is not binary: in the case of stratospheric aerosols, one can choose not only how much aerosol to add but also where (e.g., latitude), when (e.g., season), and even what (the composition of the aerosols). The resulting climate is influenced by these choices [*Ban-Weiss and Caldeira*, 2010; *MacMartin et al.*, 2013; *Ferraro et al.*, 2015; *Weisenstein et al.*, 2015], and in turn, these choices can be made based on how they affect desired outcomes and other impacts. As such, the trade-offs regarding whether or not to deploy geoengineering cannot be fully assessed except in the context of an approach intentionally designed to meet specific goals [*Kravitz et al.*, 2016].

Relevant unknowns therefore include not only "scientific" uncertainties such as understanding stratospheric processes, but also engineering-design questions such as what geoengineering can and cannot do, and how to design the intervention to meet particular goals. Scientific and engineering research are tightly linked, in that one needs to understand the science sufficiently well to answer design questions, while the design questions provide information about where to focus scientific investigation.

The effectiveness of SAG is better quantified than for other methods of geoengineering, such as marine cloud brightening [*Latham*, 1990] or cirrus thinning [*Mitchell and Finnegan*, 2009]. This is in large part due to observations of large volcanic eruptions. These observations have been used to calibrate the responses of climate models, so there is sufficient confidence in simulations of SAG to identify and begin to address some design questions. Nevertheless, there are substantial uncertainties in observations of the effects of volcanic eruptions, and climate models are parameterized with representations that are not always well constrained by existing data.

## 2. Uncertainties

The list of unresolved issues below represents a current snapshot of the evolving state of knowledge. No such list can be complete, as any compilation will inherently have some subjectivity, and by definition cannot include "unknown unknowns." Our ordering broadly moves from small to large spatial scales without explicit prioritization. These uncertainties are deeply intertwined, with uncertainty in one item leading to uncertainty in others. For example, critical questions regarding the climate impacts of SAG on humans and ecosystems (#8 and 9 below) cannot be adequately addressed today without first reducing uncertainty in all of the preceding questions, and potentially most of the subsequent ones as well — we believe that none of the other uncertainties listed can be deemed "unimportant" and deprioritized.

*Uncertainty in stratospheric and upper tropospheric processes:*

1. What aerosol size distribution results from a given injection strategy? More specifically, how does the size distribution depend on the total injection amount, the injection latitude, altitude, and season? The size distribution affects the aerosol lifetime (and hence concentration for a given mass injection rate), the aerosol optical depth (and hence radiative forcing produced for a given concentration), and changes in stratospheric dynamics and chemistry. The size distribution is also influenced by many of these same factors, including lifetime [*Pitari et al.*, 2016]. As noted above, observations after volcanic eruptions provide some constraints on this and many of the subsequent uncertainties. However, models do not yet consistently reproduce aerosol distributions and forcings from large volcanic eruptions [*Driscoll et al.*, 2012], and thus will clearly have uncertainty in their simulations of geoengineered aerosols. Furthermore, aerosol coagulation differs between impulsive (volcanic) and continuous (SAG) injection. Finally, it may also be possible to intentionally influence the size distribution through injection strategies that affect aerosol coagulation [*Pierce et al.*, 2010].
2. What spatial distribution of aerosols results from a given injection strategy? The spatial pattern and the radiative forcing this produces will influence the pattern of resulting tropospheric climate effects. The spatial pattern also influences (and is in turn influenced by) changes in stratospheric dynamics and chemistry. Aerosols are transported by the stratospheric Brewer–Dobson circulation, which varies seasonally; the spatial pattern also depends on the phase of the quasi-biennial oscillation (QBO), which also alters aerosol lifetime and size [*Pitari et al.*, 2016].
3. What impact will SAG have on stratospheric dynamics and chemistry? This area of research involves complex interdependencies between aerosol spatial distribution, scattering and absorption of radiation, ozone chemistry, modes of variability of stratospheric circulation (e.g., the QBO), and the concentration of stratospheric water vapor; changes in each of these feed back onto the others. Impacts after volcanic eruptions have been studied, for example, by *Aquila et al.* [2013] and *Pitari et al.* [2016]; for impacts in the context of geoengineering see, e.g., *Pitari et al.* [2014]; *Aquila et al.* [2014]; and *Tilmes et al.* [2015]. All of these interacting factors will influence radiative forcing and tropospheric climate, both directly and through far-field effects (e.g., surface winds that influence sea ice distribution and ocean mixing near Antarctica [*McCusker et al.*, 2015]).
4. What impact does SAG have on cirrus clouds? Mechanisms have been proposed by which SAG might act to increase or decrease cirrus cloud cover, both directly from aerosols contributing to ice crystal formation via homogeneous freezing [*Cirisan et al.*, 2013], and indirectly through changes in temperature, vertical velocity, and water vapor [*Kuebbeler et al.*, 2012]. Different ice nucleation parameterizations used in different models can lead to different conclusions [*Gettelman et al.*, 2012]. Since cirrus clouds result in net warming, any effect will either amplify or attenuate the overall effectiveness of SAG.
5. What types of aerosols, other than sulfate, might have a reduced impact on atmospheric chemistry or improved scattering efficiency? The potential use of sulfates was inspired by the effects of large volcanic eruptions, but other aerosols may prove more suitable for meeting specific objectives and avoiding side effects [*Pope et al.*, 2012; *Ferraro et al.*, 2015; *Weisenstein et al.*, 2015]. Other aerosols will introduce additional uncertainties associated with their chemical and radiative effects.

*Uncertainty in surface climate effects and impacts:*

6. What climate effects does SAG have for a particular magnitude and spatial pattern of radiative forcing? This includes effects on multiple fields (e.g., temperature, precipitation and other hydrological

indicators, sea ice, sea level rise) across multiple spatial and temporal scales (such as annual mean change, shifts in seasonal timing, and changes in the probability of extremes). In particular, how are the climate effects of SAG different from simply reversing the effects of increased greenhouse gas concentrations? The exploration of climate effects has been a significant focus of research to date including both simulations of solar reductions [e.g., *Kravitz et al.*, 2013] and stratospheric aerosols [e.g. *Niemeier et al.*, 2013; *Pitari et al.*, 2014; *Kalidindi et al.*, 2015]. While models agree that surface temperatures are reduced everywhere, the magnitude and sign of regional precipitation changes is less consistent [e.g., *Kravitz et al.*, 2014a]. Furthermore, the response will depend on the specific choices made regarding aerosol injection, as well as the factors listed above that influence stratospheric circulation and the spatial pattern of radiative forcing.

7. What are the human impacts that result from the climate changes? These include variables that aggregate regional climate information or require their own model [as in the Intersectoral Impact Model Intercomparison Project; *Warszawski et al.*, 2014], such as agricultural changes, drought, or vector-borne diseases. Some initial model-based estimates have been made for agricultural impact, for example [*Pongratz et al.*, 2012], but broader studies of the impacts of geoengineering are both lacking and sorely needed [*Irvine et al.*, 2016].
8. What ecosystem response results not just from induced changes to the climate, but from other effects of SAG, such as changes in surface ultraviolet radiation from stratospheric ozone loss [*Tilmes et al.*, 2012; *Pitari et al.*, 2014] or the ratio of diffuse to direct light [*McCormack et al.*, 2016]? Depending upon the amount of stratospheric sulfate, some ecosystems could be adversely impacted by surface deposition associated with SAG [*Kravitz et al.*, 2009].
9. What overall effect does SAG have on the carbon cycle? For example, through enhancement of terrestrial photosynthesis, SAG may result in a drawdown of atmospheric $CO_2$ concentrations [*Mercado et al.*, 2009; *Xia et al.*, 2016]; decreased temperatures will also enhance ocean $CO_2$ uptake.

*Strategic/design uncertainty:*

10. Can any observed climate effects be correctly attributed, either to the intervention or not? Changes in stratospheric aerosol concentrations may be relatively straightforward to detect, given adequate observational systems. However, detection and attribution of regional tropospheric climate effects are challenging today for $CO_2$ and other forcings, both natural and anthropogenic. For SAG, new emphasis on these challenges is introduced to address questions of harm or to adjust the geoengineering strategy to improve outcomes.
11. How well can the spatial pattern of radiative forcing from SAG be controlled by varying the amount, latitude, altitude, and season of injection? Atmospheric circulation will impose some constraints on what can be achieved.
12. What can geoengineering do, and what can it not do? As an example, SAG could simultaneously influence global mean temperature and tropical precipitation through independent adjustment of the levels of intervention in the Northern and Southern hemispheres, or emphasize high-latitudes more than low-latitudes [*Kravitz et al.*, 2016], but the limitations of these strategies have not yet been evaluated, and no set of design choices will enable simultaneous control of every relevant variable in every region.

Although we focus here only on the uncertainties introduced by our understanding of the physical climate system and our ability to manage it, there are equally important and challenging uncertainties associated with societal impacts and feedbacks [*Schäfer et al.*, 2015; *Gardiner*, 2016]. For example, how will the availability of geoengineering strategies influence mitigation efforts (the "moral hazard" argument against pursuing geoengineering research [e.g., *Morton*, 2015])? How might one govern geoengineering?

An important but fundamentally different type of question is, "What are the goals?" An approach designed only to limit Arctic sea-ice decline might require only high-latitude aerosol injection and will have different impacts from an approach designed to keep global mean temperatures from exceeding 1.5°C or 2°C while aggressive emission mitigation takes place. The impact on ozone depends on when geoengineering starts as well as on how much SAG is deployed. Uncertainties thus ultimately need to be discussed in the context of specific goals for geoengineering deployment. The choice of goal is primarily a social and political issue, informed by scientific and engineering assessment.

## 3. Future Research

The science of anthropogenic climate change shares some of the uncertainties above, leading to co-benefits in any research agenda [*Robock and Kravitz*, 2013]. However, a number of the uncertainties are either unique to SAG or take on a different character or importance in the context of SAG research. The first set of questions above, aimed at providing more precise estimates of radiative forcing from aerosol addition, all have analogous questions in understanding the climate impacts of volcanic eruptions. However, the impact of continuous aerosol injection will differ from impulsive volcanic eruptions, leading to different needs for SAG research. Furthermore, questions such as how the spatial pattern of radiative forcing can be adjusted by changing the latitude of injection, or how different chemical effects can be influenced by choosing aerosols with different properties, are unique to geoengineering research, although there may be some potential synergies. Fundamentally, SAG requires design and consequently has to go beyond pure climate science questions.

Further research has the potential to reduce (but not resolve) many of the uncertainties associated with geoengineering. Climate modeling can provide a great deal of information about the climate response to geoengineering [e.g., the Geoengineering Model Intercomparison Project; *Kravitz et al.*, 2011]. However, structural and parametric assumptions in models lead to uncertainty in future climate projections. Models cannot be directly validated with observations of geoengineering prior to deployment. Nonetheless, despite volcanic eruptions being imperfect analog of geoengineering [*Robock et al.*, 2013], model improvements that lead to a better match to observations [e.g., *Neely et al.*, 2016] would greatly increase confidence. Such comparisons are currently limited by insufficient past data, but improved observations of future eruptions could improve model validation. Better observations of the current climate state could also be used to increase the accuracy of model assumptions, e.g., in situ stratospheric chemistry observations or measurement of cirrus response to naturally occurring aerosols. Improving climate model predictions of the response to increased greenhouse gases will also improve confidence in the models' responses to other forcing agents.

Modeling or observational research cannot resolve all uncertainties. Small-scale intentional perturbation experiments could help resolve some uncertainties, such as stratospheric aerosol size distributions or stratospheric chemical processes [e.g., *Dykema et al.*, 2014]. In contrast, experiments to resolve climate effects would require a scale and duration similar to deployment [e.g., *MacMynowski et al.*, 2011]. This means that uncertainty about the full global impact of a potential SAG deployment will never be fully resolved prior to any deployment decision.

Given that some uncertainty will remain, research should also explore strategies that can help assess and manage risks — where the concept of risk combines both the uncertainty (how wrong might one be) and the consequences of that uncertainty (how much it matters for the ultimate variables of interest). For example, if society ever wants to start deployment, slowly ramping up the amount of geoengineering while monitoring the climate system might allow for detection and some assessment of undesirable effects before their consequences become severe [*Keith and MacMartin*, 2015; *Tilmes et al.*, 2016], and deployment could be quickly wound-down if necessary. Research could also explore adaptive management strategies that adjust the amount and spatial pattern of aerosols to meet some objectives in the presence of (potentially irreducible) uncertainty [*MacMartin et al.*, 2013; *Kravitz et al.*, 2014b, 2016]. This may lead to more predictable outcomes, limiting the potential consequences of some uncertainties. These examples illustrate the breadth of research questions that will need to be addressed to inform future societal choices.

Few would assert that the current state of knowledge is sufficient to support a decision to deploy. Ultimately, any decision to deploy decades-hence will necessarily involve a tradeoff confounded by risks associated with either choosing deployment or choosing not to. (See *Stirling* [2010] for a more complete and nuanced view of the role of uncertainty assessment in informing policy decisions.) Research should thus aim to address key uncertainties associated with SAG, such as those listed here, in order to support well-informed future decisions. Up to now, geoengineering research has been dominated by scientific questions, but as research proceeds, it will need to also address important outstanding engineering or design questions. Instead of asking "What will geoengineering do?" we will have to ask: "Can geoengineering do what we want it to do, and with what confidence?"

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