Holistic Assessment of SO₂ Injections Using CESM1(WACCM): Introduction to the Special Issue

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Abstract We introduce a special issue on a holistic assessment of solar geoengineering via stratospheric SO₂ injection in the state-of-the-art climate model, Community Earth System Model, version 1 with the Whole Atmosphere Community Climate Model as its atmospheric component (CESM1(WACCM)). This model has numerous complexities that allow it to represent some of the most important nonlinearities associated with stratospheric SO₂ injection, including aerosol microphysical growth and stratospheric chemistry. The studies described herein represent the steps toward and first attempt in a state-of-the-art climate model to use solar geoengineering to meet multiple simultaneous objectives via SO₂ injection at multiple locations. First, a set of simulations was carried out to better understand the response of the model to variations in latitude, altitude, and amount of sulfur dioxide injections. Subsequently, in a century-long simulation, a feedback algorithm was employed to meet specific objectives and manage uncertainty, wherein the injection amount at each location was adjusted every model year. Most of the analyses contained in this special issue focus on surface climate and stratospheric changes in the simulations. In addition, 20 ensemble members of the feedback simulation have been carried out and provided to the community (the Geoengineering Large Ensemble) to expand the scope of analyses to low signal-to-noise ratio fields, including regional effects, impacts assessment, and extreme events. The demonstration provided by these simulations is a step toward understanding the space of achievable climate objectives via solar geoengineering or, phrased differently, determining what solar geoengineering can do and what it cannot do.

1. Introduction

Solar geoengineering describes a set of technologies designed to rapidly, temporarily offset some of the effects caused by anthropogenic greenhouse gas emissions (National Research Council, 2015). Many different potential methods of solar geoengineering have been proposed, although two have emerged to the forefront of scientific discussion. Stratospheric sulfate aerosols are designed to mimic the cooling of large volcanic eruptions by creating a large amount of backscattering sulfate aerosols in the stratosphere, often via sulfur dioxide (a gaseous precursor) injection (e.g., Crutzen, 2006). Marine cloud brightening seeks to seed marine low clouds with soluble particles, often sea salt, thereby reducing the average cloud droplet size and causing an increase in cloud albedo (Latham, 1990; Latham et al., 2012; Twomey, 1977). An additional proposal, called cirrus thinning, has emerged recently; this involves seeding cirrus with ice nuclei, causing them to thin or dissipate, allowing more outgoing longwave radiation to escape to space (Lohmann & Gasparini, 2017; Mitchell & Finnegan, 2009).

Model simulations of idealized solar geoengineering (either solar irradiance reduction or stratospheric sulfate aerosol geoengineering) indicate that many of the effects of greenhouse gases would be offset by these global solar geoengineering methods (Govindasamy & Caldeira, 2000; Irvine et al., 2016; National Research Council, 2015). Not only could solar geoengineering offset changes in global mean temperature (Kravitz et al., 2013) but also changes in the hydrological cycle (Tilmes et al., 2013), cryosphere (Moore et al., 2014), ocean circulation (Hong et al., 2017), and extreme events (Curry et al., 2014). However, these offsets are unlikely to be perfect, raising the potential for novel climates (Irvine et al., 2010; Schmidt et al., 2012). Many of these effects have been studied in a multimodel context using standardized solar geoengineering

simulations under the Geoengineering Model Intercomparison Project (GeoMIP; Kravitz et al., 2011), adding a degree of robustness to the conclusions.

There is also the potential for tradeoffs. For example, model simulations have shown that uniform solar geoengineering cannot completely offset both temperature and precipitation changes (Tilmes et al., 2013); if one completely restores global mean temperature to a previous state, the resulting climate has lower global mean precipitation than the baseline state. Also, offsetting CO_2-induced global temperature changes via globally uniform solar reduction tends to cool the tropics beyond baseline values, while the poles remain warmer than the baseline, and it preferentially cools the Northern Hemisphere more, in large part due to the larger land mass and hence lower heat capacity (Kravitz et al., 2013). In addition, there are numerous critical side effects and implications that extend beyond natural science, including economics, politics, ethics, law, and governance. While the scope of this special issue is limited to physical climate investigations, we would be remiss in not mentioning these important areas.

Nevertheless, many of these past results represent an incomplete picture of the expected and potential effects of solar geoengineering. Limiting the discussion to stratospheric sulfate aerosol geoengineering, past studies have generally either directly simulated tropical injection of sulfur dioxide or a solar irradiance reduction pattern that is broadly consistent with tropical sulfur dioxide injection. The motivation for doing so has often been based on efficiency: Injecting in the tropics will result in global coverage due to zonal winds and the transport of air (and particles) from low to high latitudes. However, a few studies have looked at alternate injection strategies. For example, high-latitude injections (either volcanic eruptions or solar geoengineering) or single-hemisphere solar geoengineering tend to result in aerosol layers that stay in a single hemisphere (Haywood et al., 2013; MacCracken et al., 2013; Robock et al., 2008; Tilmes et al., 2014). The results of these simulations show different side effects on various Earth systems, such as on the hydrological cycle: The intertropical convergence zone tends to shift toward the warmer hemisphere, resulting in drying or greening of the Sahel region and potentially shifting midlatitude storm and tropical cyclone tracks.

This suggests two important points, both of which were strong motivations for this special issue. First is that the effects of solar geoengineering strongly depend upon how it is performed. And second, to some degree, the effects of solar geoengineering can be designed. As such, the often asked question "what will happen if society performs solar geoengineering?' is ill defined. Instead, we argue, with evidence provided in the papers included in this special issue, a more relevant question is, "Can solar geoengineering be designed to meet specific climate objectives?"

There are three parts to these sorts of investigations: (i) What is the space of independent degrees of freedom? (ii) How can those degrees of freedom be combined to achieve objectives? (iii) How can those objectives be met in the presence of uncertainty? By combining these ideas, one in principle can design a simulation in which one can test whether an objective is achievable, and in doing so, begin to understand the space of achievable climate objectives.

MacMartin et al. (2016) identified several degrees of freedom that are available for stratospheric sulfate aerosol injection, including altitude, latitude, magnitude, and time of year. (Aerosol composition is also a potential degree of freedom, as different aerosol types will undoubtedly have different climate impacts, but we eschew such discussions here, as do we eschew description of differences between pulsed and sustained injections, as were explored by Heckendorn et al., 2009.) Robock et al. (2008) and Caldeira and Wood (2008) were the first to explore the effects of latitude on the climate impacts of changing latitude of injection, albeit with simple treatments (bulk aerosol treatment and solar reduction, respectively). Kravitz and Robock (2011) explored the effects of high latitude eruptions at different magnitudes and times of year. MacMartin et al. (2013) performed a systematic study of different latitudes, magnitudes, and times of year of solar irradiance reduction. Single-hemisphere geoengineering has also been evaluated to some degree (e.g., Haywood et al., 2013; Jones et al., 2017). Dai et al. (2018) explored the different efficiencies of injection at different latitudes, altitudes, and (to a lesser degree) times of year but in a two-dimensional simplified climate model.

The other major point is the ability to meet specified climate objectives in a climate model in the presence of potentially irreducible uncertainty. Jarvis and Leedal (2012) were the first to point out this problem in the context of GeoMIP. The first solution, which was offered by MacMartin et al. (2014), demonstrated the use of

feedback on the observed climate state to meet a global mean temperature objective via uniform solar reduction. This involves annual adjustments to the amount of geoengineering under a simple heuristic: If global temperature is too warm as compared to the objective, reduce incoming sunlight, and if too cold, increase incoming sunlight (i.e., reduce the amount of geoengineering). Kravitz et al. (2014) showed that such a feedback algorithm can be designed so it is robust to uncertainties in the sensitivity of the model to greenhouse gases or geoengineering.

Kravitz et al. (2016) were the first to combine these two points into a single study involving different patterns of solar reduction that are managed independently and simultaneously via feedback to meet three simultaneous temperature objectives (global mean temperature, interhemispheric temperature gradient, and equator-to-pole temperature gradient) in a climate model. Not only were they able to meet those three objectives successfully, but they were able to do so when porting their feedback algorithm to an entirely different climate model.

An important shortcoming of past explorations of stratospheric sulfate aerosol geoengineering is the ability to represent all of the relevant processes, particularly those that contribute to nonlinearities. These include a detailed representation of gas-to-particle conversion of the sulfate aerosols; growth, coagulation, and sedimentation; heterogeneous chemistry on the aerosol surfaces; and the quasi-biennial oscillation, which is an important determinant of whether aerosols tend to collect in the tropics or spread to higher latitudes. Before this special issue, no model had representations of all of these processes that was sufficient for capturing the nonlinearities associated with stratospheric sulfate aerosol geoengineering.

Adequately representing these relevant processes and feedbacks is essential to capture to understand the space of achievable climate objectives under solar geoengineering. While Kravitz et al. (2016) provided the path toward addressing this question, demonstrations with solar irradiance reduction ultimately have limited utility for studies of stratospheric sulfate aerosol geoengineering. In addition to climate response nonlinearities introduced by aerosol microphysical growth and stratospheric chemistry, there is a major difference in the achievable degrees of freedom. Idealized solar irradiance reduction can be prescribed in any simulation, independent of discussions as to how that forcing might be imposed. In the Earth's atmosphere, stratospheric sulfate aerosols are transported by stratospheric circulation patterns and winds, so one cannot necessarily have tight control over where aerosol radiative forcing is imposed, and in turn, what the resulting climate effects may be. All of these factors contribute to fundamental limitations in what solar geoengineering is likely able to achieve.

2. Studies in This Special Issue

In this special issue, we describe the next major steps in furthering this work, providing the first demonstration of using stratospheric sulfate aerosol geoengineering to meet multiple simultaneous climate objectives in a state-of-the-art climate model and examining the effects of different injection parameters on surface climate, which allowed such progress to be made. For this demonstration, the objectives were to maintain global mean temperature, the interhemispheric temperature gradient, and the equator-to-pole temperature gradient at 2020 levels against a background of the RCP8.5 scenario over the years 2020–2099. Although pessimistic (i.e., the inherent assumption is that solar geoengineering is the only employed method of addressing climate change), this simulation results in a high signal-to-noise ratio, making the conclusions more easily discernible than in more moderate scenarios. All of the simulations performed for this series of studies are described in Table 1.

The first stage in this study is to ensure that we have the correct model to represent all of the important processes in stratospheric sulfate aerosol geoengineering. Mills et al. (2017) describe the 1° horizontal resolution version of CESM1(WACCM), the Community Earth System Model with the Whole Atmosphere Chemistry Climate Model as its atmospheric component. Mills et al. discuss in detail the components of the model, including aerosol microphysics, an internally generated quasi-biennial oscillation, and representations of stratospheric chemistry. They also validate the model against the 1991 eruption of Mt. Pinatubo; modeled aerosol size distributions, optical depth, and ozone show excellent agreement with observations.

After validating the model, the next stage was to conduct a systematic exploration of the various degrees of freedom available in designing stratospheric sulfate aerosol geoengineering. Tilmes et al. (2017) describe the

Table 1
Table of Simulations Performed for the Studies Described Here

Altitude (km)	Latitude	Magnitude (Tg SO_2 a^{-1})	Ensembles	Simulation length (years)	Note	Reference
N/A	N/A	N/A	21[a]	21[b]	RCP8.5	Mills et al. (2017); Tilmes, Richter, Kravitz, et al. (2018)
12, 17	50°S	6, 8, 12	1	10	6 total simulations	Tilmes et al. (2017)
18, 23	30°S	6, 8, 12	1	10	6 total simulations	Tilmes et al. (2017)
20, 25	15°S	6, 8, 12	1	10	6 total simulations	Tilmes et al. (2017)
20, 25	Equator	6, 8, 12[c], 24[d]	1	10	7 total simulations	Tilmes et al. (2017)
20, 25	15°N	6, 8, 12	1	10	6 total simulations	Tilmes et al. (2017)
18, 23	30°N	6, 8, 12	1	10	6 total simulations	Tilmes et al. (2017)
12, 17	50°N	6, 8, 12	1	10	6 total simulations	Tilmes et al. (2017)
25	Equator	24	1	10	1 total simulation	Richter et al. (2017)
25	Equator	12[e]	1	10	Specified chemistry	Richter et al. (2017)
20,[f] 25[f]	15°N and 15°S	6,[g] 12,[g] 16[g]	1	10	3 total simulations	MacMartin et al. (2017)
23,[h] 25[h]	15°N and 30°N	12[g]	1	10	1 total simulation	MacMartin et al. (2017)
23,[h] 25[h]	15°S and 30°S	12[g]	1	10	1 total simulation	MacMartin et al. (2017)
23,[h] 25[h]	30°N, 15°N, 15°S, and 30°S	6[g]	1	10	1 total simulation	MacMartin et al. (2017)
23,[h] 25[h]	30°N, 15°N, 15°S, and 30°S	Variable[i]	1	80		Kravitz et al. (2017)
23,[h] 25[h]	30°N, 15°N, 15°S, and 30°S	Variable[i]	20	80	Geoengineering Large Ensemble (GLENS)	Tilmes, Richter, Kravitz, et al. (2018)
25	Equator	Variable[i]	3	80	Simulations underway	N/A

Note. Total number of simulation years was (not including test runs) 3,141, costing approximately 30 million core hours on Yellowstone and Cheyenne combined. RCP = Representative Concentration Pathway. [a]One for the original suite of simulations and 20 for Geoengineering Large Ensemble. [b]Seventeen were run 21 years (2010–2030) for Geoengineering Large Ensemble. Three more were run for 88 years (2010–2097) for Geoengineering Large Ensemble. One additional simulation for the original feedback suite was run for 80 years (2020–2099). [c]Extended to 20 years. [d]Only at 25-km altitude. [e]Simulation was conducted with specified chemistry. The aerosol distribution was prescribed based on the equatorial 12 Tg SO_2 a^{-1} injection simulation. [f]Twenty-five kilometers for 6 and 12 Tg SO_2 a^{-1} and 20 km for 16 Tg SO_2 a^{-1}. [g]At each location, simultaneously. [h]Twenty-three kilometers for 30°-latitude injection and 25 km for 15°-latitude injection. [i]Magnitude was adjusted independently at each location every year via feedback.

results of a set of forty-two 10-year simulations involving different latitudes, altitudes, and magnitudes of stratospheric SO_2 injection (the bulk of Table 1). Richter et al. (2017) explored the different stratospheric dynamics impacts of these simulations, including the influence on the quasi-biennial oscillation. MacMartin et al. (2017) explored nonlinearity in this original suite by evaluating combinations of different injection locations and showed that one could achieve three independent degrees of freedom in aerosol optical depth that lead to independent influences on surface air temperature.

All of this information was used to design a feedback algorithm whereby injection of SO_2 at 30°N, 15°N, 15°S, and 30°S were adjusted independently every year to offset changes in the three aforementioned global-scale temperature objectives. This feedback algorithm is based on the past observed climate state, taking into account past departures from the chosen objectives. The results of this simulation are documented by Kravitz et al. (2017). An additional 20-member ensemble of simulations using this same feedback algorithm have been prepared and released to the broader research community as the Geoengineering Large Ensemble (GLENS) (Tilmes, Richter, Kravitz, et al., 2018).

In addition to these studies, several other investigations have been performed. Tilmes, Richter, Mills, et al. (2018) explored in more detail the different stratospheric and surface climate effects resulting from different altitudes of injection. Richter et al. (2018) evaluated the stratospheric response in the feedback simulations and mechanisms of change in stratospheric dynamics. And finally, MacMartin, Wang, et al. (2018) used the statistical power provided by multiple ensemble members to quantify signal-to-noise ratios and limits of detectability in GLENS.

3. Results, Conclusions, and a New Paradigm of Geoengineering Research

Up to this point, nearly all studies involving stratospheric sulfate aerosol geoengineering have been conducted with equatorial injection. Many of these studies have noted several side effects, including confinement of aerosols in the tropics relative to other latitudes (English et al., 2011; Niemeier et al., 2011), decreasing radiative forcing per unit injection with increasing injection rate (Niemeier & Timmreck, 2015),

and a persistent westerly phase of the quasi-biennial oscillation (Aquila et al., 2014; Niemeier & Schmidt, 2017). By exploring off-equatorial injection at multiple simultaneous locations, we have shown that many of these side effects can be reduced or may be nonexistent under different stratospheric injection strategies. Several simulations of equatorial-only injection under a similar framework to GLENS are underway, to provide a more detailed comparison of equatorial and off-equatorial injection.

Another important purpose of the studies presented here is to demonstrate that, even in a model as complex as CESM1(WACCM), one can design a solar geoengineering strategy to meet multiple simultaneous prechosen objectives. This had never before been demonstrated, and it was not a priori obvious that such an effort would indeed be successful. Geoengineering with stratospheric sulfate aerosols as conducted here has many potential sources of uncertainty, including nonlinearity (both with injection amount and due to interactions between multiple injection locations), designing a feedback strategy based only on information from relatively short simulations, and natural variability (including interannual variability in the pattern of aerosol optical depth resulting from a particular injection rate). Not only have these studies provided a proof of concept that some of these uncertainties can indeed be managed, but they also outlined the process by which other objectives could be explored or the process could be repeated in different models. Feedback is an effective strategy for managing several sources of uncertainties.

However, there will necessarily be a limit to what degrees of freedom in the climate system can be modified and hence which objectives can be met. Moreover, objectives with finer temporal and spatial scales are more difficult to meet, as they require finer control over the system; there may be a lower bound beyond which there are no robust methods for meeting objectives in the presence of uncertainty. This set of questions frames the need for solar geoengineering research to move from being curiosity driven to mission driven, meaning a focus on key uncertainties in stratospheric aerosol geoengineering (MacMartin et al., 2016; Visioni et al., 2017). What are the most critical uncertainties in the field? How can those be identified, prioritized, and systematically reduced? The studies described here have made a substantial push in that direction by demonstrating strategies for reducing and managing uncertainties to meet specified climate system objectives. A plausible next stage of research would be to explore that space of objectives. This will necessarily include research into robust effects of geoengineering on impacts (e.g., food and water security; Xia et al., 2014; Proctor et al., 2018) and extreme events (Irvine et al., 2017). It will also require research into feedback design and optimal methods of managing uncertainties in specific contexts. Especially important will be the use of multiple models to identify and reduce sources of intermodel uncertainty and improve feedback algorithm robustness. Such directions will be crucial for informing broader societal and governmental debate on solar geoengineering.

The tools and methodologies described here could also be adapted to other methods of geoengineering, like marine cloud brightening. This will be particularly important for expanding the space of achievable climate objectives. Cao et al. (2017) and Boucher et al. (2017) have shown complementarity of different methods of solar geoengineering; for example, the spatial patterns of change exerted by stratospheric sulfate aerosols, marine cloud brightening, and cirrus thinning may have large areas of non-overlap, suggesting that combinations of these methods could introduce additional degrees of freedom of control over the climate system than any single method may not. Due to the substantial uncertainties associated with these other methods, such as marine cloud brightening and cirrus thinning, as well as the more general uncertainties associated with aerosol-cloud interactions (Intergovernmental Panel on Climate Change, 2013), more research is needed to understand the feasibility of such approaches.

If solar geoengineering is to be seriously considered as an option for addressing climate change, albeit on a limited, temporary basis (MacMartin, Ricke, & Keith, 2018), it needs to be understood and its uncertainties quantified. The studies and methodologies presented here have provided a roadmap whereby the field could pursue such an endeavor, providing a holistic understanding of what solar geoengineering can and cannot do.

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