May 20-21, 2019 Geoengineering Modeling Research Consortium (GMRC) Workshop Synthesis:

In-Person Attendees:
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Remote Participant: V. Aquila (American University)

I. Introduction:

The goal of the first GMRC workshop was to identify and prioritize uncertainties in geophysical models for geoengineering research, and define short-term goals that the GMRC would address in the next year. As this was the first in-person meeting of the newly formed GMRC, discussion took place on the role of the GMRC and governance structure. GMRC members agreed that the focus of the group should be on advancing geoengineering modeling research via process understanding and model development. GMRC decided that a steering committee would be useful to coordinate efforts, organize group meetings and workshops, serve as liaisons with the broader community, and identify and coordinate funding opportunities. The steering committee would consist of six members from the community, with three people rotating off/onto the committee every year. The 2019/2020 GMRC steering committee was selected to be:

- S. Eastham (MIT)
- D. Keith (Harvard)
- B. Kravitz (IU)
- J. Richter (NCAR)
- K. Rosenlof (NOAA)
- L. Xia (Rutgers)
- J.F. Lamarque (NCAR) (*ex-officio*)

The workshop consisted of short introductory talks (listed in section V) on Monday morning, and the rest of the meeting was spent on discussion of uncertainties and ways to address them. GMRC members agreed that it should focus together on uncertainties and issues specific to geoengineering and for the uncertainties that overlap with the general climate change modeling community, should work closer together with those communities. A number of climate modeling uncertainties related to basic Earth system model understanding were identified (regional climate changes, stratospheric transport and dynamics, convective and gravity wave parameterizations), however no short-term goals were identified in these areas. Model shortcomings common to geoengineering and climate modeling in general will be addressed in future meetings that would include a broader group, including members of the climate change and variability community not necessarily involved in geoengineering research.

The GMRC discussed seven key uncertainties unique to geoengineering modeling (described in section II) and agreed on a number of near-term action items to begin to address these uncertainties as described in Section III, and began conversations about long-term goals (Section IV).

II. Key Uncertainties Highlighted by GMRC:

The uncertainties described here were discussed in some depth at the meeting. The goal was to identify priorities that the GMRC could make useful progress in the next 3 to 9 months, rather than generate a complete list of overall priorities that a larger/longer-term research program might address. After discussion, no near-term action items were identified for some of the uncertainties below; these are still listed here as actions may be identified at future meetings.

1. **Plume modeling / sub-grid scale effects:**
   Most realistic scenarios of sulfate aerosol injection will involve emission of sulfur in a plume, either in the form of SO_2 or H_2SO_4 aerosol. We know from observation that stratospheric plumes can persist for several weeks as coherent structures, and plume-scale chemistry has been shown to significantly affect the chemical outcomes of aircraft emissions. However, such processes are neglected in all simulations (to date) of sulfate aerosol injection. This constitutes an extreme form of resolution/scale dependency which needs to be investigated. A series of simulations are planned which will use an embedded plume-scale model inside a chemistry transport model (CTM) to evaluate the effect of plume-scale processes on long term regional and global aerosol optical depth (AOD). Simultaneously, a series of more conventional sulfate aerosol injection experiments will be conducted using a global CTM at 4°, 2°, 1°, and 0.5° resolution. These simulations will assess whether increasing resolution provides a solution which converges on that given by a plume-resolving model. If plume-scale effects are found to be significant, a new parameterization will need to be developed which allows such effects to be directly simulated in GCMs. This will also have broader applications by enabling in-GCM trajectory tracking.

2. **Aerosol injection strategy:**
   We discussed the fact that outcomes depend strongly on the aerosol injection strategy, including the type of aerosol, the method of producing the aerosol (e.g., for sulfate, as the precursor gas SO_2 or accumulation-mode H_2SO_4), aerosol injection locations, and times of year. Thus modeling needs to understand how these choices affect climate model outcomes, and more broadly, whether the models are adequately representing the effects of these choices - for example, whether the plume-model predictions of the aerosol size distribution resulting from accumulation mode (AM)-H_2SO_4 are valid, and how GCM simulations of stratospheric aerosol injection (SAI) differ between SO_2 injection and AM-H_2SO_4 injection. While this challenge was discussed at the meeting, no new short-term action items were identified specifically associated with this area, but rather to continue/accelerate ongoing model intercomparison for AM-H_2SO_4 injection in

several GCMs.

3. **Impacts:**
There are impacts that could result from stratospheric aerosol geoengineering that are somewhat unique (e.g., changes in surface and tropospheric ozone, UV, and diffuse radiation). It is important to study and better understand the uncertainties in these processes. There are other impacts that are important to understand but not necessarily unique to geoengineering (e.g., regional hydrology, climate extremes, crop yields, and air quality). These impacts are considered when modeling the effects of climate change, however they have implications for modeling geoengineering. For example, the impact of geoengineering on agriculture depends strongly on the choice of scenario, specific crops studied, choice of crop model, choice of downscaling method, and regional focus. Existing crop modeling results are varied and difficult to compare with each other.

Two possible strategies have been discussed during the meeting for building connections between GMRC and impact modeling groups: (1) to choose a standard geoengineering scenario; and (2) to build a lookup table. The first strategy is from climate to impact - climate modeling groups provide standard climate forcing from geoengineering to impact groups. An overshoot scenario proposed by Tilmes et al. (2016) would be the potential standard geoengineering scenario for impact groups. The reference case is SSP5-34-OV, in which temperature gradually increases, reaches ~1.5 °C higher than present (year 2019) around 2060, and slowly decreases to ~1°C higher than present at 2100. Sulfate geoengineering is applied to keep the temperature the same as present.

The other strategy – to build a lookup table, would be a combined effort from both crop and climate modeling groups. From crop modeling groups, this would be an extension of the existing GGCMI phase II project. GGCMI phase II has already tested crop model sensitivities on temperature (-1°C to 6°C), precipitation (-50% to 50%), CO_2, and nitrogen fertilizer relative to 1980-2010. To have a lookup table for geoengineering, sensitivity test for solar radiation will be added. From climate modeling group, firstly, combinations of those key climate factors (for crop) need to be identified under different geoengineering scenarios. Then an algorithm will be built to extract crop responses from the lookup table.

4. **Response to Stratospheric Heating:**
Alongside scattering radiation in the shortwave (SW), stratospheric aerosols, in particular sulfate aerosols, absorb radiation mostly in the longwave (LW) and thus heat the stratosphere. This heating is suspected to be responsible for the shut-down of the Quasi-Biennial Oscillation seen in some studies, as well as for shaping some aspects of the surface climate response such as tropical hydrology, surface wind patterns and upper-level cloudiness. However, to date little work has been done to isolate the heating effect of stratospheric aerosols from its other effects. Understanding the significance of

this heating effect and the robustness of the climatic response across models will be important not just for understanding the risks and benefits of sulfate aerosol geoengineering, but also for guiding future research into potential alternative aerosols that heat much less but have not been a research priority to date. A plan has been put in place to conduct a model intercomparison study on the effects of an imposed stratospheric heating (without the aerosols that produce it) in order to better understand the climate response. Furthermore, a second short-term action item identified at the meeting is to determine how best to conduct a simulation that would do the opposite; include the SW aerosol forcing but without any stratospheric heating - the combination of these simulations will better constrain the impact of the heating.

5. **Aerosol microphysics (in a well-mixed gridbox):**
   GCM simulations of SAI are typically validated by comparison with observations from volcanic eruptions (principally the 1991 Pinatubo eruption), but the aerosol coagulation rates, for example, may be significantly different in a continuous-injection geoengineering situation. Furthermore, for computational reasons simulations typically use a simplified modal representation (e.g., the Whole Atmosphere Community Climate Model (WACCM) uses a 3-mode aerosol model). Thus, questions include the following:
   a. How different is a modal aerosol representation from a sectional representation?
   b. More broadly, which aerosol representations can adequately reproduce observed responses to volcanic sulfur?
   c. Plume model studies have suggested that injecting H_2SO_4 instead of SO_2 can produce smaller particles with higher scattering capabilities. Is this consistent among different microphysics parameterizations, considering we do not have a natural proxy as we do for SO_2?

   We agreed on seeking resources (time/funding) to quantify the error from a sectional vs a modal aerosol microphysical model. Specifically, the Goddard Earth Observing System Model (GEOS) includes (in order of complexity) the GOCART bulk model, the MAM modal model, and the CARMA sectional model, but MAM needs to be extended to simulate stratospheric aerosol. WACCM also includes MAM, and CARMA could be implemented. With coordinated simulations we would compare the sectional and modal approaches and quantify the differences in aerosol lifetime and radiative forcing.

6. **Understanding systematic differences between climate model response to greenhouse gases vs Solar Radiation Management (SRM):** SRM may be approximated as a reduced solar constant or by more specific wavelength and zonal changes in short-wave fluxes and heating rates. GCM's consistently show that if SRM radiative forcing (RF) is small compared to greenhouse gas (GHG) RF the SRM response tends to push many climate variables closer to their pre-industrial values. These results are encouraging. It is important to explore the possibility that they might be biased. It is particularly important to know if models are biased to predict a response to SRM RF that is biased to make SRM look more effective that it can be in reality. Because the climate modeling community has focused on GHG and longwave forcing, it

is possible that GCMs may be biased toward being able to reproduce dynamical responses to changes in longwave forcings with less emphasis on correctly representing changes to shortwave forcing. Since the difference in response to SRM and GHG forcing arises, in part, from differences in vertical heating rates and the resulting convective mass fluxes it is relevant to explore climate models with unusual representations of vertical transport to see if their response to SRM forcing differs significantly from more typical models. While this challenge was discussed at the meeting, no short-term action items were identified that the GMRC could undertake in 6-9 months to better resolve this, however, it was recognized as an important topic that could potentially be taken up at a subsequent meeting that includes additional climate experts outside of the geoengineering community.

7. **Aerosol-cloud interactions:**
   The interactions between clouds and aerosols remain one of the biggest sources of uncertainties in climate modeling in general. In the context of sulfate geoengineering, the effects on cirrus ice clouds might be particularly important in terms of affecting the resulting energy balance. The reduction of homogeneous freezing, observed consistently across models, strongly depends on the parametrization used in models for upper tropospheric supersaturation, that is linked to changes in subgrid vertical velocities linked with turbulent kinetic energy. In addition, in some models, aerosol microphysics parameterizations are not conceived for the huge amount of upper tropospheric sulfate resulting from geoengineering, and might produce unrealistic results in heterogeneous freezing. A mix of these two effects, resulting in more or less upper tropospheric ice and thus in different amounts of LW radiation escaping to space, might result in changes in how efficient we consider SO_2 injections to be. This issue was discussed at the meeting, but no short-term action items were identified.

III. Short-term next steps: Goal to make progress on these by September and report on at Harvard Meeting

1) Finalize protocol for, perform, and examine stratospheric heating experiments to help better assess uncertainty #4 above (P Irvine, I Simpson, D Keith, D Visioni, C Golja, J. Richter)

2) Define plan for and begin analyzing SO_2 vs AM-H_2SO_4 injection model-intercomparison experiments (uncertainties 2 and 5 above) (D. Keith, J. Richter, D. Visioni, S, Tilmes, J. Pierce, S. Eastham)

3) Identify recommendations and resources required for simulations to compare simpler (modal) to more complex (sectional) aerosol microphysical schemes (uncertainty #5 above) (V. Aquila & M. Mills)

4) Define near-term plan for evaluating the effects of plume/sub-grid cell mixing; uncertainty #1 above (S. Eastham, D. Keith, others TBD as needed)

5) Define plan for model experiments in which the stratospheric heating has been removed; in conjunction with the first action item this helps understand uncertainty #4 above (L. Xia, K. Dagon, S. Tilmes, D. MacMartin, D. Visioni, I. Simpson, B. Kravitz)

6) Use CLM5crop to test the scenario described in section II.3 and use the results to communicate with GGCMI. Discuss plausibility of building a look-up table described in Section II.3 with experts in both climate and impact groups. (L. Xia)

7) Create taxonomy of stratospheric aerosol numerical experiments spanning range of idealized representations (P Irvine, D Keith, L. Xia)

IV. Longer-term goals:

The actions below were identified as important issues for GMRC to focus on over the longer-term, but not for specific focus in the 6-9 month timeframe.

1) Set-up policy relevant geoengineering scenarios for modelers and for communication with impacts community; Coordinate with GeoMIP and bridge with impacts community. Build connections between GMRC and impact modeling groups, such as The Inter-Sectoral Impact Model Intercomparison Project (ISIMIP) and the Global Gridded Crop Model Intercomparison (GGCMI)(S. Tilmes, P. Irvine, A. Robock, L. Xia, B. Kravitz)

2) Evaluate useful, simplifying tools for analysis of simulations, e.g., linearity assumption, emulators, “efficacy metric”, and guidance for best practices (P Irvine, L. Xia, K. Dagon, B. Kravitz)

3) Consider the impact of other (non-sulfate) aerosols and conduct simulations as appropriate to understand the impact of differences in IR absorption and interactions with other constituents (K. Rosenlof, B. Kravitz)

4) Seek critical input from and interface with the broader Earth system modeling community (including ocean, BGC, cryosphere experts and modelers) as well as other relevant geoscientists to identify potential weaknesses in earth system models which will have specific consequences for efforts to accurately model sulfate aerosol injection (connecting into uncertainty #6 earlier). (J. Richter, S. Eastham)

5) Seek funding opportunities (GMRC SSG).

V. List of Presentations:

[1] **Doug MacMartin:** *"Geoengineering Modeling Consortium"*
[2] **Mike Mills:** *"WACCM6 stratospheric aerosol and cloud interactions: validation and uncertainties"*
[3] **Sebastian Eastham:** *"Stratospheric sulfates and premature optimization"*
[4] **David Keith:** *"Testing geoengineering with AM-H_2SO_4 injections with multiple GCMs"*
[5] **Isla Simpson:** *"The role of stratospheric heating in the hydroclimate response to stratospheric sulfate geoengineering"*
[6] **Peter Irvine:** *"Idealized stratospheric heating experiments"*
[7] **Jadwiga Richter:** *"Uncertainties in stratospheric dynamics and role of parameterized GWs"*
[8] **Daniele Visioni:** *"Changes in sulfate geoengineering efficacy due to uncertainties in model representations of high clouds"*
[9] **Simone Tilmes:** *"How is stratospheric ozone changing with stratospheric aerosol geoengineering?"*
[10] **Lili Xia:** *"Solar Radiation Management Impacts on Agriculture"*
[11] **Katie Dagon:** *"Uncertainties in the response of terrestrial ecosystem to solar geoengineering"*
[12] **Colleen Golja:** *"Super-parameterized CESM to study model responses to long and short wave forcing"*
[13] **Alan Robock:** *"Impacts-relevant scenarios, integration with GeoMIP, and some remarks on governance and ethics"*