September 30, 2019 Geoengineering Modeling Research Consortium (GMRC) Workshop Synthesis

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Meeting Summary:

I. Updates on priorities identified at May 2019 workshop:

Since the May 2019 meeting, members of the GMRC made progress on the majority of the short-term goals established at the May 2019 meeting:

a) Stratospheric heating experiments:

Intercomparison of effects of stratospheric heating on tropospheric climate was motivated by the strong response to stratospheric heating present in the Geoengineering Large Ensemble (GLENS) simulations. In particular, these experiments will help to understand the role of stratospheric heating in changing tropical precipitation, mid-latitude jet streams and associated surface climate and ocean circulation changes.

The protocol for the experiments proposed back in May 2019 has been now finalized and can be found here. In short, the experiments consist of inputting standardized heating into global circulation models (GCMs) and examining tropospheric impacts. The heating was obtained using an offline chemistry transport model and radiation scheme and is designed to achieve a uniform -2 W m^{-2} radiative forcing. These heating rates were then doubled to increase the signal to noise ratio. Interactive chemistry is turned off. Insights from one of the participating models suggests that this forcing results in a roughly 5 K warming of the tropical lower stratosphere. The experimental protocol calls for 5 ensemble members of 20 year long simulations (one extended to 100 years optional). Participating models are: CESM1-CAM5

(completed simulations), GFDL-CM3 (simulations in progress), MIROC-ESM (completed), GISS (anticipated), UKMO (anticipated).

It was noted in the discussion that the ensemble of GCM used in this study is deliberately small, target in contrast to GeoMIP experiments that have a much longer turnaround time and are inclusive of more models.

b) *SO_2 vs AM-H_2SO_4 injection model-intercomparison:*

Simulations were carried out using CESM2(WACCM) comparing injections of SO_2 and H_2SO_4 following protocol designed earlier for GeoMIP in accumulation mode in order to test the efficiency of these substances in cooling Earth's surface temperature. Earlier studies suggest that H_2SO_4 produces higher aerosol optical depth (AOD) for same amount of S injected, hence injections of H_2SO_4 could be potentially more effective in cooling the Earth's climate and could avoid some scaling problems associated with SO_2 injections, such as the formation of large particles.

The experiments performed with CESM2(WACCM) had the same amount of S injected in the form of SO_2 or H_2SO_4. Simulations were carried out for 10 years with fixed sea surface temperatures (SSTs). H_2SO_4 (in accumulation mode with 0.1 um radius) and SO_2 were injected using two different injection strategies: in the 'Points' simulations, all mass was injected in one grid cell at 30^oN and 30^oS, at 180^oE and at 20 km of altitude; in the 'Region' simulations, the same mass was injected at all longitudes and at all latitudes between 30^oN and 30^oS, evenly spread between 19 and 21 km.

Results of the experiment show that with 5 Tg S injections there is a small difference in AOD between the simulations with SO_2 and H_2SO_4 injections. While the overall sulfate burden and the global AOD tend to be similar, significant differences are present in the latitudinal distribution of the AOD, due to differences in the transport of the smaller particles produced by H_2SO_4 injections at higher latitudes. Much larger differences are present when injecting 25 Tg S: the global AOD is doubled in the case of H_2SO_4, and the radius of the particles is half of that in the case of SO_2 injections. Due to the increase in lifetime resulting from the smaller radius, the overall S burden is also 50% larger in the H_2SO_4 cases. These differences also translate in different changes to stratospheric heating (smaller particles absorb less in the long wave) and in significant changes in the ozone loss, due both to different SAD at to the increased transport to high and polar latitudes.

During the discussion reasons for the differences in efficiency of SO_2 vs H_2SO_4 were discussed. Results suggest that greater coagulation in the simulations with SO_2 injections drives most of the differences. In addition, some SO_2 stays in that form and is not converted into H_2SO_4, contributing to the smaller effectiveness of SO_2.

c) *Taxonomy of methods for numerically modeling stratospheric aerosols*

Any large-scale numerical simulation faces choices between using models that aim to incorporate all relevant processes versus the use of combinations of models which are

specialized in various relevant domains whose results are knitted together by scenario analysis and the matching of parameters or conditions.

In the case of Stratospheric Aerosol Intervention (SAI) one can consider two broad approaches:

- Single model: use a single GCM with a good representation stratospheric processes coupled to an ocean model and drive it by some specific stratospheric aerosol injection scenario.
- Disaggregated models: use models with state-of-the-art representation of relevant stratospheric processes to estimate the aerosol distribution produced by some injection strategy, then estimate the radiative consequences of that aerosol distribution, then use a separate ocean atmosphere GCM to study the climate response to that radiative perturbation.
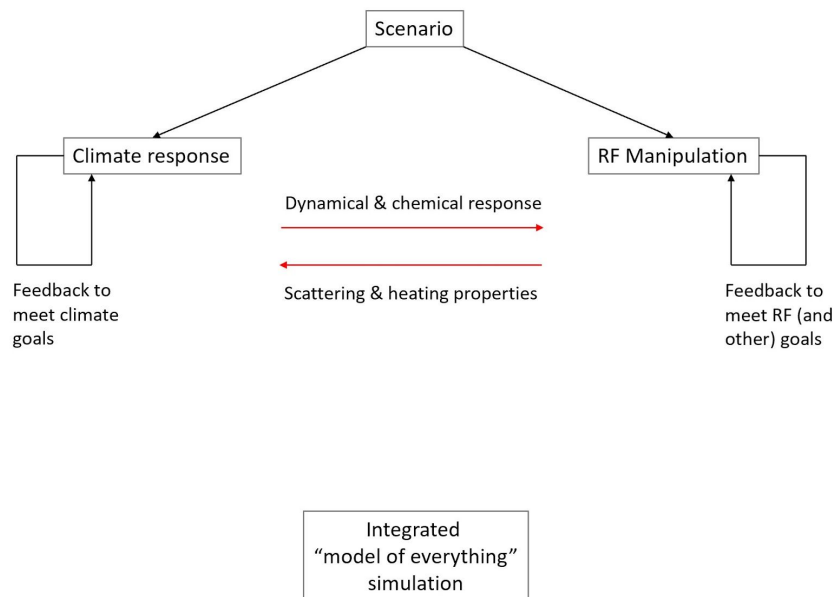
There is no right answer. Both approaches are important.

Some comments on the disaggregated approach:

- The disaggregated approach can allow aerosol models that include treatment of aerosol formation in aircraft plumes, and more complete sectional aerosol representations.
- An obvious weakness of the disaggregated approaches is that there is not an easy way to incorporate the impact of the geoengineering climate response on stratospheric mixing processes. This can be addressed in a decoupled manner using numerical experiments that explore the dynamic response to a radiative perturbation in a model with high quality stratospheric dynamics, and then providing that altered dynamics/circulation to the aerosol process model which is used to generate the radiative perturbation.
- Note that in some cases the aerosol model would pass scattering in radiative heating properties to the OAGCM, while in other cases it might pass the aerosol distribution.
- An advantage of the disaggregated approach is that they can provide a range of

uncertainty as there are very few earth system models that can capture all of the needed interaction. Disaggregated models are usually much more computationally efficient than full earth system models, hence allow for greater exploration of parameter space.

The GMRC should explore both aggregated and disaggregated approaches as they are complementary.

This two-step view is related to a high-level taxonomy for understanding the consequences of any particular geoengineering scenario. This high-level taxonomy breaks problem down to two broad questions. First, what are the climate responses—e.g. the change in relevant climate hazards--to a particular radiative forcing scenario. And, second, is it feasible to engineer such a radiative forcing scenario? And, what are the side-effects/consequences of doing so?

d) *How to study SRM impacts on agriculture?*

The ultimate goal of GMRC is to produce output that can inform society-relevant research. Although GMRC does not directly conduct research in those areas, it is important to maintain effective communication and strong connection with the climate impacts research community. We collaborate closely with the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP) and the Global Gridded Crop Model Intercomparison Project (GGCMI) to ensure that demands and questions exchange smoothly among groups. We encounter three key problems when bridging the climate study and the impact studies and will illustrate them below using agriculture impact study as an example.

First, which SRM scenario should be used for agriculture impact study? There are many SRM scenarios from the Geoengineering Model Intercomparison Project (GeoMIP), Stratospheric Aerosol Geoengineering Large Ensemble (GLENS) and other projects. With different reference lines and geoengineering strategies, agriculture responses might be inconsistent or even contradictory. On one hand, using different SRM scenarios for crop impact study helps us understand the importance of our current decision – which will lead our next generation to different futures. On the other hand, too many SRM scenarios make multi-climate models and multi-crop models assessment impossible. Therefore, the crop model community would like us to provide one or two standardized SRM scenarios for a comprehensive assessment. Currently, ISIMIP and GGCMI are developing Phase III protocol for future scenarios, and tend to incorporate SRM as one of the branch experiments. Since they are using CMIP6 result in the core experiments, it would be convenient for the crop modelers, if we formulate a standard SRM scenario using CMIP6 as the baseline, such as the overshooting scenario Simone Tilmes is working on. Crop model could also use G6solar and G6sulfur output to identify the differences in impacts between those approaches.

Another way to address this question is to build a look-up table of agriculture responses to climate changes. GGCMI Phase II is a sensitivity test with a temperature range of -1 °C and 6 °C, precipitation range of -50% and 50%, and other agriculture management changes. If solar radiation change were added, GGCMI Phase II test result would become a potential look-up table of agriculture responses to SRM and provide a fast way to evaluate different SRM impacts on agriculture. However, there still exist a few caveats: (1) the table only contains temperature, precipitation and solar radiation impacts whereas other important factors such as diffuse

radiation are not included; (2) the method ignores the horizontal communication among crops in grid cells; and (3) under extreme conditions some parameters may exceed the sensitivity test range.

Second, how to pass climate forcing to crop models that don't include interactive crop models (some, like WACCM6 do)? There are many ways to feed crop models with climate forcing. Downscaling is a popular research topic and has been extensively studied. ISIMIP provides a method to bias-correct the mean and variance in the future simulation. However, since CESM2 is coupled with a crop model, it is important to compare the agriculture response from offline crop model simulations using traditional downscaling methods with that from coupled crop model simulations. We need to investigate whether running crop model with different strategies will bring uncertainties to agriculture response to SRM and how large those uncertainties are.

Lastly, which climate variables should be passed to crop models? In general, crop models need daily maximum 2 m air temperature, minimum 2 m air temperature, daily precipitation, and daily total solar radiation. However, more parameters need to be taken into consideration under stratospheric aerosol injection geoengineering. Aerosols in the stratosphere may (1) alter the solar radiation partitioning – more diffuse radiation and less direct radiation; (2) change surface ozone concentration through ozone stratosphere-troposphere exchange and tropospheric chemistry; and (3) scatter UV directly through external injection or affect surface UV level through stratospheric ozone depletion and near-surface aerosol concentration change. Currently those climate changes cannot be simulated by crop models. We will invite agriculture modeling experts interested in this topic to evaluate the influences and develop simulation algorithms based on current crop models.

e) Evaluating effects of plume/sub-grid scale mixing:

Modeling of stratospheric chemistry and transport to date has been dominated by coarse, Eulerian models, with grid cells on the order of 10,000 km^2 in area. However, observations of (eg) rocket emissions have shown us that plumes can remain as coherent, filamentary structures for weeks or longer in the stratosphere. At the same time, studies have shown that chemistry in aircraft plumes is misrepresented at the grid scale, and that this misrepresentation can result in significant errors in the estimated impacts of aviation on atmospheric composition.

Considering these findings together, work is needed to ensure that we are correctly representing plume-scale effects in geoengineering emissions. Most proposals to date have focused on aircraft-based deployment, which will likely result in long plumes of aerosol in the stratosphere. We need to know:

1. How different does the global AOD distribution look when considering plume-scale effects for a single given scenario?
2. How sensitive is the global AOD distribution to sub-grid-scale changes in the injection strategy (e.g. flight paths)?
3. How fine do our simulation grids need to be before we can resolve these effects?

We are now performing two sets of experiments. The first uses conventional Eulerian modeling, but explores the resolution dependency of the problem by running at resolutions from

~1,600 km^2 to ~25 km^2, including high-fidelity chemistry and aerosol microphysics. The second uses embedded Lagrangian modeling, in which plumes are simulated as discrete entities which can diffuse and deform over time. This will provide an upper limit on the answer, as it represents the higher possible resolution.

At this time, we have completed development of an Eulerian model which can be run at the target resolutions in a consistent manner. We are using the GEOS-Chem High Performance (GCHP) chemistry transport model, which has been extended to make use of the 40-bin sectional aerosol scheme previously implemented in the AER-2D CTM and the SOCOL 3-D GCM. Simulations are underway which consider an equatorial point injection of SO$_2$ at 20 km altitude, with results anticipated in the coming months.

We have also made progress in developing the embedded Lagrangian model. We have a working prototype in the GEOS-Chem Classic CTM, in which an arbitrary number N of plume segments can be independently transported through the model based on assimilated wind data. This component alone has been sufficient to perform preliminary assessment of numerical diffusion in the Eulerian model. Each plume segment is now being modified to incorporate R nested rings. These rings will provide a 2-D representation of the plume, including the concentration of all relevant chemical species. We are working to incorporate diffusion, chemistry, shear, and aerosol microphysics into this ring system, in addition to exchange of material with the global grid. We are also working to incorporate a system where the plume's contents are eventually dumped into the global grid, so that plume interaction and quantities such as AOD can be meaningfully calculated.

Questions which were raised during the GMRC discussion included:

- Is a 1-D ring system sufficient?
- How should we measure the degree of diffusion, so that we can estimate when a plume segment should be removed and its contents added to the parent model?
- Are there mechanisms of diffusion and dispersion, or other physical processes, which our approach might miss?
- Should stretched-grid simulations, such as are possible with WACCM, be considered?

f) Comparison of simple to more complex aerosol schemes:

In general, validating the aerosol schemes in climate models is critical, but the question remains of what to do with those results. Aerosol optical properties do depend on particles size: the scattering of SW radiation is increased for a certain range of radii, and LW absorption is larger the bigger the particles, therefore the results of a sulfate geoengineering simulation strongly depend not only on the strategy of the injection, but also on the kind of microphysical scheme used in the model. The GeoMIP participating models had different approaches, ranging from a bulk approach (very fast, a prescribed distribution - usually from Pinatubo measurements), a modal approach (mid complexity, overlapping lognormal modes, but internal mixing of different aerosol families) or a sectional approaches (very complex and slow, population of aerosols simulated in size bins). This resulted in large differences in the GeoMIP simulations. A possible mixed approach, as shown in GEOS5 simulations, is to use a bulk approach buth with the radius parametrized as a function of the mass mixing ratio, informed through more sophisticated

sectional-approach simulations. This has the merit of more correctly reproducing the sulfate behavior in the stratosphere while maintaining a fast approach that saves computational time.

In various MIPs it has been noticed that models with higher spatial resolution usually have simpler microphysics, since both are usually very computationally expensive. Therefore, we should reason on where to invest our computational power. We're not sure that adding complexity to the microphysical scheme always helps: for instance, for smaller eruptions than Pinatubo, a modal approach can be as good as a much slower sectional approach.

We should reason on what kind of level of complexity we want to include in our MIPs, and if it makes sense to exclude some, and maybe invest in some other aspects such as parametrize the output from plume models instead of just injecting uniformly in a grid box.

II. Science updates and questions on cirrus seeding and cloud brightening:

The first meeting of the GMRC focused entirely on SAI. During this 2nd workshop the discussion was expanded to include discussions of geoengineering methods involving aerosol-cloud interactions. These include presentations on seeding cirrus clouds (Ulrike Lohmann and David Mitchell) and some coordinated activities around marine cloud brightening (Phil Rasch).

a) Model challenges of cirrus seeding (Ulrike Lohmann)

In the ECHAM general circulation model, cirrus exert a warming effect on the planet by 5 W m^{-2} on average. If a portion of these cirrus could be reliably seeded such that they dissipate, this would cause a substantial cooling effect. However, there are numerous challenges associated with cirrus that confound our ability to precisely understand the effectiveness and side effects of cirrus seeding.

Cirrus seeding is most effective on cirrus clouds that are formed via homogeneous nucleation. This has a net effect of "transitioning" the cirrus from homogeneous to heterogeneous (i.e., forming around an ice nucleating particle), resulting in fewer, larger ice crystals. Such clouds have lower optical depth and the ice crystals sediment faster, removing water vapor from the upper troposphere. Models and observations suggest that these homogeneous cirrus form best in regions that are orographically complex, making them difficult to seed.

Models do not agree on the effectiveness of cirrus seeding. Depending upon the amount of seeding, some models show cooling, some show little effect, and some models even show an increase in cirrus. Some of this discrepancy could be due to the way cirrus seeding is represented in models. Because the ice microphysics of cirrus are complex and to some degree poorly understood, a proxy for cirrus seeding is to increase the fall speed of the ice crystals in the model. However, this tends to skew the ice crystal size distribution in unreasonable ways. In one model, increasing sedimentation velocity caused cooling, whereas actually seeding cirrus with ice nucleating particles caused warming.

The take-home message is that there are currently substantial uncertainties associated with cirrus seeding. In addition to the profound uncertainties in cirrus formation itself, the discussion

raised further concerns, including that targeted seeding would be critical (seeding in the wrong place could lead to warming from increased cirrus). Feedback would be fundamental to any deployment and could be a useful research tool, potentially providing more realistic estimates of effectiveness.

b) *Evaluating cirrus cloud thinning using CALIPSO satellite data and WACCM6 (David Mitchell)*

According to satellite measurements (CALIPSO), homogeneous nucleation appears to be responsible for higher ice nuclei concentration outside of the tropics. In these regions, effective ice nuclei diameter is smallest at high latitudes and over high terrain, especially in the Arctic winter.

To study the effectiveness of cirrus thinning the research team used WACCM6, first attempting to make the model consistent with observations. They conducted two simulations in which the CALIPSO-observed relationship for heterogeneous nucleation between effective diameter and temperature was imposed in the model: one applied this relationship to all cirrus and one imposed it only on tropical cirrus (30°S-30°N). They found that with this new parameterization/constraint, the largest effects are in lower altitude mixed phase clouds, where higher fall speeds produce higher ice growth rates and larger ice crystals. Results indicate that a global negative forcing of magnitude 2-3 W m^{-2} from thinning cirrus is possible, with the greatest cooling occurring when longwave cloud forcing dominates (high latitude winters).

The study provides three suggestions for climate model improvements:

- This CALIPSO data can and should be used to constrain models to understand whether their internal microphysics is consistent with observations.
- Alternatively, there can be efforts to improve model physics (e.g., orographic gravity waves) and then validate the improved model against CALIPSO.
- Models can undergo tests to understand their sensitivity to ice fall velocity schemes. This could eventually involve moving to explicit cloud microphysics without making assumptions about ice fall speed changes.

The discussion reflected that model improvements are important for a variety of contexts, as the cirrus impact has a 10-20% effect on radiative forcing in SAI studies. A question that was raised is that some models (like CESM) that estimate overall aerosol quantity: how important is this?

c) *Marine Cloud Brightening (Phil Rasch)*

This presentation was a description of progress in the Marine Cloud Brightening Project, a partnership primarily led by the University of Washington and Pacific Northwest National Laboratory, with partners at the University of Frankfurt, Palo Alto Research Center, and SilverLining.

This is a proposed effort to combine modeling and field studies to understand aerosol-cloud interactions in marine low clouds, which is one of the largest sources of uncertainty in climate science. The efforts are based on the idea of marine cloud brightening; early simulations show that brightening 10-30% of marine low clouds could offset the radiative forcing from a doubling

of the CO_2 concentration. The potential effectiveness of marine cloud brightening has recently been reinforced by the eruption of Holuhraun, in which the first aerosol indirect effect was observed, and those effects were then verified in some models (although there were large disagreements between models - could this be a useful method of validating/calibrating model representations of aerosol indirect effects?).

The proposed project has two parts. The first is developing a marine cloud brightening aerosol spray system; nozzles have already been developed that produce the optimal particle size (~90 nm diameter). The second is a detailed study of aerosol-cloud interactions. Both components require modeling across scales, including computational fluid dynamics, plume models, cloud-resolving/large eddy simulation, and global models.

Although the remit of the GMRC has thus far been limited to SAI, incorporating MCB could provide some useful synergies. For example, plume-scale modeling is a common problem across multiple methods of geoengineering and climate science more generally, as is determining the consistent response to a local forcing. Also, global models continue to fall short in representing aerosol-cloud interactions; perhaps viewing this problem from a geoengineering perspective could be insightful. Perhaps in suggesting specific ways in which controlled experiments could reduce uncertainties about cloud-aerosol interactions.

Several specific future research questions around MCB were raised in this presentation. We include them here rather than in Section III, as the scope of the GMRC, and thus the prominence of MCB research in it, is still to be determined.

- What is the best-estimate and uncertainty range in the maximum albedo perturbation that can be achieved through MCB in key regions and globally?
- What is the relationship between albedo response and MCB deployment level, accounting for energy used in the process of deploying MCB?
- What is the expected impact on global and regional temperatures and precipitation patterns for the application of MCB deployment scenarios?
- How would other climate-related parameters (e.g. atmospheric circulation) be affected by MCB deployment scenarios?
- How effectively can MCB be deployed to address specific interest areas (e.g., hurricane mitigation, protection of coral reefs by mitigation of local ocean temperatures, and protection of coastal forest systems through regulation of temperature and precipitation at a local scale)?
- What does our work on MCB with sea salt aerosol tell us about the possible range of anthropogenic radiative forcing via aerosol-cloud interactions?

III. Discussions on future directions and research needs

The May 2019 GMRC meeting identified several key uncertainties related to solar geoengineering. Some of these uncertainties were further discussed at this meeting in terms of future needs and in the context of a serious research agenda, and role of GMRC.

a) Realism of scenarios/injection strategies

There have been tremendous advances made in modeling of geoengineering using stratospheric aerosols in the last 5 years. Simulations with CESM1(WACCM) and a sophisticated strategy for deciding the amount of location and amount of SO_2 injections have shown that many of the commonly talked about side-effects of geoengineering can be reduced or removed using such a strategy. A large ensemble of these simulations, GLENS, has enabled the community to examine in detail tropospheric and stratospheric impacts of this strategy, including regional changes. Hence, a lot of progress has been made on quantifying impacts of geoengineering via these studies, however, the emissions scenario used was quite unrealistic, and details of the prescribed injection strategy, in particular the altitude of injection, might not be physically feasible. Since impacts of geoengineering depend on injection strategy (and emissions scenario) it would be worthwhile to move towards modeling a series of geoengineering scenarios that would be more realistic and feasible in terms of engineering constraints. Injection altitude of 25 km in the tropics, and 23 km near 30ºS/30ºN are very high, which pose unique demands on geoengineering, however engineering advances could possibly be made if it was determined that higher injection was far more desirable from the perspective of reducing side-effects of geoengineering. Short simulations with injections at lower altitude indicate that side-effects of lower injections would be larger compared to higher altitude injections, especially in terms of the increase of stratospheric water vapor and changes to ozone. Due to changes in the distribution of stratospheric heating in these simulations, surface impacts are also likely to differ. Results of a more sophisticated injection strategy have so far been based on one model, limiting confidence. A multi-model comparison of different injection strategies could be useful.

b) Stratospheric transport

We have a very limited knowledge of the current state of the stratosphere and stratospheric circulation. Stratospheric transport differs between climate models. One of the most illustrative example of this is is the age of air, which in the same location in the stratosphere can vary between 3.5 and 5 years across different models. Validating stratospheric transport with observations would be crucial in order to consider deployment of geoengineering, as is understanding of what causes the differences between the models. Field tracer experiments would be very beneficial to understanding stratospheric transport as would be injection of plumes into the stratosphere to understand how a plume behaves on horizontal scales that are not captured in global models. A potential monitoring program has been described by Moore and Ray (2014). There also have been measurements made of aircraft engine plumes (e.g:. Fahey et al. 1995) to evaluate emission indices. An aircraft instrumented with required measurements self-sampling its own contrail could be a good start.

c) Answering policy relevant questions

One of the motivators for GMRC is to be able to answer society-relevant questions related to geoengineering, in particular: "What will policymakers want to know in N years?" in order to make a decision on whether geoengineering could be a viable strategy to avoid the worst consequences of climate change. The key questions are:

- What are the options: SAI and/or MCB, how much, where to inject, etc.?
- What are the projected impacts of each option?
- What is our confidence in those projections?
- What additional research would improve confidence?

In order to assess impacts, scenarios and goals need to be defined/prescribed. Although this is extremely important, defining scenarios are beyond the scope of GMRC. However, there is a need to have a close collaboration with that community as we need to iterate between impacts analysis and goals, and we need to understand what features of scenarios are important to simulate, and what aspects of different scenarios may not need separate computationally-intensive simulations (see later discussion regarding emulators). The implications of this for research moving forward are:

- need to understand how impacts and uncertainties depend on approach
  - what features do we need to capture?
  - don't want to capture only one scenario
  - dimensions - CO2, cooling, goals
  - develop a few scenarios that capture these?
- need to go further on impacts analysis
- need to get more rigorous / explicit in our assessment of uncertainty
- how much does this research cost?

Importance of building an emulator for policy analysis was also briefly discussed. It could be a very useful tool, however need to be careful about caveats - this could be outside the scope of GMRC.

GMRC should primarily focus on hazards rather than impacts. In the language of the IPCC "hazards" are physical climate variables that are important in determining human and environmental impacts. Such variables include maximum temperature, seasonal water availability, extreme precipitation, ozone concentration, etc. These are distinct from impacts which may be assessed by impacts on human health or in economic terms. There was general agreement that GMRC should focus on assessing hazards to facilitate impact analysis but should not itself focus on impact analysis. However, a connection with the impacts community should be cultivated.

d) Modeling Framework

SAI research using climate models to date has been primarily carried out using long term climate simulations, and looking at long-term averages of climate. Although this has been very

useful in initial stages of research and will continue to do so, in order to explore impacts of geoengineering on society-relevant quantities, climate variability will need to be explored as well shorter-term analysis of impacts. CESM2(WACCM) is now set-up for studies of subseasonal to decadal prediction which would be very useful in studies of variability changes associated with geoengineering, attribution and understanding of these changes, as well as make a great complement to field campaigns. Other modeling centers are also developing similar prediction frameworks.

e) What would a significant geoengineering research program look like?

In order to allow for decisions ~ 15 years out from present, a serious research program is needed that would begin addressing questions described above. A serious research program would include a combination of modeling, lab and field experiments, continuous observations, and engineering of deployment systems, with the four parts of the program working hand in hand: modeling providing input into what experiments we need, and observations verifying models. Similarly, engineering constraints need to feed-back into models, and models can inform what engineering capabilities would be needed in order to address the problem most effectively.

A lot of the modeling needs were already described earlier in this section. In addition plume modeling and integrating knowledge from plume models into GCMs is needed in order to get the large scale response to SAI correct. A range of models is also needed to address questions related to MCB. Cloud resolving models could be used to assess what what will happen to the clouds, then models that can simulate a longer time range could be used to describe the evolution of the clouds, and global models need to be incorporated to assess whether and how changes in sea surface temperatures due to changes in clouds affect the large scale circulations and other components of the earth system. There are many uncertainties that can be addressed relatively simply using lab and field experiments. Examples of laboratory experiments related to stratospheric aerosols include (a) measurements of rate coefficients for interactions of stratospheric the relevant gases with particles, and (b) measurements of the ice nucleating characteristics of aerosols it might be generated in the stratosphere from SAI and then sediment into the troposphere where they can affect cirrus. Examples of field experiments include (a) use of lightweight remotely piloted aircraft and/or "drones" to disperse ice nucleating material in locations relevant for cirrus cloud formation combined with remote-sensing measurements of cirrus cloud extent, (b) use of sea salt aerosol generators to explore impact on marine boundary layer clouds, (c) generation and in situ observation of particle formation and interaction particles with in small stratospheric plumes formed either by aircraft or by balloons with propellers.

We need better knowledge of the current stratospheric state and its variability. In particular we need observations to better constrain the strength of the Brewer Dobson Circulation and its variability. We have an excellent understanding of ozone chemistry, however little understanding of new particle formation, ice nucleation, aerosol dispersion or aerosol composition.

Lastly there is a need to begin exploring engineering of deployment systems. To date, albedo modification research has been theoretical rather than practical. The vehicles to disperse the appropriate particles do not exist at present. Large scale deployment will require engineering

solutions to produce both appropriate size particles and aircraft/balloon/ship systems to actually get these particles to where they will be effective. Although not within the purview of GMRC, practical engineering research will be essential for climate intervention efforts to be possible, and can guide the choices made in modeling simulations.

e) NAS and research agenda

The ongoing NAS study and report will describe a research agenda. The GMRC discussed what inputs it could give to the study before the end of the year. GMRC is in a good position to provide input on modeling needs.

f) International development of GMRC

The GMRC discussed how to approach international development/membership. It was decided that the GMRC will be open to groups from different countries joining if they would like to be involved in the effort, but won't actively push it.

g) Which models are 'good enough'

Several discussions raised the question of "which models are "good enough" to use for geoengineering studies and whether models should meet certain criteria in order to be used in future studies. The Chemistry Climate Model Initiative (CCMI), supported by Future Earth's IGAC and the WCRP's SPARC projects, in preparation for the 2022 ozone assessment, is starting discussions on an updated assessment of the representation of stratospheric chemical and dynamical processes in stratosphere resolving CCMs. CCMI's goal is to have a more holistic and process-based analysis of CCMs to more fully understand the strengths and weaknesses of our current generation of models. The selection of models used for geoengineering studies by GMRC could perhaps consider results from CCMI evaluations and use only models that well represent stratospheric chemical and dynamical processes based on reference simulations compared with historical data on constituent distributions and dynamical fields.

IV. Funding for solar geoengineering research:

At present, dedicated funding for geoengineering research is limited, but has grown from 2008 to 2018. Estimates suggest that in 2018, less than $10 million per year was spent toward solar geoengineering related work around the world. The United States saw the most funding, with approximately $6 million supporting efforts in 2018. There are philanthropic groups funding individual projects, and some government funding. The United States has the highest amount of funding from philanthropic sources, with the largest amount going to Harvard's Solar Geoengineering Project (SGRP), whereas the primary source of geoengineering funding in Europe and Asia is from governments. Between 2008 and 2018, North America saw $7.18 million from government and $18.09 million from philanthropies, whereas Europe saw $20.35 million from government and $1.38 million from philanthropies, and Asia saw $3.84 million from government and $300k from philanthropies. Many countries don't have any funding at all. SGRP

funding comes from individuals and foundations, all concerned about climate change. US government funding for climate research, including climate engineering, is relatively consistent, although not large. A large portion of geoengineering research is done in the 'off-hours' by scientists interested in the topic, dedicating their nights and weekends to the cause. In addition, there is funded work related to solar geoengineering such as volcanic aerosol injection, studies of ship tracks, and control of aerosol in the asian monsoon which help with the fundamental understanding of the processes involved.

The National Academies of Sciences, Engineering, and Medicine has undertaken a study to develop a research agenda and recommend research governance approaches for climate intervention strategies that reflect sunlight to cool Earth. This study has support from NOAA, NASA and DOE, and helps legitimize the topic and creates a context for moving ahead. The hope is that one result of the NAS study will be a roadmap to government agencies as to best funding targets for government agencies for future research.

The current versions of both the House and Senate FY2020 appropriations bills contain $15M for cloud and aerosol research for the Department of Energy, and the House CJS bill contains $13M for the National Oceanic and Atmospheric Administration to study stratospheric aerosol and radiative forcing.

The NOAA Office of Oceanic and Atmospheric Research (OAR) is currently working towards devising an action plan if the $13M in funding becomes available in FY2020. Some of the funds could be used to support high altitude stratospheric aerosol measurements in conjunction with an NSF sponsored Asian Summer Monsoon measurement program (ACCLIP) based in Okinawa in summer 2020.   It would measure aerosol properties in Asian summer monsoon high altitude outflow. Measurements will include 1) aerosol composition 2) UTLS particle size, water isotopes, SO_2 and NO measurement, complementary gas species using Gulfstream-5 aircraft. There is a proposed high altitude component that is not fully funded yet, but prospects are looking promising. Ideally, a long-term stratospheric aerosol baseline measurement program should be established that will provide measurements of the current stratospheric aerosol background, so that we are able to detect perturbations to the system in the future. ACCLIP measurements could be tied to GMRC goals because the ATAL (Asian Tropopause Aerosol Layer) is essentially an unintended geoengineering experiment. Such a collection of data should lead to improved accuracy in representing and understanding stratospheric processes related to the budgets and formation of aerosol particles. Modeling studies in conjunction with data analysis will be crucial to maximize benefits.

DOE is directed in the FY2020 House and Senate bills to spend $15M on measurements and modeling to reduce uncertainty in understanding cloud aerosol effects, and marine cloud brightening efforts should fall into that funding line.

V. Update on Related Efforts

This workshop included short discussions and updates on ongoing initiatives/projects related to the main goals of GMRC, but that were not discussed during the May 2019 meeting:

1) NCAR and UCAR Climate Intervention Strategies Project (NCIS):

NCAR/UCAR Climate intervention Strategies Project hosted an NCAR/UCAR internal workshop this summer and discussed the current status of activities at NCAR to holistically evaluate the effectiveness of climate intervention strategies, including their intended and unintended impacts and the need for more integrative research. The goal of the first workshop was to increase communication across UCAR and NCAR labs, to identify new cross-lab collaborations, and discuss how best NCAR and UCAR can contribute to this topic within the wider research community. This workshop concluded that there is an urgent need to explore the effects of climate intervention strategies by considering a portfolio of options. This requires a unifying strategy that streamlines and connects the various ongoing research efforts of currently disparate communities. NCAR will be therefore hosting the Community Climate Interventions Strategies Workshop: The Future of Research from April 15–17, 2020. The purpose of this workshop is to bring together key members from different research communities, including experts in integrated assessment modeling, global modeling, SRM and CDR, the impact community, as well as ethical and social scientists, to develop a coordinated interdisciplinary path for future research on combined climate intervention strategies. For more information contact Simone Tilmes (tilmes@ucar.edu).

2) Biogeochemical carbon coupling influences

Fyfe et al. 2013 showed that carbon coupling is responsible for a large fraction of the global precipitation reduction in CanESM2 SRM experiments. The primary effect comes from reduced transpiration through the leaves of plants and trees in the terrestrial component of the carbon cycle due to elevated CO_2. The study suggests that biogeochemical interactions are as important as changes in net radiation and that the lack of inclusion of carbon coupling in climate models may be significantly underestimating precipitation reductions in geoengineering simulations.   The discussion around this topic focused on how big is the uncertainty in this study and how to quantify carbon coupling influences.

3) Work at ETH Zurich:

Work related to GMRC's goal is taking place at ETH, Zurich in particular in areas of effectiveness of H2SO4 vs SO2 injections, evaluating the effects of these injections on stratospheric and tropospheric dynamics. There is potential for collaboration between their efforts and GMRC in the future.

4) Analysis of winter warming over the Northern Hemisphere:

There is ongoing work at NOAA/ESRL on understanding the reasons for winter warming over

the Northern Hemisphere in the GLENS simulations and understanding how much of that warming comes from natural variability. Understanding the role of the stratosphere in this is a complimentary effort to the specified heating experiments.

VI. Next-steps:

1) Analyze heating experiments with participation of completed and anticipated models (I. Simpson, D. Visioni, P. Irvine)

2) Continue analysis of SO_2 vs AM-H_2SO_4 injection model-intercomparison experiments with CESM2(WACCM). Compare results with the ECHAM simulations (simulations performed already) and wait for the SOCOL simulations (not done yet- who's doing them?) to compare to, in order to have 2 modal-approached and 1 sectional one. Compare results from all models. A call should be set up with all interested parties to determine who's interested in analyzing what, and to define a plan for papers to write. David Keith is going to present some results at the AGU meeting, so possibly some new comparisons should be performed before then. (D. Visioni, D. MacMartin, U. Niemeier, S. Vattioni, D. Weisenstein, J. Richter)

3) Compile a document outlining observational and experimental needs (K. Rosenlof)

4) Compile research needs to begin understanding sensitivity of geoengineering impacts to design strategy and model assumptions (perhaps on the latter) (D. MacMartin, J. Richter)

5) Contact CCMI for coordination regarding assessment of models for purposes of solar geoengineering research (K. Rosenlof)

6) Begin compiling a requirements list for improvement of models. This list of requirements would be similar to the requirements of modeling developments such as NCAR's MUSICA, the Multi-Scale Infrastructure for Chemistry and Aerosols.

7) Provide input to NAS study on Research Needs (D. Keith, S. Eastham):

- couple of pages, focus on model gaps and solutions (not scenarios and broader Qs)
- based on last meeting and this one, though longer term considerations should be factored in
- open to whole GMRC for comments
- committee revises based on comments
- summary done at AGU by Jan for NAS reports
- doesn't need to be citable, only has to be made public

8) Emulators (Doug McMartin in collaboration with Ben Kravitz)

There are numerous aspects of solar geoengineering that simply cannot be simulated adequately with expensive general circulation models. One example is scenarios: for projecting the response to climate change, there are only four central RCPs because that's all that the climate modeling centers could afford, but for developing policy-relevant assessment of impacts of solar geoengineering there are many other potential scenarios that could be valuable to understand. Another example is probabilities of outcomes and projections of rare events; a standard approach to quantifying these aspects is to conduct large ensembles, which is prohibitively expensive.

Potentially useful tools in these contexts are climate model emulators. Which aspects of climate are well represented by linear emulators (e.g., global mean temperature response to CO_2 or solar forcing) and which are not (e.g., ozone changes)? Expanding the use of emulators will not only allow us to explore different parameter spaces more thoroughly, but will also inform us about predictability and the necessity of using a complex model. The question of when an emulated response is useful is thus closely connected to determining what set of standardized scenarios may be useful to define, and the latter should not be defined without some understanding of the former. Existing simulation output can be used to provide some preliminary assessment of where emulators are valid (e.g., tuning an emulator from SSP5-85 scenario and assessing the error in capturing the response to an overshoot scenario).

9) Organize GMRC meeting at AGU (Lily).

VII. Panel discussion:

At the end of the workshop a panel discussion took place open to faculty and students from Harvard University. Panelists included: Mariana Linz (Harvard University), Steve Wofsy (Harvard University), Frank Keutsch (Harvard University), and Jadwiga Richter (NCAR). The key messages from the panelists were:

- Large-scale stratospheric basic state (aerosols, dynamics, transport, …) is uncertain. Stratospheric reanalysis products disagree on strength of circulation. This has implications for how we understand strategies of SRM. It's important to think about an adequate measurement system and consider using tracers such as N_2O to verify our understanding of the stratosphere and our models. We need about 5 to 10 years of stratospheric observations before considering introducing a perturbation. Global observations of the stratosphere are needed including the whole vertical column.

- Validation of smaller-scale models and processes with observations is also very important. In particular particle formation after injection and impacts on cloud. This processes are currently parameterized in large-scale models and need to be better understood. There are also other parameterization in global models (such as gravity wave parameterizations) that are poorly constrained by observations, yet greatly affect stratospheric circulation. Combination of smaller-scale models and observations would be needed to reduce the uncertainty in the representation of these processes.

- Small scale perturbation studies will be needed. Volcanoes are a good natural analog, however can not count on them happening in the right place and at the right time to provide us with the information that we would need for geoengineering.

- Transparency and openness of Earth system models could be useful in entraining more people on working and verifying parameterizations, hence reducing uncertainty.

- It's important to increase communication between the modeling and observational communities

VIII. List of Presentations:

[1] Isla Simpson: "Update on stratospheric heating model intercomparison project"

[2] Daniel Visioni: "Comparison of SO_2 and H_2SO_4 injection strategies using a model aerosol microphysics representation"

[3] David Keith: "Taxonomy"

[4] Lili Xia: "How to study SRMs impact on agriculture"

[5] Ulrike Lohman: "Model challenges associated with cirrus seeding"

[6] Jadwiga Richter: "Advances in modeling of stratospheric aerosol geoengineering: recent progress and future directions"

[7] Seb Eastham: "Resolution and Lagrangian modeling"

[8] Valentina Aquila: "How much aerosol complexity do we need when modeling SAI"

[9] Simone Tilmes: "NCAR and UCAR Climate Intervention Strategies Project and the upcoming Community Climate Intervention Strategies workshop"

[10] Phil Rasch: "Marine cloud brightening"

[11] Doug MacMartin: "Solar geoengineering: what do we need to know?"

[12] Antara Banerjee: "Robust winter warming over NH through strat-top coupling in GLENS"

[13] David Mitchell: "Evaluating cirrus cloud thinning using CALIPSO retrievals and the Whole Atmosphere Community Climate Model, version 6"

[14] Jason Cole: "Biogeochemical carbon coupling influences global precipitation in CanESM2 SRM experiments"

[15] Elizabeth Burns: "Private funding for geoengineering research"

[16] Karen Rosenlof: "ACCLIP and measurements proposed for the CJS appropriations"