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The Geoengineering Model Intercomparison Project – introduction to the second special issue

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Abstract. The Geoengineering Model Intercomparison Project (GeoMIP) has just concluded its second special issue, which this article introduces. Here we discuss the history of GeoMIP, what was learned in the first special issue, why a second special issue was needed, the additional knowledge that was provided in that issue, and some next steps for GeoMIP and the field of geoengineering research. We focus on response and uncertainty across climate models, questions for which GeoMIP is particularly well suited.

1 Introduction

Founded in 2011, the Geoengineering Model Intercomparison Project (GeoMIP; Kravitz et al., 2011) was conceived to understand the robustness of how climate models respond to solar geoengineering (also called solar radiation management or albedo modification – here we simply refer to these techniques as "geoengineering", which in this paper is not meant to include techniques for carbon dioxide removal that are sometimes included under that term). GeoMIP has now been adopted as a formal component of the Coupled Model Intercomparison Project Phase 6, CMIP6 (Kravitz et al., 2015; Eyring et al., 2016). GeoMIP has thus far resulted in 67 peer-reviewed publications and 12 non-peer-reviewed publications featuring simulations conducted under the project or affiliated with its efforts. Many of the peer-reviewed publications have appeared in two special issues, the first in *Journal of Geophysical Research-Atmospheres* (Kravitz et al., 2013c), and the second jointly in *Atmospheric Chemistry and Physics* and *Geoscientific Model Development*, which this article introduces. Figure 1 summarizes the number of GeoMIP publications by year since 2011.

Proposals for solar geoengineering are associated with numerous uncertainties regarding physical climate responses in Earth System Models (e.g., Robock, 2014; MacMartin et al., 2016), along with many other important research areas, such as impacts assessment, engineering feasibility, ethics, governance, law, and geopolitics. While it is not the purpose of GeoMIP to address all the uncertainties regarding the climate response to geoengineering, it is uniquely suited to reveal model commonalities and differences in the responses to standardized geoengineering scenarios. Thus far, GeoMIP has seven such scenarios (see Table 1) with model output that is publicly available to the scientific community (Kravitz et al., 2011, 2013d). These are designated as "Tier 1" scenarios in the CMIP6 parlance, indicating required experiments for models participating in GeoMIP. Output for four more

Table 1. Summary of all Tier 1 experiments in GeoMIP, with references for further description.

Experiment Name	Description	Years/Duration	Phase of GeoMIP
G1	abrupt4xCO2 plus reduce solar constant so net TOA radiative flux does not change ($\pm 0.1\,\mathrm{W\,m^{-2}}$)	1–50	1 (Kravitz et al., 2011)
G2	1pctCO2 plus reduce solar constant so net TOA radiative flux does not change	1–50 geoengineering + 51–70 termination	1 (Kravitz et al., 2011)
G3	RCP4.5 plus sulfate aerosol geoengineering so that net TOA radiative flux remains at 2020 values	2020–2069 geoengineering + 2070–2089 termination	1 (Kravitz et al., 2011)
G4	RCP4.5 plus 5 Tg SO_2 injection per year starting in 2020	2020–2069 geoengineering + 2070–2089 termination	1 (Kravitz et al., 2011)
G1ocean-albedo	abrupt4xCO2 plus increase in ocean albedo so net TOA radiative flux does not change	1–50	2 (Kravitz et al., 2013d)
G4cdnc	RCP4.5 plus increase in cloud droplet number concentration in marine low clouds by 50 %	2020–2069	2 (Kravitz et al., 2013d)
G4sea-salt	RCP4.5 plus injection of accumulation mode sea salt into marine boundary layer to achieve effective radiative forcing of $-2.0\,\mathrm{W\,m^{-2}}$	2020–2069	2 (Kravitz et al., 2013d)
G1ext	Same as G1 but run for 100 years	1–100	6 (Kravitz et al., 2015)
G6solar	RCP8.5 plus solar constant reduction so that net TOA radiative flux remains at 2020 values	2020–2100	6 (Kravitz et al., 2015)
G6sulfur	RCP8.5 plus sulfate aerosol geoengineering so that net TOA radiative flux remains at 2020 values	2020–2100	6 (Kravitz et al., 2015)
G7cirrus	RCP8.5 plus increase in cirrus ice crystal fall speed to achieve effective radiative forcing of approximately $-1.0\,\mathrm{W\,m^{-2}}$	2020–2100	6 (Kravitz et al., 2015)

scenarios (also see Table 1) is expected to be available in the coming months (Kravitz et al., 2015), and output is presently available for several additional scenarios that, while not formal Tier 1 GeoMIP experiments, are designed to be simulated in multiple models (e.g., Tilmes et al., 2015; Gabriel et al., 2017).

In this introductory article, we discuss the history and accomplishments of GeoMIP since 2014, which was the closing date of the previous special issue and the starting date of the present one. We review why a second special issue was needed, what has been learned over the course of this issue (2014–2018), and what some of the next steps are for GeoMIP and the field of solar geoengineering research as a whole.

2 Looking back: why a second special issue?

Since the inception of GeoMIP through the end of the first special issue, there was a flurry of activity and new information that was provided regarding robust model response to various geoengineering simulations. Although not exclusively, much of the activity to that point was focused on experiment G1, involving offsetting an abrupt quadrupling of the CO_2 concentration with total solar irradiance reduction. Despite being idealized in nature, that simulation provided a wealth of information about the broad climate response to solar geoengineering, particularly methods like stratospheric sulfate aerosol geoengineering (e.g., Irvine et al., 2016).

Publications in that first special issue and prior to it looked at a variety of domains, including the broad temperature response (Schmidt et al., 2012; Kravitz et al., 2013a), hydrologic cycle (Tilmes et al., 2013; Kravitz et al., 2013b), cryosphere (Berdahl et al., 2014; Moore et al., 2014), regional effects (Kravitz et al., 2014), stratospheric chemistry and dynamics (Aquila et al., 2014; Pitari et al., 2014), extreme events (Curry et al., 2014), agricultural impacts (Xia et al., 2014), various aspects relating to sensitivity, forcings, and feedbacks (Irvine et al., 2014; Huneeus et al., 2014), and the so-called "termination shock" if geoengineering were abruptly ceased (Jones et al., 2013).

While these results have been essential for understanding broad responses to solar geoengineering, there remained numerous unanswered questions after the conclusion of the first special issue, some of which are summarized here:

1. Few topics were investigated in depth. For example, only a handful of studies focused on the hydrologic cycle, and they only provided a rudimentary understanding of the effects.

2. With a few notable exceptions, most of the studies described in the previous paragraph focused only on one simulation, experiment G1.

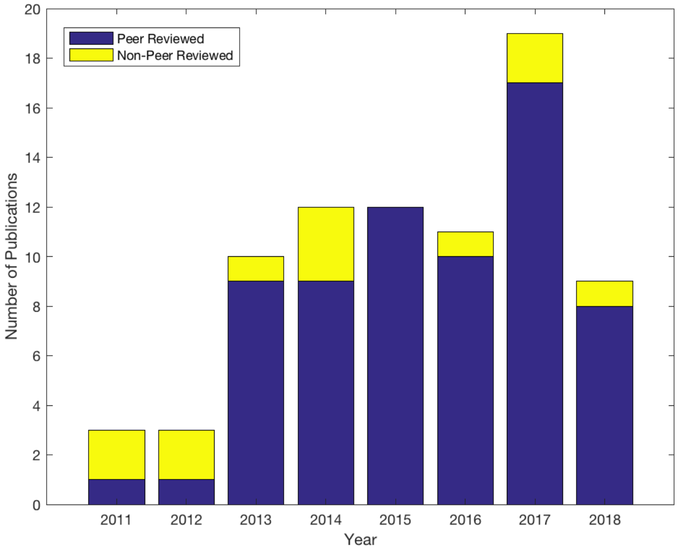

Figure 1. The number of GeoMIP publications by year since its inception in 2011, as listed on the GeoMIP website. This includes both peer-reviewed (accepted or in discussion) and non-peer-reviewed (e.g., meeting reports) publications. The publication count for 2018 was current as of the time of closing of the second special issue, 31 March 2018.

3. The focus of those initial experiments was deliberately narrow, concentrating on stratospheric sulfate aerosol geoengineering or total solar irradiance reduction) While a GeoMIP protocol for solar geoengineering by sea spray injections (which we refer to here as marine cloud brightening) was introduced in that special issue (Kravitz et al., 2013d), only one set of multi-model studies evaluating robust model responses to such technologies had been performed up to that time (as a component of the Implications and Risks of Engineering Solar Radiation to Limit Climate Change, or IMPLICC project; Alterskjær et al., 2013).

4. Many important fields were relatively untouched. As an example, in the special issue, there were few papers that focused on the areas of extreme events and impacts.

While this list is certainly not exhaustive, it became immediately clear upon the conclusion of the first special issue that GeoMIP still had an important role in increasing the body of knowledge around solar geoengineering. That, combined with the new set of climate modeling experiments focusing on experiments that mimic marine cloud brightening (e.g., changing the albedo over the ocean or directly injecting sea salt aerosols into the marine boundary layer), prompted the project to propose a second special issue. The issues raised in the previous list germinated a list of anticipated publications that were formally proposed as examples of what the second special issue might include.

3 The second special issue: what have we learned?

As of 31 March 2018, 27 articles have been published or are in discussion in the second special issue. Rather than listing and describing all of these individually, we summarize the broad themes of research and findings contained in this issue.

An important component of this second special issue is the presentation of results around the sea spray experiments that were proposed by Kravitz et al. (2013d) for the second phase of GeoMIP (Ahlm et al., 2017; Stjern et al., 2018; Kravitz et al., 2018); also see Table 1. In particular, Ahlm et al. (2017) found that even in areas where cloud cover is not persistent, injecting salt particles into the marine boundary layer uniformly across the Tropical belt still results in increased albedo through backscattering of solar radiation under clear-sky conditions. These findings thus show promise in adding an additional level of controllability to marine sky brightening.

Relatedly, a recent research direction in the field is to treat geoengineering as more of a design problem (MacMartin et al., 2014b; Kravitz et al., 2016), exploring the different climate effects that result when one changes injection strategies: latitude, altitude, time of year, amount, and composition of the aerosol or aerosol precursor injection. Several of these aspects have been investigated in the second special issue, including nonlinearities with increasing sulfate injection amount (Niemeier and Timmreck, 2015; Kleinschmitt et al., 2018), effects of different aerosol types (Jones et al., 2016), impact on stratospheric dynamics (Aquila et al., 2014; Niemeier and Schmidt, 2017), seasonally varying injection

(Laakso et al., 2017), the effects of stratospheric variability on aerosol location and impact (Visioni et al., 2018a), upper tropospheric ice sensitivity to sulfate geoengineering (Visioni et al., 2018b), and various other design aspects (Visioni et al., 2017a; Kleinschmitt et al., 2018). From these studies, it is apparent that the relationship between sulfur injection rate and net radiative forcing still has substantial uncertainties. Niemeier and Tilmes (2017) and Visioni et al. (2017a) summarize resents results on impact of sulfate geoengineering on stratospheric and tropospheric climate and dynamics.

The ultimate purpose of adopting the perspective that geoengineering can be treated as a design problem is to improve the ability to manage changes in multiple different variables or locations. However, doing so requires a much more in-depth understanding of how those aspects of climate might be affected. This second special issue saw a great increase in the diversity of climate features being studied, including extreme events (Aswathy et al., 2015; Ji et al., 2018; Wang et al., 2018; Wei et al., 2018), the El Niño Southern Oscillation (Gabriel and Robock, 2015), terrestrial photosynthesis (Xia et al., 2016), circulation patterns and energy transport (Davis et al., 2016; Smyth et al., 2017; Niemeier and Schmidt, 2017; Guo et al., 2018; Russotto and Ackerman, 2018a; Kashimura et al., 2017), clouds and thermodynamics (Russotto and Ackerman, 2018b), atmospheric chemistry (Xia et al., 2017; Visioni et al., 2017b), and high mountain glaciers (Zhao et al., 2017).

A final broad theme of the second special issue is a wealth of new experimental protocols proposed to GeoMIP. Foremost is GeoMIP6 (Kravitz et al., 2015), a new set of four Tier 1 experiments to be included in CMIP6. One of these experiments is aimed at cirrus thinning (Mitchell and Finnegan, 2009), a relatively new idea that involves seeding cirrus, causing the ice crystals to sediment, allowing more outgoing longwave radiation to escape to space. Gasparini et al. (2017) have raised the important question as to whether the simple representation of increased fall speed can adequately represent the intended effects of cirrus fall speed. There are remaining issues surrounding whether Earth System Models can adequately represent the resulting change in ice crystal size distribution and also whether the models even capture the correct upper tropospheric ice properties that would allow this simulation to provide useful information about cirrus thinning. Several additional experiments have been submitted to the GeoMIP Testbed (Kravitz et al., 2015, also see the GeoMIP website, below), which is a platform whereby experiments can be simulated by single models prior to being formally adopted as core GeoMIP experiments. Two that have been submitted are G4Foam (Gabriel et al., 2017), which involves targeted ocean brightening that causes cooling which is amplified by internal climate feedbacks, and Land-GeoMIP, looking at different strategies for increasing land albedo (Irvine et al., 2011; Seneviratne et al., 2018). Finally, MacMartin and Kravitz (2016) used existing GeoMIP output to train a climate model emulator that can allow for exploration of additional scenarios that are not included in GeoMIP, albeit with reduced complexity that potentially limits the output that can be produced.

4 Conclusions and next steps for GeoMIP

While the advances made by GeoMIP have been substantial, there are many areas that still need progress, and many other important areas have not yet been explored. Here we describe several key areas in which GeoMIP could play a role in advancing the field of geoengineering research, acknowledging that there may be many others. All of the latest information about GeoMIP, as well as the full set of experiment protocols, can be found on the GeoMIP website (http://climate.envsci.rutgers.edu/GeoMIP, last access: 10 May 2018).

The design perspective described earlier still has substantial room for expansion. There have been demonstrations of meeting multiple simultaneous climate objectives via stratospheric sulfate aerosol geoengineering (Mills et al., 2017; Tilmes et al., 2017; Richter et al., 2017; MacMartin et al., 2017; Kravitz et al., 2017), but these studies need to be replicated with multiple models, and beyond the single scenario investigated by those studies, there needs to be a more thorough understanding of the space of achievable geoengineering objectives. Recently, a large ensemble of geoengineering simulations has been produced (Tilmes et al., 2018), enabling the community to analyze fields with low signal-to-noise ratios. Techniques developed for meeting geoengineering objectives in the presence of uncertainty (MacMartin et al., 2014b) could be adapted to GeoMIP in the future, where multiple models are used to meet the same specified objectives, and the side effects compared across models.

Of these potential side effects, of particular importance is impacts assessment, which is still fruitful and is well poised for exploration in the context of geoengineering. The field of impacts assessment covers a variety of disciplines, but with the exception of a few areas (discussed previously) is largely unexplored (Tilmes et al., 2017). In particular, research into the effects of geoengineering on vegetation, net primary productivity and more generally ecosystems has only recently seen progress (Glienke et al., 2015; Trisos et al., 2018), despite the topic having been raised several years ago (Russell et al., 2012). Relatedly, other areas of importance include extreme events, local effects, and the responses of other climate variables with low signal-to-noise ratios. An important emerging theme is a broadening of the conversation surrounding geoengineering to include subjects and impacts that have not formerly been incorporated or investigated.

A key focus area of GeoMIP is enabling researchers in the developing world to access GeoMIP output and conduct their analyses. It is precisely these countries that are projected to be hardest hit by the impacts of greenhouse gas forcing and are the least able to afford adaptation measures, potentially prompting interest in the possibilities geoengineering may offer (Rahman et al., 2018). Members of the project are exploring methods of disseminating GeoMIP output, which is already in the tens to hundreds of terabytes, to these researchers. A simple yet effective method has been distributing hard disks of model output to participants at regular summer schools held at Beijing Normal University.

Furthermore, GeoMIP has informally partnered with the Solar Radiation Management Governance Initiative (SRMGI) in their research fund called Developing Country Impacts Modeling Analysis for Solar Geoengineering (DECIMALS), administered by The World Academy of Sciences and financed by the Open Philanthropy Project. This fund will serve as a mechanism for researchers from developing countries to conduct their own analyses on climate model output of geoengineering scenarios, including GeoMIP, and build capacity for research on geoengineering throughout the world.

Another important area relates to carbon cycle feedbacks. Jones et al. (2013) first noticed that among GeoMIP models simulating experiment G2, the results for net primary productivity separated according to which land model was used. Glienke et al. (2015) further investigated terrestrial carbon cycle feedbacks in GeoMIP experiment G1, followed by a review of the effects of geoengineering on the carbon cycle by Cao (2018). Most of the findings regarding carbon cycle effects are single-model studies, such as Xia et al. (2016), who found an increased carbon sink in the G4SSA experiment (Tilmes et al., 2015), and additional multi-model studies are necessary to increase robustness.

Comparisons of different methods of geoengineering have proven fruitful and are underexplored in geoengineering research. Niemeier et al. (2013) and Keller et al. (2014) compared the effects and side effects when specific climate objectives were met with different methods of geoengineering (e.g., stratospheric sulfate aerosols and marine cloud brightening). The next phase of GeoMIP has formally adopted two experiments aimed at comparing solar irradiance reduction and stratospheric sulfate aerosol geoengineering in a multi-model context (Kravitz et al., 2015). This combination of two experiments will further explore how well stratospheric sulfate aerosol geoengineering can be approximated by more simple representations in climate models (e.g., Kalidindi et al., 2014), particularly given inter-model differences in aerosol location and transport.

One of the most fruitful aspects of geoengineering research is its ability to reveal some of the fundamental underpinnings and processes of climate model response. To that end, there is a need to better integrate the processes involved in representing solar geoengineering into Earth system models. This includes tropospheric and stratospheric chemistry, the effects on diffuse light, land surface and ecosystem response, and changes in regional effects. Of particular note is aerosol-cloud interactions, which are some of the most important uncertainties in climate science today and are not well handled by Earth System Models, as the relevant processes take place on scales smaller than model grid boxes. Because of the lack of testing of geoengineering, there are limited data for validating the results of including these additional processes in models, raising important questions about uncertainty and the limitations of climate models in this research area.

The next phase of GeoMIP (Kravitz et al., 2015) will include longer simulations that allow for investigation of low signal-to-noise ratio features of climate system response. As mentioned previously, also included will be two experiments with the same objectives but different methods of geoengineering, allowing for comparison of differences in the responses. The GeoMIP Testbed remains an important feature of the project, providing a platform for new experiments to be proposed to GeoMIP. If useful, these experiments may end up being simulated by a large number of models, effectively establishing them as core GeoMIP scenarios. In addition to these planned experiments, there is also the potential to include an overshoot scenario (e.g., Tilmes et al., 2016), in which geoengineering is used to temporarily offset some of the effects of climate change while mitigation and carbon dioxide removal are ramped up. Conversations surrounding a potential overshoot scenario are likely to benefit from coordination with the Carbon Dioxide Removal Model Intercomparison Project (CDR-MIP; Keller et al., 2018), which was recently adopted as a formal part of CMIP6. Other potential Testbed experiments may include combinations of multiple types of geoengineering, such as have been studied by Cao et al. (2017) and Boucher et al. (2017).

MacMartin et al. (2016) provided a summary of broad gaps in solar geoengineering research, particularly related to stratospheric sulfate aerosol geoengineering, while Quaas et al. (2016) highlighted the prospects for regional solar geoengineering. GeoMIP likely has a role in addressing some of those gaps, specifically related to questions that require an understanding of robust model response to specified scenarios. While GeoMIP cannot answer every important question in geoengineering research, it is readily apparent that there is a continuing role for GeoMIP and multi-model comparisons in general, possibly including a third special issue of a journal.

Data availability. All data for GeoMIP is publicly available through the Earth System Grid, as described on the GeoMIP website: http://climate.envsci.rutgers.edu/GeoMIP/ (Kravitz and Robock, 2018).

Competing interests. The authors declare that they have no conflict of interest.

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