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Opinion

Opinion: The scientific and community-building roles of the Geoengineering Model Intercomparison Project (GeoMIP) – past, present, and future

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Abstract. The Geoengineering Model Intercomparison Project (GeoMIP) is a coordinating framework, started in 2010, that includes a series of standardized climate model experiments aimed at understanding the physical processes and projected impacts of solar geoengineering. Numerous experiments have been conducted, and numerous more have been proposed as "test-bed" experiments, spanning a variety of geoengineering techniques aimed at modifying the planetary radiation budget: stratospheric aerosol injection, marine cloud brightening, surface albedo modification, cirrus cloud thinning, and sunshade mirrors. To date, more than 100 studies have been published that used results from GeoMIP simulations. Here we provide a critical assessment of GeoMIP and its experiments.

We discuss its successes and missed opportunities, for instance in terms of which experiments elicited more interest from the scientific community and which did not, and the potential reasons why that happened. We also discuss the knowledge that GeoMIP has contributed to the field of geoengineering research and climate science as a whole: what have we learned in terms of intermodel differences, robustness of the projected outcomes

for specific geoengineering methods, and future areas of model development that would be necessary in the future? We also offer multiple examples of cases where GeoMIP experiments were fundamental for international assessments of climate change.

Finally, we provide a series of recommendations, regarding both future experiments and more general activities, with the goal of continuously deepening our understanding of the effects of potential geoengineering approaches and reducing uncertainties in climate outcomes, important for assessing wider impacts on societies and ecosystems. In doing so, we refine the purpose of GeoMIP and outline a series of criteria whereby GeoMIP can best serve its participants, stakeholders, and the broader science community.

1 Introduction

The comparison of results from nominally identical experiments in multiple, distinct climate models is useful for understanding models' biases, for assessing robustness in the climate response to external forcings, and for partitioning sources of uncertainties in future climate projections (Lehner et al., 2020). There is a long history of such model intercomparison projects (MIPs) going back several decades (Cess et al., 1989). This process has become more formalized and rigorous and now falls under the auspices of the Coupled Model Intercomparison Project (CMIP; Meehl et al., 2005), which is one of the flagship efforts of the World Climate Research Programme. CMIP is key to our understanding of future climate change projections, and its results are prominently featured in the Intergovernmental Panel on Climate Change's assessment reports, among other numerous studies. With Phase 6 (CMIP6; Eyring et al., 2016), the decision was made to move from a centralized effort to a more distributed MIP approach, allowing different modeling groups to focus on different aspects of the Earth system. One of the most widely used MIPs is ScenarioMIP, which aims to produce "multi-model climate projections based on alternative scenarios of future emissions" (O'Neill et al., 2016), forming the basis for future projections of climate change. There are over 20 other MIPs spanning a wide variety of research topics, including the Chemistry-Climate Model Initiative (Morgenstern et al., 2017) aimed at evaluating model projections of the stratospheric ozone layer, tropospheric composition, and interactions with climate, the Volcanic Forcing Model Intercomparison Project (VolMIP; Zanchettin et al., 2016) aimed at assessing the robustness of the modeled response of the atmospheric–oceanic coupled system to a volcanic forcing, and the Land Use Model Intercomparison Project (LUMIP; Lawrence et al., 2016) aimed at understanding the climatic contribution of changes in land use activities.

Global mean surface air temperature in the decade 2011–2020 is around 1.2 °C higher than the preindustrial period (Chen et al., 2021), and most future climate projections suggest continued warming in the future, with only a very few ambitious scenarios managing to stabilize temperatures in the second half of the century. The rate of warming in recent decades is unprecedented in at least the last 2000 years. Mitigation efforts to reduce emissions of greenhouse gases, which are the root cause of global warming and the associated climate change, have been insufficient, with concentrations of atmospheric carbon dioxide over the last 30 years being accurately represented by the IS92a "business as usual" scenario that was developed over 30 years ago (Pedersen et al., 2020). Even though countries across the world agreed in the Paris Agreement (UNFCCC; The Paris Agreement, https://unfccc.int/documents/184656, last access: 3 May 2023) to keep "the increase in global average temperature to well below 2 °C above preindustrial levels and pursuing efforts to limit temperature increase to 1.5 °C", their submitted Intended Nationally Determined Contributions (INDCs) of greenhouse gas emissions would be consistent with a projected median warming of between 2.6 and 3.1 °C by 2100 (Rogelj et al., 2016).

Because of the uncertainty of remaining below 1.5 or 2 °C of warming through emission cuts alone, around 10 years ago, an international group of researchers (Kravitz et al., 2011) proposed a new framework to coordinate climate modeling experiments to study proposals for solar geoengineering (also known as solar radiation modification – SRM – or solar climate intervention), aimed at understanding the impacts of proposed methods to offset the warming produced by an increase in greenhouse gases by directly intervening in the Earth's radiative balance. Fundamentally, these studies aim to produce a negative radiative forcing by increasing the planetary albedo to partly counteract the positive forcing of CO_2 and other greenhouse gases. For comprehensive reviews of the scientific aspects raised by solar geoengineering techniques, see for instance Lawrence et al. (2018), Kravitz and MacMartin (2020), and international reports such as those from the National Academy of Science, Engineering and Medicine (National Academies of Sciences Engineering and Medicine, 2021) and EuTRACE (Schäfer et al., 2015). These summaries build upon the long history of discussion of solar geoengineering (see for instance Budyko, 1978; Keith, 2000; Govindasamy et al., 2003), but the 2006 editorial essay by Paul Crutzen, "Albedo Enhancement by Stratospheric Sulfur Injections: A Contribution to Resolve a Policy Dilemma?" (Crutzen, 2006), was a landmark in drawing the attention of the scientific community on the topic, as can be seen by the immediate responses it elicited (Bengtsson, 2006; Cicerone,

2006; Kiehl, 2006; MacCracken, 2006; Lawrence, 2006) and in the follow-up reflections a decade afterwards (Lawrence and Crutzen, 2017; Boettcher and Schäfer, 2017).

This international framework, the Geoengineering Model Intercomparison Project (GeoMIP), was initially coordinated in parallel with the European Union project "Implications and Risks of engineering solar radiation to limit climate change" (IMPLICC; Schmidt et al., 2012b), which included the intercomparison of simulations of four climate models for some of the same simulation setups as used in the first round of GeoMIP simulations (Schmidt et al., 2012a). The motivation for the initiation of this project was the lack of consistency between initial geoengineering studies, which resulted in very different climate outcomes, complicating the process of disentangling some of the observed differences (Rasch et al., 2008; Jones et al., 2010). A set of standardized experiments comprising a reduction in the solar constant and the injection of SO_2 in the equatorial stratosphere was proposed and later expanded to encompass other geoengineering techniques (such as marine cloud brightening and cirrus cloud thinning) and following climate change scenarios described by CMIP6 (Kravitz et al., 2013, 2015). The GeoMIP community has produced over 100 papers (121 in November 2022 following the self-reported list tracked on the GeoMIP website, http://climate.envsci.rutgers.edu/GeoMIP/publications.html, last access: 3 November 2022) discussing or analyzing the impacts of these standardized experiments on the atmosphere, ocean, ecosystems, and human societies. As an officially endorsed part of CMIP, GeoMIP has enjoyed a collaborative relationship with other MIPs, exchanging findings and lessons learned and co-developing experiment protocols, moving our knowledge of climate geoengineering forward compared to 10 years ago.

The purpose of this paper is to take stock of GeoMIP as a project based on our collective experience in this field. What have been its successes in advancing knowledge around geoengineering or climate science as a whole? What are some shortcomings with its experiments, analysis, or coordination? What collaborations has it facilitated, and what are some missed opportunities? Perhaps most importantly, what are its next steps and the outstanding questions it needs to address? There are, of course, few objective answers to these questions; we have identified when we are making subjective judgments and upon what values those opinions are based. In the next three sections we provide overviews of past (CMIP5) and present GeoMIP (CMIP6) experiments, test beds for experiment development, and planned future experiments. Following that, in Sect. 5, we reflect on the role of GeoMIP and provide our conclusions and outlook in Sect. 6.

2 An assessment of past and present GeoMIP experiments

The CMIP protocol specifies that MIP experiments be divided into tiers. Tier-1 experiments are the most scientifically relevant to the broader community and hence are the highest-priority ones and are sometimes considered the minimum requirements for participation in that MIP. Subsequent tiers, while also scientifically relevant, are considered lower priority. The philosophy of GeoMIP has always been to keep the number of Tier-1 experiments small so as to reduce barriers to participation and increase the number of models conducting these core experiments. In Table 1, we provide a summary of all the formally adopted GeoMIP experiments to date, including the number of models that have participated in each experiment. Tier-1 experiments are summarized in Fig. 1.

2.1 Solar dimming: G1, G1ext, G2

Of all possible experiments, the simplest and easiest to replicate in different climate models aims to offset the radiative forcing from an increase in CO_2 with a reduction in the model's solar constant. This method directly represents the idea of space sunshades (Angel, 2006): while potentially effective, technical feasibility and costs associated with deployment presently make such an approach prohibitive when compared to other proposed climate geoengineering methods (e.g., The Royal Society, 2009). More relevant for immediately practical geoengineering methods, solar dimming approximates the broad radiative effects of stratospheric aerosol injection.

Experiments G1 (CMIP5) and G1ext (CMIP6) involved offsetting the forcing from an instantaneous quadrupling of the CO_2 concentration (abrupt4 $\times CO_2$, a standard CMIP experiment) with solar constant reduction, so that the net top-of-atmosphere (TOA) radiative flux in each model was within $\pm 0.1\,W\,m^{-2}$ of the baseline value in the first decade of simulation (Kravitz et al., 2011). The high level of replicability means that results between CMIP5 and CMIP6 could be easily compared (Kravitz et al., 2021), even in some cases allowing for a comparison between different model versions; in Fig. 2 we show such a comparison across CMIP5 and CMIP6 models reproduced from Kravitz et al. (2021). For instance, such a comparison showed that across the 20 models that performed this experiment across two generations, the value of the solar reduction needed ranged from 3.8 % to 5.0 % (Kravitz et al., 2021). G1 has been extensively studied in terms of the hydrological response (Tilmes et al., 2013; Kravitz et al., 2013, 2014) and from an energetic and thermodynamics perspective (Russotto and Ackerman, 2018a, b; Virgin and Fletcher, 2022), highlighting both some commonalities in the response of the hydrological cycle to a reduction in incoming shortwave radiation and some large discrepancies in the cloud response. Similar experiments have also

Table 1. Summary of all experiments in GeoMIP, with the specific reference of the paper in which they were described for further detail (last column). CDNC: cloud droplet number concentration, GHG: greenhouse gas, ODS: ozone-depleting substance, PI: preindustrial, SST: sea surface temperature, TOA: top of atmosphere.

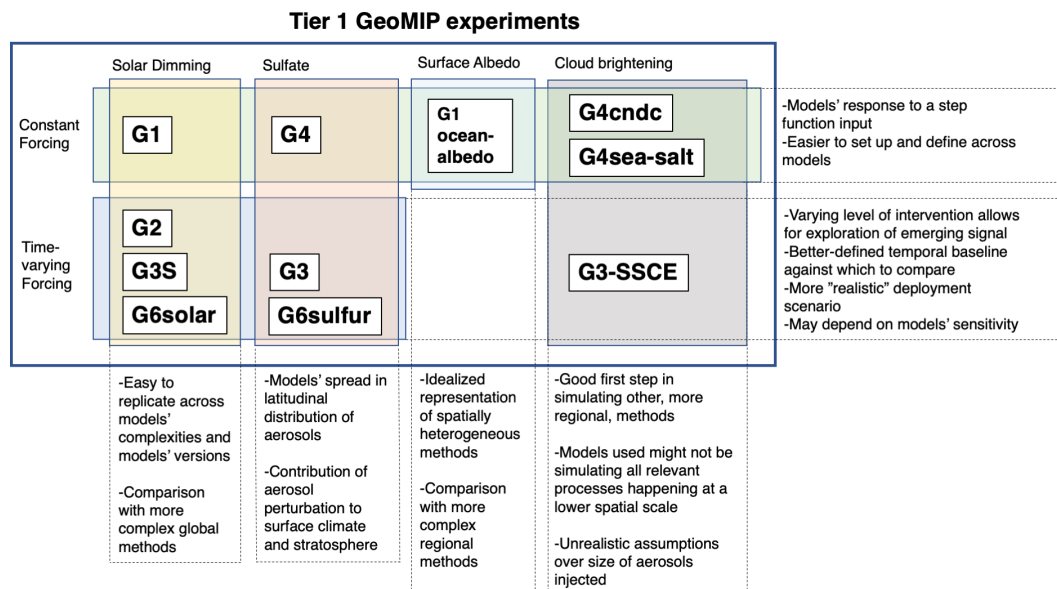| Experiment name	Background scenario	Description	Participating models	Tier	First described in
G1	$4 \times CO_2$	Solar constant reduction	13	1	Kravitz et al. (2011)
G1ext	$4 \times CO_2$	Solar constant reduction	7		Kravitz et al. (2015)
G1ocean-albedo	$4 \times CO_2$	Ocean albedo increase	12	1	Kravitz et al. (2013)
G2	1pctCO2	Balance CO_2 increase via solar irradiance reduction	11	1	Kravitz et al. (2011)
G3	RCP4.5	SO_2 injections to counteract increasing GHG forcing	7	1	Kravitz et al. (2011)
G3S	RCP4.5	Solar dimming to counteract increasing GHG forcing	1	1	Niemeier et al. (2013)
G3-SSCE	RCP4.5	Sea salt injections to counteract increasing GHG forcing	3	1	Alterskjaer et al. (2013)
G4	RCP4.5	Constant SO_2 injections on RCP4.5 background	10	1	Kravitz et al. (2011)
G4cdnc	RCP4.5	50 % increase in the CDNC of marine low clouds	9	1	Kravitz et al. (2013)
G4sea-salt	RCP4.5	Sea spray intervention to offset a fixed amount of TOA forcing	3	1	Kravitz et al. (2013)
G4foam	RCP6.0	Localized increase in ocean albedo	1	Test bed	Gabriel et al. (2017)
G4SSA	RCP4.5	Specified aerosol field for climate-chemistry models	1	Test bed	Tilmes et al. (2015)
senD2-sai	refD2	Specified aerosol field for CCMI-2022	4	Test bed	Plummer et al. (2021)
G6solar	SSP5-8.5	Solar reduction to reduce increasing temperatures to SSP2-4.5	6	1	Kravitz et al. (2015)
G6sulfur	SSP5-8.5	SO_2 injections to reduce increasing temperatures to SSP2-4.5	6	1	Kravitz et al. (2015)
G7cirrus	SSP5-8.5	Reduce cirrus cloud optical depth by a fixed amount	2	2	Kravitz et al. (2015)
Overshoot	SSP5-8.5 SSP5-3.4OS	SO_2 injections to keep temperatures at 1.5 and 2 °C above PI	1	Test bed	Tilmes et al. (2020)
H_2SO_4	SSP5-8.5	Fixed SO_2 and H_2SO_4 injections, 2040 conditions for ODS and GHG, fixed SSTs at 1990 levels	3	Test bed	Weisenstein et al. (2022)

Figure 1. Schematic summary of all Tier-1 GeoMIP experiments across different iterations (Kravitz et al., 2011, 2013, 2015). In rows, experiments are categorized based on how the geoengineering forcing is applied: constant or time-varying. In columns, experiments are categorized based on the method of applied forcing. Reference scenarios for each experiment are listed in Table 1.
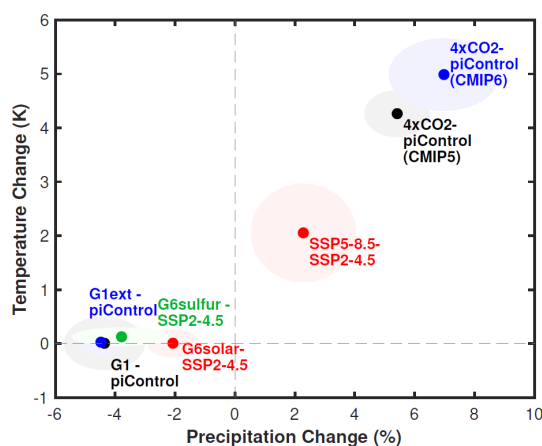
Figure 2. A comparison of global temperature (K) and precipitation (%) changes for some Tier-1 GeoMIP experiments across CMIP5 and CMIP6. Points represent the multimodel averages for each experiment, and shaded areas represent 2 multimodel standard errors. Values for G1 and $4 \times CO_2$ (CMIP5, 13 models averaged) and G1ext and $4 \times CO_2$ (7 models) are from Kravitz et al. (2021), comparing against piControl values in the last 40 years of the experiment (years 11–50). Values for G6solar, G6sulfur, and SSP5-8.5 (six models) are from Visioni et al. (2021b), comparing against SSP2-4.5 values in the last 20 years of the experiment (2080–2099).

been performed outside of the GeoMIP framework: for instance, Irvine et al. (2019) used a higher-resolution model to understand changes in extremes and precipitation in a case where a doubling of preindustrial CO_2 is partially offset by a reduction in the solar constant. Results from G1 have been used for more specific impact analyses (e.g., Bal et al., 2019; Harding et al., 2020), which poses two important issues. First, G1 is an extreme, idealized case, and thus a straightforward analysis of climate model output from G1 cannot be used as a prediction of what climate engineering would do under any practical deployment strategy. This is particularly true for variables such as regional precipitation for which solar dimming is a poor proxy for aerosol injections or other methods (see Niemeier et al., 2013; Visioni et al., 2021a) or for comparisons of tropical and high-latitude effects, considering that uniformly reducing the solar constant tends to produce a stronger cooling in the tropics (e.g., Govindasamy et al., 2003; Kravitz et al., 2013). Second, there is no single answer for what climate engineering "would do", as the effects of climate engineering can, to some degree, be designed to mitigate any residual climate change impacts (e.g., Kravitz et al., 2016); this is discussed further in Sect. 3.5 below.

G2 similarly prescribes a solar reduction to offset an increase in the CO_2 concentration, but in this case CO_2 is increased by 1 % every year, and the solar constant is successively reduced each year, with similar intermodel differences to G1 (Jones et al., 2013). G2 has been more seldom used and usually as a way to test linearity assumptions in G1 (Mac-Martin and Kravitz, 2016). It was, however, featured in the

first multimodel intercomparison of the termination effect (Jones et al., 2013); the gradual change in forcing allowed for a computation of rates of climate change under geoengineering with rates of change under termination.

G1 has substantial advantages that merit keeping it in future iterations of GeoMIP. First, while solar dimming does not capture some important features of climate response to stratospheric aerosol injection (Visioni et al., 2021a), it does capture some of the broad radiative effects, giving an indication of some of the radiative impacts. Also, G1 is easy to perform in all climate models, providing a low barrier to participation in GeoMIP, which is important for community-building and developing high confidence in results. Nevertheless, its limits as compared to more detailed representations of the effects of more practical geoengineering methods should always be well communicated (Reynolds, 2022).

2.2 Surface albedo modification: G1ocean-albedo

Marine cloud brightening (MCB; Latham, 1990) is also a commonly researched method of conducting geoengineering, but simulating MCB in a multimodel context has proven challenging for experimental design. Pre-GeoMIP simulations either injected sea salt aerosols directly into the marine boundary layer (e.g., Jones and Haywood, 2012) or increased the cloud droplet number concentration (CDNC) in marine low clouds (e.g., Jones et al., 2009; Rasch et al., 2009). However, because different models have different cloud cover amounts and locations and the key processes behind MCB need to be parameterized in global models, any multimodel comparison of these methods will necessarily impose different amounts and locations of forcing, and thus comparison and interpretation of the results may be challenging. While this can still be useful for a multimodel comparison (see Sect. 2.5 below), a more idealized experiment with a more controlled forcing could also be useful.

G1ocean-albedo involves offsetting the forcing from an abrupt quadrupling of the CO_2 concentration with an increase in surface albedo over all ocean regions (Kravitz et al., 2013). While only loosely approximating the effects of MCB, it does capture differential forcing between land and ocean as well as a different perturbation to column absorption and vertical motion than would result from solar dimming. One study thus far has looked at a multimodel comparison of G1ocean-albedo results, finding that even though the models were in net top-of-atmosphere energy balance, global average temperature increased due to differential warming of the atmosphere and ocean, resulting in increased land–ocean energy transport (Kravitz et al., 2018). While perhaps this experiment has limited relevance for understanding potential geoengineering deployments, it does indicate the usefulness of geoengineering simulations for understanding fundamental climate responses to forcing.

2.3 Stratospheric aerosol injections: G3 and G4

One of the first proposed methods of conducting geoengineering is to mimic the cooling effects of a volcanic eruption by injecting sulfate aerosol precursors into the (tropical) stratosphere (Budyko, 1978). The first general circulation model simulations of this method of geoengineering (Robock et al., 2008) described their simulations in terms of $\frac{1}{4}$ or $\frac{1}{2}$ of a Pinatubo eruption every year (5 Tg SO$_2$ and 10 Tg SO$_2$ per year, respectively, based on Pinatubo estimates by Timmreck et al., 2018). The experiments G3 and G4 (Kravitz et al., 2011) aimed to reproduce this in multiple models: in G3, the injection of sulfate was aimed at maintaining net top-of-atmosphere radiative forcing at 2020 levels under an RCP4.5 scenario, and in G4, a fixed injection rate of 5 Tg of SO$_2$ per year from 2020 to 2070. In both cases, the injection was at the Equator between 16 and 25 km in altitude, similar to how those same models would reproduce the Pinatubo eruption. As different models have varying assumptions in terms of the initial Pinatubo plume, this protocol led to some discrepancies between models: a more in-depth discussion of this intermodel discrepancy is given by Timmreck et al. (2018), which motivated the development of a modeling volcanic experiment named the Historical Eruption SO$_2$ Emission Assessment (HErSEA) and whose results were recently described by Quaglia et al. (2023). Indeed, Pitari et al. (2014) reported large discrepancies in the amount of global aerosol optical depth necessary in G3 (0.025 in GISS by 2070 and 0.1 in ULAQ-CCM) and a general disagreement over the latitudinal distribution of the aerosols in the G4 experiment. The paucity of models that could reproduce the full cycle from SO$_2$ oxidation to heterogeneous chemistry processes crucial for ozone chemistry was also highlighted. The termination of the implementation in 2070 has also produced interesting research on the impacts of a potential "termination effect", were geoengineering to be stopped abruptly (Robock et al., 2008; Jones et al., 2013; Parker and Irvine, 2018; Trisos et al., 2018).

In retrospect, these two experiments involved a learning process for GeoMIP. Experiment G3 was difficult to perform, as it involved regular radiative forcing calculations (often via a double-radiation call), and many groups reported having to redo periods of the experiment because they injected too much or too little SO$_2$. Also, because the protocol specified that net top-of-atmosphere radiative forcing should remain at 2020 levels, temperature steadily increased in the simulations because the climate was already in imbalance in 2020. This exacerbated climate adjustments, increasing the spread and uncertainty in the multimodel ensemble. As a result, few models participated in G3, and most of the analysis of this experiment was used to supplement analysis of G4 (Berdahl et al., 2014; Yu et al., 2015), although the runs were used, for instance, to study the impacts on agriculture (Singh et al., 2020), Atlantic hurricanes (Moore et al., 2015), Arctic per-

mafrost (Chen et al., 2020), and flood return frequency (Wei et al., 2018).

In turn, one of the intended purposes of G4 was to "do the experiment the same way that [you] would simulate Pinatubo", and the groups would then look at the model spread in the climate outcomes. However, because the models had such different microphysics representations, aerosol distributions, and circulation patterns, it was difficult to attribute the spread to any particular processes or model features. However, these experiments did result in quite useful analysis and enabled some conclusions about tropical stratospheric aerosol geoengineering, amongst them the potential stratospheric ozone depletion at high latitudes (Berdahl et al., 2014) and its effect, its capability to reduce (but not halt altogether) ice melting (Berdahl et al., 2014; Zhao et al., 2017), and the dependency of the simulated precipitation reduction on the aerosol interaction with radiation (Ferraro and Griffiths, 2016). They were also used to study the impacts on ecosystems (Trisos et al., 2018). Nevertheless, they also provided important lessons about how to design a controlled experiment for GeoMIP and reinforced the community's notion that aerosol microphysics and circulation patterns are important contributors to model spread.

2.4 Compare and contrast: G6solar and G6sulfur

At the first GeoMIP meeting, there was a proposal (akin to what became the test bed) for G3solar, in which the protocol for G3 was followed up using solar reduction instead of stratospheric sulfate aerosol injection. Although this proposed experiment did not receive much participation, the idea of comparing solar dimming and sulfate aerosols in identical protocols emerged as a Tier-1 experiment in CMIP6 in the form of experiments G6solar and G6sulfur (Kravitz et al., 2015). Similar to G3, the amount of sulfate to be injected varies every year (or later modified to be every decade due to the difficulty in calculating forcing in transient runs) to obtain a certain target: in this case, the aim was to reduce global mean surface air temperatures from those under an SSP5-8.5 scenario to those under an SSP2-4.5 scenario, "mitigating" the warming produced by high greenhouse gas (GHG) concentrations. To do so, starting in 2020, models would reduce the solar constant (G6solar) or inject SO$_2$ in a band between 10° N and 10° S and between 18 and 20 km in altitude (G6sulfur). The presence of two different experiments with similar targets allows for a broader assessment of the differences between solar dimming as a proxy and an actual sulfate injection (Niemeier et al., 2013; Visioni et al., 2021a, and Fig. 2) and has allowed us to assess the contribution of stratospheric uncertainties to overall uncertainties in the climate response to geoengineering (Jones et al., 2021; Visioni et al., 2021b; Bednarz et al., 2022). Of the six models that originally participated in G6, only two had comprehensive enough stratospheric chemistry to make them viable for assessing ozone changes. At the same time, three

used a prescribed aerosol distribution and three used actual SO_2 injections; the overlap between those with comprehensive chemistry and those with interactive aerosols was two (CESM2 and UKESM) (Tilmes et al., 2022). Experiment G4 had a similar mix of explicit and prescribed representations of these processes.

In G6, modeling centers have demonstrated that it is feasible to modify the amount of intervention in the models even once per decade to maintain a predetermined temperature target; the available comparison between temperatures under SSP2-4.5 (same global temperatures, different amount of CO_2) allows for a contrast throughout the entire simulation period of multiple scenarios and can also be used to understand when the emerging signal of a geoengineering deployment would be distinguishable from natural variability.

The Max Planck Institute Earth System Model (MPI-ESM) performed two sets of G6 simulations with the same prescribed aerosol forcing but two different horizontal resolutions (roughly 200 and 300 km; Muller et al., 2018). A focused analysis of the differences in the climate response between these two versions could shed light on the impact of higher-resolution modeling on projected geoengineering impacts.

There is an interesting observation that can be made from the G6 experiments and that multiple users of the data have noticed. Six years passed from when the experiment was officially proposed in 2015 (Kravitz et al., 2015), when the modeling centers produced the simulations (early 2020 at the earliest), and when the first analyses came out in 2021 (Jones et al., 2021, with a subset of the models and Visioni et al., 2021b, with all six). With geoengineering studies being a novel, fast-paced field, in those 6 years multiple discussions and studies led many to question the relevance of both a high-emission scenario like SSP5-8.5 and the strategy aiming to "halve" warming to that of SSP2-4.5, as opposed to other, more moderate scenarios that try to discuss geoengineering in the light of the Paris Agreement targets (see Sect. 3.4 for instance). Furthermore, the injection strategy of injecting into the tropical pipe has also been found to be suboptimal (Kravitz et al., 2019; Visioni et al., 2021a). In this sense, some may feel that analyses of G6 results may already look outdated due to the relevance of the specific scenario selected. While this is not necessarily true, as there is a great deal of merit in analyzing results from the latest iteration of CMIP6 models, it is a valid concern. If there is a lesson to learn, it might be that there is a need for "future-proofing" the next generation of proposed GeoMIP experiments, so that they remain relevant for as long as possible. While a focus on "realistic" scenarios will produce results that are seen as more policy-relevant, there is a danger that they will not stand the test of time. Changes to baseline scenarios and assumptions about what is realistic may evolve, but idealized, high signal-to-noise experiments like G1 are timeless.

2.5 Sea spray geoengineering: G3-SSCE, G4sea-salt, and G4cdnc

As discussed in Sect. 2.2 above, GeoMIP developed several Tier-1 experiments to explore multimodel uncertainty in the climate response to marine cloud brightening. They were based on the G3 and G4 experiments described by Kravitz et al. (2013) but substituting sulfur injections with the addition of sea salt.

The first one, G3-SSCE, was described by Alterskjaer et al. (2013); three models involved with IMPLICC participated in that experiment, simulating the effect of an increase in sea salt aerosols in the lower atmosphere. Later, the experiment G4cdnc prescribed increasing the cloud droplet number concentration in all marine low clouds (lower in altitude than 680 hPa), which replicates the net microphysical effect of MCB but without relying on different parameterizations of aerosol–cloud interactions. G4sea-salt on the other hand involved direct aerosol injection into the marine boundary layer (between 30° S and 30° N), which is the most realistic representation of MCB in GeoMIP but also runs the risk of resulting in a large model spread due to dependence on aerosol–cloud interaction parameterizations as well as intermodel differences between cloud location and forcing strength. Both experiments are less controlled than G1ocean-albedo, in that in G4cdnc and G4sea-salt the MCB forcing will only be applied where there are clouds, which differs between models.

Nevertheless, G4cdnc and G4sea-salt revealed important insights about MCB, including the importance of cloud differences between models (Stjern et al., 2018) and that the aerosol direct forcing of sea salt aerosols can be quite important in MCB applications (Ahlm et al., 2017). Arguably, more of the model spread in these MCB experiments was attributable to specific processes than was the case for G3 and G4, which could reflect community investment in uncertainty: aerosol–cloud interactions have received vastly more attention than stratospheric processes. Results from G4cdnc and G4sea-salt have only been investigated in a few studies each (Xie et al., 2022), so it is presently difficult to draw conclusions about how one might design a more controlled MCB experiment for Earth system models.

2.6 Cirrus cloud thinning: G7cirrus

Due to increasing interest in cirrus cloud thinning (CCT; Mitchell and Finnegan, 2009; Storelvmo et al., 2013), GeoMIP proposed a Tier-1 experiment, G7cirrus, in which the fall speed of upper-tropospheric ice crystals was increased (Muri et al., 2014) to achieve a negative radiative forcing. However, due to large uncertainties in model representations of cirrus and upper-tropospheric ice water paths and a disconnect between the ice crystal distribution from increasing fall speed and the distribution that would result from CCT (Gasparini et al., 2020), the GeoMIP community chose to re-

classify G7cirrus as a lower-tier experiment. This happened prior to most modeling groups conducting their simulations for Phase 6, which in part explains why only two models have performed G7cirrus simulations to date.

Nevertheless, the tier of the experiment has historically not been a huge barrier to participation, so we suspect there are other issues at play. Based on discussions with the community, there are several main reasons as to why G7cirrus has not received much attention. From a scientific standpoint, during the first Gordon Conference on Climate Engineering held in 2017, some members of the GeoMIP community pointed out that cirrus clouds are rather poorly represented in global circulation models (GCMs), and large challenges remain even in the observational record about the main sources of cirrus cloud formations and their properties (Gasparini et al., 2018; Sourdeval et al., 2018). Fundamentally, this would make the results of such an experiment rather untrustworthy.

From an operational point of view, G7cirrus is also not necessarily easy to perform, as it often requires code editing and testing. We hypothesize about potential ways to mitigate this in Sect. 5 below. Despite not necessarily being a realistic representation of CCT (as well as doubts about the effectiveness of CCT), a multimodel analysis of G7cirrus results would still represent a learning opportunity for the community. Indeed, GeoMIP has thrived on learning from experiments that lack realism, most prominently G1.

2.7 GeoMIP6 time-slice experiments

In addition to the Tier-1 experiments in GeoMIP6, there were several time-slice experiments proposed as Tier-2 simulations. These experiments involve 10-year simulations with fixed sea surface temperatures in which an external forcing is applied around a particular time, branched from the Tier-1 experiments. These were introduced to aid in separating the rapid adjustments from the feedback response, which was a major focus of GeoMIP analyses in previous iterations. As of the writing of this paper, few (if any) modeling groups have completed these experiments, and there does not appear to be widespread interest in conducting them. We suspect this is for a few reasons. First, the GeoMIP community seems to be uncertain about the value of these time-slice experiments, so they have been deprioritized. Also, many of the analysis directions in GeoMIP have moved away from fast–slow response diagnostics, due perhaps to a stronger focus on a "gradual" deployment, obviating the need to complete the time-slice experiments.

While these experiments would still be useful, they were introduced at a time when the analysis they would engender was not as popular. Perhaps the lesson learned is to design experiments that could serve multiple purposes rather than a narrow purpose (diagnosing fast–slow responses). However, one could argue that lower tiers are well suited for this sort of specificity, and even if only a few models conduct those sim-

ulations, it would still be effort well spent. Nevertheless, the time-slice experiments proposed could easily fit within the spirit of other MIPs that are aimed at diagnosing these processes, indicating that it would be prudent to more actively pursue coordination between GeoMIP and other MIPs.

3 Test-bed experiments and other relevant experiments

Together with the experiments discussed in Sect. 2, numerous other experiments have been proposed and performed as test-bed experiments. Kravitz et al. (2015) initiated the GeoMIP test bed whereby groups could propose simulations and conduct them with a limited set of models, providing a pathway toward formal adoption by GeoMIP if those simulations go well. Here we discuss some of the proposed test-bed experiments and other relevant geoengineering experiments that have been or could be leveraged by the community and replicated.

3.1 Considering other sulfate precursors: SO_2 and H_2SO_4 injections

Most model simulations of stratospheric aerosol injections have simulated the release of SO_2, due to the volcanic analog. While this allows for some calibration based on observations of volcanic eruptions, modeling studies indicate that using SO_2 injection results in large aerosols, which reduces the scattering efficiency, increases fall speed, and increases side-effects (like stratospheric heating). Pierce et al. (2010) and following works (Benduhn et al., 2016; Vattioni et al., 2019) have proposed direct injection of H_2SO_4 particles into the accumulation mode, which would avoid H_2SO_4 vapors formed from SO_2 oxidation from coagulating on preexisting particles and having them grow too much. A test-bed experiment was carried out by Weisenstein et al. (2022), comparing and contrasting the injection of SO_2 and H_2SO_4 with the aim of observing the response of a subset of GeoMIP models with interactive aerosol microphysics. The injection of 5, 10, and 25 Tg of S in either form was simulated in two different injection strategies, one uniformly spreading the aerosols between $30° N$ and $30° S$ at all longitudes and one injecting at $30° N$ and $30° S$ in only one grid box. As in G4, the injection of fixed amounts of materials highlighted models' differences in their formation of aerosols, forcing efficiency, and cascading impacts, such as the response of stratospheric dynamics (Franke et al., 2021), and confirmed the possibility of H_2SO_4 injections as a way to constrain aerosol sizes towards more efficient radii. The use of three models with different aerosol treatments also allowed for more in-depth analyses of models' differences in terms of simulated size distribution, possibly also highlighting the need for more detailed aerosol microphysics in climate models.

3.2 Isolating uncertainties through prescribed aerosol fields: G4SSA and Chemistry-Climate Model Initiative (CCMI) senD2-sai

The complex contribution of aerosol microphysics, chemistry, and dynamical changes in determining the overall stratospheric response has been highlighted in many of the general GeoMIP experiments (Visioni et al., 2021b). One way to constrain part of the response may be by prescribing an identical aerosol field in different models in order to obtain a similar perturbation and understand how and why models differ in their projection of stratospheric heating and chemical changes to an identical perturbation; such an experiment can also overcome the lack of a detailed interactive aerosol treatment in some ESMs. Tilmes et al. (2015) first proposed a similar experiment called G4 Specified Stratospheric Aerosols (G4SSA), offering the community a prescribed aerosol data set determined using the ECHAM5-HAM microphysical model. At least one model with detailed chemistry but lacking a high top and stratospheric aerosol treatment performed the simulations as they were prescribed (Xia et al., 2017), and one model scaled the field to perform G6sulfur simulations (Visioni et al., 2021b). However, in this latter case, while the model prescribed the aerosol distribution, it made its own assumption about the size distribution of the particles that form the optically thick cloud (Tilmes et al., 2022). This highlights the difficulties in properly performing such an experiment, making sure all models capture the same aerosol properties in order to reduce sources of uncertainty in projections.

Some insights into best practices for such an experiment could be gained by experiments with a similar philosophy described by Zanchettin et al. (2022) for VolMIP. After highlighting the intermodel disagreement in a Tambora-like simulation (Clyne et al., 2021) where injection rates of SO_2 were prescribed, Zanchettin et al. (2022) discussed the prescription of a volcanic forcing input between models, so as to focus on intermodel differences in the surface climate response. They showed that, by combining the forcing prescription with a robust sampling of initial conditions between models (something that is fundamental in volcanic simulations but that would not be in long-term geoengineering ones), model disagreement could be reduced, and a further focus could be given to the climatic surface response.

CCMI has collaborated with some in the GeoMIP community to set up a new shared experiment in order to support the new phase of CCMI (CCMI-2022) meant to inform the 2026 World Meteorological Organization (WMO)/United Nation Environment Programme (UNEP) Scientific Assessments of Ozone Depletion. In particular, CCMI models expressed interest in an experiment similar to G4SSA in which chemistry-climate models could prescribe the same aerosol distribution and observe changes in key stratospheric quantities. This experiment, senD2-sai, described in the July 2021 Stratosphere-troposphere Processes And their Role in Climate (SPARC) newsletter (Plummer et al., 2021), will use a new aerosol field produced with CESM2-WACCM6, symmetrical around the Equator, maintaining sea surface temperatures fixed at present levels and running for 75 years from 2025 to 2100. The synergy between GeoMIP and CCMI, with all the expertise such a joint effort could leverage, is an exciting opportunity for GeoMIP.

3.3 Isolating the role of the stratospheric heating contribution to stratospheric aerosol injection (SAI) experiments

The absorption of longwave radiation by the sulfate aerosols and the enhanced absorption of shortwave radiation by ozone induced by aerosol scattering lead to a higher stratospheric warming that has long been known to produce numerous effects, both in the stratosphere and in the troposphere. Different sizes, spatial distributions, persistence, and chemical compositions of the injected aerosols would modify the specifics of this warming. Studies of past volcanic eruptions (Robock and Mao, 1995; Polvani et al., 2019; Coupe and Robock, 2021; DallaSanta and Polvani, 2022) have revealed little consensus about the dynamical effects of this stratospheric warming on surface climate. Furthermore, observing systems are either sparse or, in the case of satellite-based infrared sounders, influenced by the presence of the volcanic aerosols. Radiosonde and satellite-based microwave sounders do indicate some warming, but the amount remains uncertain. So, while experiments that prescribe the aerosol field can highlight how different models warm the lower stratosphere differently, experiments that directly prescribe a stratospheric heating perturbation (e.g., Simpson et al., 2019) may help isolate model spread in the dynamical and surface responses, such as the models' response to El Niño events (Liu et al., 2022). Nonetheless, these experiments could shed light on which processes contribute more to the overall intermodel spread in experiments such as G6sulfur.

Two shared protocols have been proposed for this purpose: one aimed at observing surface changes induced by the stratospheric heating and one aimed at observing stratospheric dynamics changes. The fact that two different sets of models have been used for this purpose highlights the possibility of exploring some of the processes involved in geoengineering through the use of multiple tools: for surface changes, lower-resolution models with prescribed ozone and preindustrial conditions that allow for the production of a larger ensemble of simulations in order to better quantify the significance of some of the observed changes; for stratospheric changes, models with high stratospheric vertical resolution used for the QBOi experiments (Butchart et al., 2018).

One of the issues with determining a shared protocol for this kind of experiment is the determination of the amount of stratospheric warming to simulate. A higher warming signal obviously allows for a larger signal-to-noise ratio, but there

might be questions over the realism or the relevance of such warming signals, particularly if that large heat flux results in nonlinearities in the model response. For instance, in the G6sulfur experiments, for a global increase in optical depth of 0.1, models provide a range of warming in the lower tropical stratosphere between 1 and 5 K to offset a surface warming of roughly 0.5 K, whereas by the end of the century the stratospheric warming ranges between 5 and 14 K to offset a surface warming of (on average) 2 K. Simpson et al. (2019) and Visioni et al. (2021a) both imposed a stratospheric heating signal to isolate its impacts on the surface climate. They used an average value of 12 K based on results from GLENS simulations (described in Sect. 6) under an RCP8.5 scenario. Results found this would offset almost 5 K of surface warming.

On the other hand, the first proposed protocols mentioned in this section decided to use a stratospheric heating perturbation consistent with a forcing offset of $2 \, \mathrm{W \, m^{-2}}$ derived from Dai et al. (2018), which would result in a much lower average stratospheric heating. This choice will thus produce results that would be expected for a "moderate" deployment and clearly a much lower signal for the surface perturbation obtained.

Both approaches have merits and shortcomings, depending on their specific intent. Nonetheless, both are fundamental pieces of the puzzle in trying to separate uncertainties related to the dynamical perturbations that stratospheric sulfate would produce. Such perturbations might be difficult to isolate in more comprehensive experiments such as G6sulfur. In this way, stratospheric heating experiments can be seen as complementary to experiments such as G1, isolating the contribution of changes in the incoming shortwave radiation (although solar dimming experiments might also modify stratospheric dynamics, as pointed out by Bednarz et al., 2022).

3.4 Considering other scenarios: the Overshoot experiment

Tilmes et al. (2020) proposed a new GeoMIP test-bed experiment that aimed to examine the response to multiple stratospheric aerosol geoengineering scenarios aimed at keeping temperatures at two targets (2 and 1.5 °C above preindustrial), not only under a high-emission scenario (SSP5-8.5), but also under a scenario representing an "overshoot" (SSP5-3.4OS, Meinshausen et al., 2020), that is, a scenario with very large carbon dioxide removal after 2040 which results in only a brief exceedance of the 2 °C target. This idea of "peak shaving" has long been part of the discourse around geoengineering to represent temporary deployment to keep temperatures down while mitigation and negative-emission efforts are ramped up (Long and Shepherd, 2014; MacMartin et al., 2018). While this experiment could be part of a broader discussion around multiple scenarios involving high and low levels of intervention, SSP5-3.4OS is a Tier-2 experiment in ScenarioMIP, and thus modeling centers may not have

the underlying emission scenario simulations. Furthermore, the geoengineering overshoot scenario uses the same feedback algorithm (Sect. 3.5 below) described by Kravitz et al. (2017), which not many modeling centers have implemented yet.

Lastly, some modelers might feel that when it comes to simulating "policy-relevant" scenarios, one should prioritize those that appear to be more plausible (although, while implausibility can be determined in some cases, plausibility is entirely subjective), and a scenario with very large amounts of greenhouse gas removal already by 2040 might very well be considered unrealistic. Meinshausen et al. (2020) describe SSP5-3.4OS as "geophysically interesting", and perhaps the proposed geoengineering overshoot scenario should be viewed through the same lens. It also has the merit of fostering discussions about how to select policy-relevant scenarios that might be important for future CMIP choices; for example, considering a geoengineering scenario that includes carbon removal could lead to studies that quantify the interaction between solar geoengineering and carbon removal holistically (Xu et al., 2020). In particular, as SSP5-3.4OS relies heavily on bioenergy crops to reduce the CO_2 concentration in the second half of the century (Melnikova et al., 2022), it will be interesting to investigate the interactions between stratospheric aerosols and the potential for mitigation through Bioenergy with Carbon Capture and Storage (BECCS).

3.5 Expanding the strategy space: single-point injection simulations and explicit feedback

The idea of using control theory to modify the annual SO_2 injection amount (MacMartin et al., 2018; Kravitz et al., 2016, 2017) has been gaining traction in the geoengineering research community. In recent years, multiple experiments using CESM in various configurations have used a feedback algorithm to demonstrate that surface impacts of stratospheric aerosol geoengineering can be reduced if, instead of simulating equatorial or tropical injections of SO_2, these injections are distributed over other latitudes (namely, 15° N, 15° S, 30° N, and 30° S) to control not just global mean temperatures, but also interhemispheric and Equator-to-pole temperature gradients (see Kravitz et al., 2017; Tilmes et al., 2018; Richter et al., 2022). The merits of this strategy have been discussed in depth by Kravitz et al. (2019) as they compare to equatorial injections, leading many to ask whether future GeoMIP experiments should incorporate an explicit strategy dimension (MacMartin et al., 2022); for example, future GeoMIP experiments could include off-equatorial injection strategies instead of the equatorial strategy used in G4 and G6sulfur.

Two obstacles limit this option: the working of the feedback algorithm that directly imposes in the model how much SO_2 to inject every year may depend on exactly how each climate model imposes emissions in the model, requiring both

an interactive SO_2-to-sulfate aerosol treatment, which not all models have, and some software engineering applied to each model to make the algorithm work. Secondly, developing the control algorithm that manages more than one degree of freedom required previous sensitivity studies that determine the response of single-point injections at the required injection locations, as done by Tilmes et al. (2017) and MacMartin et al. (2017) for CESM1(WACCM). A GeoMIP test-bed experiment reproducing the single-point injection simulations and developing a similar algorithm for multiple models has been performed and described by Visioni et al. (2023) and Bednarz et al. (2023), but these studies were built upon the substantial body of work that had already been conducted. Any additional models wishing to engage with such a simulation would need to conduct their own single-location injection simulations, which is computationally expensive. The feasibility of expanding this idea to a larger host of GeoMIP models still needs to be discussed, and some groups may opt to study simpler strategies that still reduce impacts compared to equatorial injection but that are easier to implement.

The ARISE-SAI (Assessing Responses and Impacts of Solar climate intervention on the Earth system with stratospheric aerosol injection) protocols could offer an example of how such a feedback-driven experiment could work: the ideas behind the underlying scenario choices have been described by MacMartin et al. (2022), while Richter et al. (2022) clearly lays out the injection protocols, the overall setup for one model (CESM2-WACCM), and the required variables needed for analyses (that for things like aerosol fields might expand on what is recommended by CMIP in terms of required variables). A similar protocol (or the ARISE protocol itself) could be adopted as a future GeoMIP experiment.

3.6 The effects of surface brightening: G4foam

Experiment G4Foam (Gabriel et al., 2017) involves surface brightening, similar to G1ocean-albedo (Sect. 2.2), but only in selected oceanic regions where the forcing is expected to be amplified via cloud feedbacks. This idea is related to the idea of Green's function approaches to forcing that have been gaining traction recently in the study of climate feedbacks (Dong et al., 2019). Indeed, Harrop et al. (2018) showed that in CESM there are certain oceanic regions where, if one adds a positive heat flux, global mean temperature decreases. This raises the question as to whether there are high-leverage locations where small amounts of forcing could have robust, disproportionate effects. This area requires substantial further study, as it is not presently known whether these results are replicable in other models and, if so, what the physical mechanisms behind these effects may be. This experiment also reinforces the idea that issues central to geoengineering are also central to climate science in general – in this case, the relationships between forcing, rapid adjustments, feedbacks, and responses.

4 Future experiments

Based on the review of current and past experiments as well as community discussions, we have formulated opinions about which future experiments could be considered in geoengineering research. In the last two GeoMIP meetings, the GeoMIP community broadly agreed that the lack of person power, the computational expense, and the general uncertainty over future directions of CMIP indicated that the proposal of new Tier-1 experiments could be premature (Visioni and Robock, 2022); this of course might change in 2023, spurred by recent analyses, new community input, a notably increased interest in the theme by climate and impact scientists, and, perhaps, this piece. However, there was also a general agreement that we could use this time to better evaluate the models we currently have through process-based, more narrowly defined experiments to better constrain the intermodel spread observed in current GeoMIP iterations (Visioni et al., 2021b). These process-based experiments often do not need to be run with fully coupled Earth system models, relieving part of the computational cost and making these experiments interesting to a wider community. These efforts need to be run in parallel with efforts aimed at defining future policy-relevant scenarios that include geoengineering (Tilmes et al., 2020; MacMartin et al., 2022). In this section we describe some of these ideas and the reasons why we believe they are high priority for the research community.

Unlike other modeling experiments for which measurements are readily available to constrain model uncertainty (like volcanic eruptions or past stratospheric ozone evolution), there has been no implementation of geoengineering on a climate-relevant scale, and thus there are no observations of geoengineering. However, diagnosing the spread in the response of different models in a widening set of impacts on the natural and human world is always useful and may inform future plans for research (MacMartin and Kravitz, 2019) and, perhaps, contribute to the discussion around the need for future outdoor experiments (Golja et al., 2021).

4.1 Exploring Arctic-focused SAI: G6polar

In addition to equatorial injection, Robock et al. (2008) tested the climate effects of injecting SO_2 into the polar stratosphere (67.5° N/S). Its inefficiency at reducing global mean surface temperatures and its impact on global precipitation, predominantly shifting the Intertropical Convergence Zone (ITCZ), was noted (Haywood et al., 2013). More recently, Lee et al. (2021) reevaluated polar injection by considering seasonal injections in the spring, which would result in less perturbation overall, and highlighted the efficacy of such a strategy in restoring sea ice and the benefit of having to loft material at lower altitudes given the lower height of the tropopause there (Smith et al., 2022). This illustrates that geoengineering may have important tradeoffs that need to be

uncovered and discussed to inform future decisions around whether and how geoengineering might be deployed.

The need to address this question opens up the opportunity of devising a test-bed experiment aimed at analyzing the response to Arctic stratospheric injection in multiple models. However, because ITCZ shifts are a known consequence of single-hemisphere injection, care should be taken in considering the precipitation response, perhaps by devising an experiment that injects into both the North Pole and South Pole stratospheres in order to balance the forcing. If such an experiment is to be carried out, care should also be taken over the determination of a target: Lee et al. (2021) prescribed a fixed injection rate of $6\,Tg\text{-}SO_2$ in various seasons and simply observed the resulting changes (like in a G4-like experiment), whereas Lee et al. (2023) and Jackson et al. (2015) devised a target based on restoration of sea ice. It is likely that a fixed injection rate would be easier to analyze in the beginning (and would ultimately inform development of a feedback algorithm to target specific objectives), leading to clearer differences between different models. A well-designed experiment such as G6polar could also serve as a useful tool to better understand the potential of SAI to provide an emergency brake on some high-latitudinal tipping elements of the Earth system (Lenton et al., 2008), which have been understudied up to now in the context of geoengineering.

4.2 Isolating uncertainties through specified dynamics simulations

The effects of intermodel differences in large-scale circulation have been highlighted in multiple venues, especially in CCMI (e.g., Eichinger et al., 2019). For stratospheric aerosol geoengineering, Niemeier et al. (2020) showed large differences in the baseline residual vertical velocities, aerosol confinement in the tropical pipe, and the surface response to an aerosol perturbation. Large-scale differences in the circulation result in different latitudinal distributions of the aerosols, especially if injections happen close to the tropical pipe (Laakso et al., 2017; Bednarz et al., 2023), but aerosol microphysical growth and the dynamical perturbation itself also play important roles (Visioni et al., 2023). It could therefore be posited that another way to separate specific differences between models can be through the nudging of stratospheric dynamics to common values, as was done in CCMI in the RefC1-SD experiments (Orbe et al., 2020). Nudging climate models to reanalysis meteorology fields has also been done for simulations of volcanic eruptions, for instance by Schmidt et al. (2018), resulting in better agreement with observations in terms of the global mean forcing produced. However, recent studies (Chrysanthou et al., 2019; Davis et al., 2020) observed that, in multiple climate models, nudging schemes may fail to better reproduce or constrain (compared to free-running simulations) long-term trends in the residual vertical upwelling.

So, while there could be merit in observing the response of GeoMIP models to nudged simulations in terms of the aerosol distribution, care should be taken in designing those simulations in multiple models. Another way could be the use of chemistry-transport models (CTMs) like GEOS-Chem that do not have interactive circulation at all, which allows for an actual prescription of circulation patterns. However, CTMs seldom have detailed aerosol microphysics in the stratosphere compared to some CCMs (Visioni et al., 2018).

In general, the use of such methods would prevent the simulation of the actual interactions between the stratospheric heating produced and the large-scale circulation: while this would not simulate the full response occurring in the atmosphere, it may help in separating the dynamical feedback from the uncertainties resulting from the aerosols.

4.3 Isolating uncertainties through analyses of model sensitivity to aerosol parameterization

While technically not a GeoMIP experiment, Laakso et al. (2022) explored using the same climate model (ECHAM-HAMMOZ) but with two different aerosol microphysical models. This highlighted the sensitivity of the baseline climate and the response to sulfate injections into the aerosol model, underscoring the need to pay more attention to aerosol parameterizations. Similarly, Visioni et al. (2023) compared two versions of GISS ModelE2.1, one with a bulk aerosol treatment and one with a quasi-modal microphysics, finding even larger discrepancies.

One possible way to more systematically understand differences between microphysical schemes could be a protocol analogous to Weisenstein et al. (2007), where an intercomparison was performed between a 0-D box model, a 2-D model (the Atmospheric and Environmental Research (AER) sectional model with multiple configurations), and a 3-D model (the Global Modeling Initiative (GMI) 3-D chemical-transport model). A similar comparison between models used for GeoMIP simulations with sulfur injections could highlight potential areas of needed improvements and perhaps even define a "minimal standard" of complexity (for some experiments) that climate models should have before they can be considered to produce robust results. This would represent an evolution of GeoMIP from its initial attitude of welcoming all 3-D models, regardless of complexity, to increase participation.

4.4 Isolating uncertainties through more in-depth analyses of the radiative transfer component

Recent studies have shown that some intermodel discrepancies in the response to CO_2 can be traced to the shortwave radiation code (Chung and Soden, 2015; DeAngelis et al., 2015). Differences in radiative transfer have long been recognized, for example, in the Radiative Transfer Model Intercomparison Project (RTMIP; Collins et al., 2006). Boucher

et al. (1998) performed a comparison of the shortwave response to sulfate aerosols for 15 radiative transfer codes produced by 12 different groups under a wide range of specified size distributions and aerosol and atmospheric optical properties. Unlike for the response to greenhouse gases, where the intermodel spread ranged up to 40 %, Boucher et al. (1998) found that the standard deviation of normalized forcing near the optimum size for maximum scattering was small (8 %). This highlights the importance of investigating fundamental model processes – we do not want to conclude erroneously that the response to geoengineering is uncertain if the actual uncertainty is in the radiative transfer code and thus somewhat independent of the forcing mechanism.

It would be extremely valuable to perform a similar intercomparison with current radiative transfer codes, especially those used or whose usage is planned for GeoMIP studies. This could be done for both shortwave and longwave forcing; in both cases, GeoMIP models show large spreads in efficiency of the forcing and in lower-stratospheric warmings (Visioni et al., 2021b; Tilmes et al., 2022). Understanding the behavior of the radiative codes separately could help understand which areas of model improvement require more focus. Recent proposed methods, such as by Jones et al. (2017) involving comparing a very specific set of diagnostics with a line-by-line radiative model, could suggest a way forward. This method has been adopted by the Radiative Forcing Model Intercomparison Project-Aerosol Instantaneous Radiative Forcing Component (RFMIP Aerosol-IRF) (Pincus et al., 2016), and a collaboration between the two MIPs could be extremely informative. Such focused experiments, including analyses of the radiative kernels, could help better understand and constrain the global response to solar geoengineering on the hydrological cycle (Kravitz et al., 2013, 2021; Tilmes et al., 2013; Kleidon et al., 2015), as has been done for a CO_2 increase (DeAngelis et al., 2015).

4.5 How do we devise the next experiments for marine cloud brightening?

Questions regarding MCB can, to some degree, be separated into two categories. First, can clouds be brightened, and if so, by how much and under what conditions? Second, assuming clouds can be brightened, what are the climate effects of brightening clouds in specific areas? Experiment G4cdnc began addressing the second one, brightening all clouds where they existed. Indeed, this second category is well within the wheelhouse of Earth system models, as they are adept at understanding the climate response to imposed forcing. Specific experiments could be designed to test MCB in a multimodel capacity, such as choosing certain locations, different-sized regions, or seasons and performing Green's function approaches (analogous to those discussed in Sect. 2.2 above) in each model to exert a specified amount of forcing. One could envision either using the model's internal cloud field

or prescribing a cloud field; each approach has its advantages and disadvantages.

The first category, as to whether clouds can be brightened, is somewhat more complicated. We argue that this category of studies is outside of the auspices of GeoMIP, although coordination with GeoMIP would certainly be valuable. Understanding this question deals with fundamental questions in aerosol–cloud interactions, namely, the susceptibility of cloud albedo to aerosol changes. This has been and continues to be the largest source of uncertainty in climate science (Chen et al., 2021). The answer varies depending upon location, atmospheric conditions, and the background aerosol state (Lee et al., 2016), among numerous other factors. Addressing these questions in a model context could be done through a series of large-eddy-simulation (LES) experiments. The advantage of LES is that because of the small grid size (sometimes on the order of meters), many cloud processes are resolved instead of parameterized, which relieves a substantial source of uncertainty. LES experiments could be conducted under a wide variety of atmospheric conditions and aerosol injection strategies to understand under what conditions marine low clouds can be brightened and by how much. This in turn could be used to constrain further GeoMIP experiments, in which regions to be brightened are selected dynamically rather than assuming that MCB automatically works. This would allow the research community to establish an upper bound on the effectiveness of MCB and to produce better assessments of the potential large-scale circulation response, which would be a necessary part of an overall assessment of MCB research (Diamond et al., 2022).

4.6 Impact assessment

A long-established need in geoengineering research is to understand downstream impacts, such as agriculture, ecosystems, and food/water security (Irvine et al., 2017). GeoMIP has been used in the past as driving information for impact models (e.g., Xia et al., 2014). Nevertheless, this process at present is woefully insufficient for quantifying benefits and risks of geoengineering. Any uncertainties or spread in the Earth system models (as discussed above) will propagate through impact models, which have their own uncertainties, leading to a wide range of results, even independent of different future scenarios of climate change and geoengineering. There is some effort to perform intercomparisons of impact models, such as in the InterSectoral Impacts Model Intercomparison Project (ISI-MIP; Rosenzweig et al., 2017) or the Agriculture Model Intercomparison Project (AgMIP; Rosenzweig et al., 2012), to understand and reduce uncertainties in impact assessments. Coordination between those MIPs and GeoMIP is in its initial stages, but developing a path forward, including specific GeoMIP experiments that are designed for impact assessment, would be of benefit to a wide variety of communities. A similar argument could be made for the ecological impacts of geoengineering, which

are poorly understood (Zarnetske et al., 2021). It is essential to mention the DEGREES initiative in this respect (https://www.degrees.ngo, last access: 3 May 2023). One of the fundamental points of DEGREES is that researchers in the Global South, who are experts in climate impacts of most concern to their region, may also have access to high-frequency (at least daily) geoengineering model output in order to properly assess specific impacts that may be related to floods, droughts, freshwater availability, food security, human health, and other important impacts of their regions. The great advantage of bringing in these often poorly funded groups is that the research is community-driven from the grassroots upwards. Impacts that may interest the modeling community of GeoMIP may be quite different from those of most impacts locally. The scope for impact studies might be expanded in future to saline intrusion into ecosystems, fisheries, pests and diseases, human health, heat stress, and interactions with tropospheric pollutants.

5 Lessons learned

From our perspective, and based on our experiences and feedback from the broader community of researchers, GeoMIP has been a resoundingly successful MIP. New analyses and publications are continually underway, and attendance at annual meetings continues to increase. GeoMIP has emerged as a flagship activity in the geoengineering research community and has served as a common venue where scientists interested in this topic can interact, and new partners are always welcome.

The experiments described in Sect. 2 have been instrumental in highlighting high-priority research areas for the community. While it has been pointed out that solar dimming has a limited value in representing stratospheric sulfate aerosol geoengineering (Visioni et al., 2021a), it is nevertheless a highly valuable experiment, since the straightforward setup allows us to be confident in the robust climate model responses to an experiment like G1 (Kravitz et al., 2021)). We are less confident in our understanding of stratospheric sulfate aerosols, and we are able to attribute those uncertainties largely to the complexities of aerosol microphysical growth, aerosol distribution, and stratospheric circulation. In doing so, we have provided an evidence base for more targeted approaches, such as the GeoMIP test-bed experiments described in Sect. 4.

As we discussed in depth in Sect. 4, GeoMIP should focus more on coordinating with other MIPs. While some may think that geoengineering itself does not overlap with the aims of other MIPs, the simulations and science objectives could serve dual purposes. As an example, during the design of CMIP6 experiments, we had conversations with the leads of the Cloud Forcing Model Intercomparison Project (CFMIP; Webb et al., 2017); their interest in comparing the effects of solar and CO_2 forcing, as well as a delineation between fast and slow responses, aligns well with G1 and the time-slice experiments. Phase 6 of GeoMIP (Kravitz et al., 2015) had an overshoot scenario that was loosely coordinated with ScenarioMIP (O'Neill et al., 2016) and led to further studies of overshoot scenarios in the geoengineering research community (Tilmes et al., 2020, also see Section 3.4). The Scientific Assessment of Ozone Depletion: 2022 (Haywood et al., 2023), which required an assessment of possible changes due to SAI, has been an opportunity for renewed talks with the CCMI community, which resulted in the senD2-sai experiment (Table 1).

Through more focused coordination efforts with other MIPs, we could co-design new experiments that serve multiple communities. This could be a way to increase the likelihood that those simulations are conducted and analyzed. Due to the number of proposed simulations across all MIPS (there are 21 endorsed MIPs for CMIP6) and the budgetary and time constraints of the modeling centers, groups need to prioritize what experiments are worth their time. "MIP fatigue" is something we hear a lot in the climate modeling community: everyone thinks their experiments are relevant and interesting (and they are), and yet it is hard for modeling centers to keep up with all the new MIPs, with the requirements of the latest iteration of CMIP, and with improving the models, all of this while keeping an eye on what the funding agencies think is a priority for them.

Lastly, the analysis of output from geoengineering simulations has proven a viable and valuable means for involving researchers from countries that do not have the capacity for highly developed modeling programs, as has been demonstrated – albeit not to the extent of other modeling frameworks – through the DEGREES initiative (see Sect. 6.1.3 for further discussion of this initiative).

We also need to note that GeoMIP experiments have been critical for some recent high-level reports such as (i) the 2022 Quadrennial Ozone Report by the WMO (Haywood et al., 2023): without G6sulfur, there would have been no multi-model intercomparison of ESM results as related to the potential impacts of SAI on the ozone layer. (ii) The Intergovernmental Panel on Climate Change (IPCC) AR6 GeoMIP-based papers contribute to an assessment of SRM in a cross-chapter box in Working Group I (CCB10) and a cross-working group in Working Group II (chap. 6). (iii) The National Academy of Science, Technology and Medicine report (National Academies of Sciences Engineering and Medicine, 2021) also extensively references GeoMIP and its related works.

Based on this, and looking forward to the next decade, it is clear to us that modeling research into geoengineering will continue and most likely grow. As the topic expands and makes its way in international assessments, GeoMIP will have to adapt and change, and we explain how we think that should happen in Sect. 6.

5.1 Summary of outstanding scientific questions

Sections 3 and 4 offer many examples of questions that the GeoMIP community is interested in. This might feel like a scattershot of very different ideas, and in some ways it is so: the topic the GeoMIP community tries to tackle is a vast problem where the single pieces are always interconnected, and yet the community is (deliberately) diverse, with all participants bringing their own backgrounds and perspectives. Here, we highlight some of the key questions that continue to motivate our work.

What is the consensus of the most up-to-date models of the likely effects of solar geoengineering on the Earth system? This is certainly the one at the core of GeoMIP itself: we use highly advanced and, hopefully, independent climate models and try to discern commonalities in their response to various geoengineering techniques. If agreement is high for a certain aspect of the system, this is presumptively a likely response of the real Earth system. In general, the topic of "tipping points" (Lenton et al., 2008) and the potential of some form of solar geoengineering to delay or halt the emergence of dangerous instabilities in the planetary system are also ones that deserve far more attention in the future.

Highlighting disagreement, however, may be as important as highlighting consensus. *Why do models disagree in their response to solar geoengineering?* This may look similar to the previous question, but it shifts the focus from the projection itself to the tools used to derive it: is the multimodel average of the response "closer to the truth" than any single model or are there individual models that are "better" at capturing the effects of geoengineering than others (and how do we even characterize "closer" and "better" in a highly complex system)? If so, how can we constrain models with observations (past and future) to narrow down the uncertainty from multimodel ensemble simulations? In its latest assessment report, the IPCC highlights in multiple places the "large uncertainties" related to geoengineering. Together with a less vague quantification of such uncertainties, GeoMIP can also help identify areas of model agreement.

Moving to the various techniques tested, questions will differ based on the level of advancement in the field: for marine cloud brightening and cirrus cloud thinning, a major question that remains is the following. *Could these geoengineering techniques measurably affect the global climate?* For stratospheric aerosol injection, which has been studied more and for which more solid evidence behind its natural analog, volcanoes, exists, questions might be focused more on some of the details of the implementation. *What are the impacts of different strategies of implementations of SAI?* This is also a very broad question but one that focuses on the potential design aspect of geoengineering rather than on the uncertainty aspect of it, even if the two are connected (it is pointless to think about designing something of which we know very little).

6 The role of GeoMIP

GeoMIP is a framework for the intercomparison of geoengineering experiments using climate models. GeoMIP does not include all geoengineering research, and not all geoengineering research should go through GeoMIP: this is a fundamental point to put forward in order to understand the present and future roles of GeoMIP itself. There are clear examples of successful modeling efforts outside of GeoMIP, with the Geoengineering Large Ensemble (GLENS; Tilmes et al., 2018) being one of the most prominent. GLENS focused on producing a large ensemble (20 members) of simulations using one model (CESM1(WACCM)) and one, at the time, novel strategy (using an automated feedback loop capable of determining where and how much SO_2 should be injected in the next year). This allowed for a more thorough exploration of, for instance, signal-to-noise emergence (MacMartin et al., 2019) and extreme events (Aswathy et al., 2015; Pinto et al., 2020; Tye et al., 2022). Both GeoMIP and GLENS have enabled numerous studies through the DEGREES initiative, enabling developing countries to assess changes they may experience under geoengineering.

With the urgency of climate change increasing impacts on societies and ecosystems, there is a great need to continue and accelerate geoengineering research (National Academies of Sciences Engineering and Medicine, 2021), and there remains much merit in scientific exploration through the use of coordinated multimodel experiments coupled with increased efforts to improve Earth observations in order to better assess the accuracy of current models. Overreliance of conclusions about geoengineering from just one climate model can be a potential pitfall and result in overconfidence in results that are model-specific. Multimodel comparisons can highlight outliers (not necessarily wrong, but different as compared to the mean), which can in turn spur further research behind the reasons why: this is for instance the case for the higher climate sensitivity of some CMIP6 models (Zelinka et al., 2020). This in turn can direct effort towards improving our understanding of model performance, with experiments such as those described in Sect. 4. In addition, knowledge-sharing and expertise-building are both at the core of GeoMIP and of fundamental importance in the field of geoengineering studies. In the previous sections we have tried to outline how much the process behind defining new experiments for GeoMIP relies on "learning by doing (and making mistakes)". Yearly in-person GeoMIP meetings (except two online during the COVID pandemic) have been an opportunity for the community to grow and learn and share knowledge across different continents and levels of expertise: for each meeting, every year, a report is available (see the list at http://climate.envsci.rutgers.edu/GeoMIP/publications.html, last access: 4 May 2023) detailing both the discussions that took place and the novel science presented by researchers at every stage of their career.

Indeed, this opinion piece was strongly inspired by the discussions had during the Gordon Conference on Climate Engineering that took place in Newry, ME, in the summer of 2022, both in terms of the future plans and in terms of the level of enthusiasm we saw in the meeting, which involved over 50 early career researchers (while the first Gordon Conference, held in 2017, had fewer than 10). The yearly GeoMIP meeting was held during one of the afternoons of the Gordon Conference both times, and a very large portion of the people that were at the conference attended. This social aspect of GeoMIP is as valuable as the purely scientific one and, to some degree, those two aspects are inseparable.

With these reflections in mind, in this section we want to look even more broadly at the future of GeoMIP and discuss what direction we think the community should (and should not) move towards.

6.1 What should not be in GeoMIP's purview?

Here we want to summarize some of the most recent research or discussions around future geoengineering directions but which we think are either too premature to be considered in GeoMIP or which simply do not fall in its purview.

6.1.1 Is it necessary to simulate pathological scenarios in GeoMIP?

In the past, there have been studies aimed at understanding "pathological" SRM deployments or events: the effect of an abrupt termination (Jones et al., 2013; Trisos et al., 2018) or those of a single-hemispheric deployment (Haywood et al., 2013; Jones et al., 2017). The point of analyzing such scenarios is mostly to answer the question "what could go wrong?", which is extremely important. However, it could also be misinterpreted in communication of the results as "this is what SRM would (always) do" (Reynolds, 2022), and therefore there can be a legitimate discussion over whether such scenarios are needed. In particular, because GeoMIP has served as a community-building and organizing effort, the project speaks with a loud voice; if GeoMIP explores pathological scenarios, this may send the signal that such scenarios are considered to potentially be realistic.

At the time the termination effect was proposed for inclusion in GeoMIP, few studies had explored it (e.g., Wigley, 2006; Robock et al., 2008). As such, there were numerous questions about the detailed effects of termination, including whether models would respond on similar timescales and with similar accelerations of climate change. The community has since learned a great deal from those simulations, and while there may remain open questions about termination, we presently see no need to conduct such investigations in numerous models. A similar discussion could be had for single-hemispheric deployment. This scenario is interesting and instructive from a basic-response standpoint and has resulted in fundamental knowledge that has informed geoengi-

neering discussions. There is also some value in comparing the results of these experiments in multiple models (Haywood et al., 2016) to understand the degree of changes and whether there are robust signals. However, it is hard to envision a situation in which geoengineering would only be deployed in a single hemisphere for multiple decades. As such, these experiments may not be appropriate to adopt as formal GeoMIP experiments.

There has recently been increased discussion of uncoordinated geoengineering or "rogue actors" where there is no centralized decision-making about an optimal aerosol distribution or target, but rather multiple actors may be attempting to meet multiple, independent, perhaps conflicting targets (Rabitz, 2016). The lack of climate model simulations of this scenario in the geoengineering literature has been discussed before (McLaren and Corry, 2021). Nevertheless, we argue that this is not an experiment that should be adopted by GeoMIP. Policy experts or game-theory analysts could in principle devise a scenario involving multiple actors. However, the challenge would then be translating such a scenario into a specific experiment that could be run consistently in multiple models. Moreover, it is not obvious that there would be advantages to conducting such a specific simulation; for example, GLENS involved independent injections at four different locations, and it is unclear how different a simulation with decentralized geoengineering would be from GLENS. We do not rule out the possibility of this being explored in the future, especially as more concrete policy decisions emerge over the coming years, but we do not see a role for GeoMIP in these scenarios at this time.

6.1.2 Alternate materials for stratospheric aerosol injections

To date, all GeoMIP experiments involving solar geoengineering through the injection of aerosols into the stratosphere have consisted of injections of SO_2 or H_2SO_4 (Weisenstein et al., 2022, Sect. 3.1). Global modeling of alternate aerosols is sparse, with some exceptions for black carbon or titania (Kravitz et al., 2012; Ferraro et al., 2015; Jones et al., 2016). Alternate, potentially less impactful materials such as calcium carbonate have been proposed to overcome the problem of ozone changes and lower-stratospheric temperature perturbations (see for instance Keith et al., 2016; Dykema et al., 2016), but since those materials are not naturally occurring in the atmosphere, information is still being sought on the chemical reaction rates (Dai et al., 2020). For this reason, it is clearly premature to consider such experiments for GeoMIP, but the potential for future intercomparisons would arise if the inclusion of these novel materials were to be tested in multiple climate models independently.

6.1.3 Subgrid-scale processes

One of the shortcomings of using climate models for SAI simulations is the inability to resolve fine-scale behaviors once the materials have been injected. In Sect. 2.5 we discussed some of the cloud processes that are unresolved at the scale of Earth system model grids, requiring parameterization. For stratospheric aerosol injection, there are additional uncertainties at the subgrid scale. For example, models often assume that once SO_2 is injected into a grid box it becomes immediately uniformly distributed. This is uncharacteristic of diffusion processes or mixing forced by an aircraft jet. Additionally, many relevant weather and climate processes happen at the subgrid scale, which is particularly relevant for quantifying changes to extreme temperature and precipitation.

While many of these topics are certainly relevant for GeoMIP and may affect model capabilities and experiments in the future, as an Earth system model intercomparison, studying the importance of subgrid-scale processes is outside of the purview of GeoMIP and is better left to individual studies. There are numerous other MIPs and perturbed parameter ensembles that are focused on understanding parametric and structural uncertainty; through coordination and communication, such lessons can be conveyed to GeoMIP without requiring a specific GeoMIP experiment. New work involving a Lagrangian plume model that can be embedded in ESM grid boxes (Sun et al., 2022) is underway, but it needs further testing and has not been widely implemented, so using this capability in GeoMIP is premature.

Dynamical downscaling, either using a regional model or a regionally refined global model, is a standard technique for gaining finer-scale information. Downscaling has been shown to add value to GCM data over regions of topography, at land–water boundaries, and in better representing extremes (Ekström et al., 2015). Currently these methods are being tested for geoengineering applications (Wang et al., 2022), so adoption by GeoMIP is still premature. However, future efforts to coordinate between GeoMIP and the Coordinated Regional Climate Downscaling Experiment (CORDEX; Kotlarski et al., 2014) could prove to be fruitful in coming years, perhaps in concert with efforts to increase impact assessment.

6.2 What should GeoMIP do next?

As an official MIP under CMIP, the primary goal of GeoMIP for the coming years should be to prepare for CMIP7 and continue to harvest potentially valuable results from the efforts put into the CMIP6 simulations. This is especially important considering the potential for results from GeoMIP to be included in future international reports like the IPCC and WMO reports, as it has been in the past.

The experiments proposed in Sect. 4 would go a long way towards building more trust in the models used for future projections, in improving the modeling tools at our disposal in future iterations, and towards better understanding the underlying processes that comprise the overall response of the Earth system to geoengineering. However, in IPCC reports there is a strong push towards the use of complex emission scenarios, developed with the use of integrated assessment models (IAMs) that can represent a range of possible and plausible futures (Nakicenovic et al., 2000) spanning greenhouse gas emissions, land use, and population changes. The process that led to the development of the set of scenarios used in the Assessment Report 6 of the IPCC has been described in detail by O'Neill et al. (2016). The whole process was defined by the ScenarioMIP Scientific Steering Committee, which included extensive discussions with members of multiple scientific communities, numerous MIPs, and IPCC task forces. The main objectives that guided the decisions were (i) facilitating integrated research between climate analyses, scenario analyses, and feedbacks between climate and society, (ii) addressing targeted science questions regarding particular components of the overall forcing, and (iii) better quantifying projection uncertainties based on multimodel ensembles.

On the other hand, and with no surprise considering the smaller scope, previous GeoMIP scenarios have been defined by a much smaller (and narrower in terms of expertise) community, mostly taking into account the modelers' needs for geoengineering scenarios that were straightforward to implement in different climate models. The amount of person time available to produce the GeoMIP simulations is perhaps 2 orders of magnitude lower than that made available by modeling centers for ScenarioMIP, and therefore it is unsurprising that GeoMIP has made use of available SSPs and added geoengineering on top. This is likely to continue to be the case for some time, but nonetheless the geoengineering research community should explore how geoengineering might be incorporated directly into the scenario development process. Learning from other MIPs and the history of geoengineering, we think it is important that future CMIP7 scenarios include geoengineering as well (in all its various forms). In our view, the scenarios that include them should address the following criteria.

1. *Plausibility*: in terms of possible start date, amount of cooling, characteristics of the deployment, and more, the scenarios should reflect to the best of our current knowledge realistic deployment options.

2. *Policy relevance*: the scenarios should be capable of informing policy-makers with regards to the possible outcomes of a geoengineering deployment by considering more than one possible scenario and strategy, as the analyses of just one case may lead to confusing a scenario-specific result with a result that is applicable to all geoengineering scenarios.

3. *Scientific relevance*: the analyses of the developed scenarios should aid in our scientific understanding of the outcomes of a geoengineering climate.

4. *Reproducibility*: the requests to the modeling teams should be as simple as possible in order to ensure the participation of as many models as possible, minimizing possible errors and ensuring reproducibility.

These four criteria present some tension between them: for instance, a scenario like G1 is very scientifically relevant, has a high signal-to-noise ratio, and is easily reproducible but not plausible or policy-relevant, whereas a scenario like G6sulfur might be scientifically relevant and policy-relevant but is not plausible (the start date has passed, and current emissions do not seem to track the SSP5-8.5 scenario), and future scenarios like those described by MacMartin et al. (2022) might not be easily reproducible in many climate models, which makes them not presently relevant for GeoMIP. In general, more plausible scenarios will have lower signal-to-noise ratios. However, there is the question of whether an effect (both direct and indirect) that is too small to be detected in a plausible simulation matters ("To whom? And for what?") and needs to be investigated. We view this tension as a good thing, and indeed scenarios should not strive to meet all four criteria equally (although meeting the reproducibility criterion should be considered essential for inclusion as a Tier-1 GeoMIP experiment). Our purpose is not to prescribe at this stage what future GeoMIP experiments should be. Rather, we argue that proposed experiments should be interrogated to ensure that they are being true to purpose so that experiments are widely adopted by modeling groups and their results can be appropriately communicated and are useful for the scientific and policy-making community.

Moreover, the process for coming up with scenarios needs to be explicit about its intended audience. In particular, new scenarios should carefully consider (i) the need for an inclusive process that takes into account multiple lines of expertise across multiple fields (climate science, ecosystem sciences, social sciences), (ii) the needs of the community of modelers on which GeoMIP depends, and (iii) the needs of the community of scientists that want to use GeoMIP output. Balancing these three different sets of needs out will also result in some tensions (for instance, between the need for high-frequency output required by the impact modeling community and the difficulty in storing the large amount of data that would be produced), but it is a necessary discussion both in order to ensure that the scenarios are as representative as possible and in order to make sure that as many researchers as possible feel represented in GeoMIP.

To offer some specific examples of the needs of the users of GeoMIP, there is a growing community of ecologists interested in understanding the impacts of geoengineering on ecosystems (Zarnetske et al., 2021) that have already successfully used GeoMIP simulations. On the other hand, GeoMIP data have only been used in 3 out of the 12 papers published to date in the DEGREES project, supported by the DMF (DEGREES Modelling Fund), which aims to supports teams of researchers in developing countries (https://www.degrees.ngo/publications/, last access: 5 September 2022). In some cases this disparity makes sense – for example, DEGREES teams who want to study extreme events (e.g., Abiodun et al., 2021) would benefit from using a large ensemble like GLENS to obtain a good signal-to-noise ratio or be able to sample rare events. For some other groups, as the number of models increases, accessibility and usability of the data become harder, especially for teams with poor Internet connectivity or teams that require computing power to conduct their analyses. GLENS is a single model, and all data are available in one place, which can make it easier to use. There are important advances being undertaken for CMIP analyses, particularly by the Pangeo community (Odaka et al., 2020), who have enabled analysis of CMIP6 data in the cloud without requiring users to download terabytes of output. Nevertheless, widespread use of GeoMIP output, including data accessibility, is currently an unresolved issue.

Lastly, DEGREES teams have repeatedly reported their need to focus on small-scale, regional-impact assessments, which often require downscaling results from available climate models. Although several teams have conducted regional-impact modeling analyses (e.g., hydrology, health, and ocean modeling), only one study has employed dynamical downscaling of GeoMIP results, a study using WRF to downscale G4 output over Northeast China in comparison with statistical downscaling (Wang et al., 2022) and another to statistically downscale G4 output over the Indonesian maritime continent (Kuswanto et al., 2022). To statistically downscale climate data on a regional scale, however, the underlying data need to reliably replicate the climatological features of the baseline climate, which in some cases some models might fail to do. The issue of "which models are best to use" is therefore also a problem which DEGREES teams are faced with.

7   Conclusions

The Geoengineering Model Intercomparison Project community has been active for more than 10 years, and its participants span numerous countries on multiple continents (Visioni and Robock, 2022). Here we have reviewed past and present proposed GeoMIP experiments, including those determined by the community as high priority (Tier-1) and those proposed by specific members as "test-bed experiments", and have reflected on the potential future development of GeoMIP.

While not a review of the state-of-the-art understanding of SRM, which exists elsewhere (e.g., Kravitz and MacMartin, 2020), critically assessing all available GeoMIP experiments is a useful exercise for understanding how the field of geoengineering modeling studies has evolved, as it gives an idea

of the current areas where research has focused and how to move forward from there.

The inclusion of recent experiments and numerous new potential experiments or areas where experiments could be devised has multiple aims, many of which have been brought up repeatedly in publications and at various meetings of the research community, amongst them (i) offering the community a way to devise new, more specific analyses of current experiments that might have been underutilized and could still be leveraged, (ii) serving as a starting point for the community to more carefully devise new experiments, both more specific ones as we detailed and also for future CMIP experiments to be included in international assessments, and (iii) currently many calls are available for "more research" into solar geoengineering, such as the report from the National Academy of Science (National Academies of Sciences Engineering and Medicine, 2021). Nevertheless, those calls for "more experiments" or "more research" often lack detail, which is a barrier to action. Based on the discussions amongst the large GeoMIP community over the years, in this piece we have provided a critical examination of where GeoMIP's research has led and what gaps need to be filled, and we provide a number of conclusions that could provide needed specificity regarding future research directions and aligned programs.

One obvious gap, which has been repeatedly highlighted by the community, is a lack of people time more than simply computer time, both in defining shared protocols for experiments and in analyzing the available output. As a simple example, even just determining injections of SO_2 in exactly the same grid box in multiple models requires more work than just specifying a certain height in the protocols: different models may have different kinds of vertical coordinates and different ways of specifying exogenous emissions. Coordinating between modeling centers and providing attention to these details are therefore crucial parts of a successful multimodel comparison. Related to this is limited funding to support geoengineering research, in terms of both people and computer time, and a lack of capacity in developing countries to operate in this space. As these countries are typically the most vulnerable to climate change, entraining local scientists into geoengineering research is especially important (Rahman et al., 2018).

We should underscore that multimodel comparisons are definitely not the only way to understand, constrain, and eventually reduce model uncertainty. As for climate change, uncertainty does not come from a single source. As explained, for instance, by Hawkins and Sutton (2009), it can come from internal variability, uncertainty in the climate response, scenario uncertainty, and parametric or structural uncertainty. Internal variability can be better studied in the context of large ensembles of simulations with single models, of which some are already available for geoengineering studies (Tilmes et al., 2018; Richter et al., 2022)): the use of multiple realizations from very similar initial conditions allows

for a better separation of a given forcing signal from noise derived from the inherent chaotic nature of the atmospheric and oceanic system and makes exploring the timing of the emergence of such a signal easier (MacMartin et al., 2019; Tye et al., 2022). GeoMIP is suited to exploring uncertainties in the climate response as it allows an exploration of structural differences between models to a standardized forcing, but it does not directly address single-model uncertainty based on specific parameters in the physical representation of various aspects of the climate system: for such an endeavor, perturbed-physics ensembles within a single model may offer a much clearer answer. One example of such a perturbed-physics ensemble is the proposed Pinatubo Emulation in Multiple models (PoEMs) experiment in the Interactive Stratospheric Aerosols MIP (ISA-MIP) (Timmreck et al., 2018), in which modeling teams already simulating the 1991 Pinatubo eruption are asked to perform additional simulations modifying some of the possible parameters (in their case, such as aerosol nucleation, coagulation, or sedimentation rates) in order to span the possible space of parameters that most closely matches observations of the eruption. Some of the GeoMIP experiments, and especially some of the experiments we have proposed in Sect. 4, may help single-modeling teams better understand where to focus their efforts in terms of parameters to analyze and may even leverage existing protocols like PoEMs in order to longitudinally compare against other realizations with the same model and with other models. An initial effort along these lines was explored by Irvine et al. (2014) for G1 using HadCM3. Carefully designed protocols that can incorporate both model and parametric uncertainty would provide numerous advantages for quantifying and attributing uncertainty in processes.

Scenario uncertainty, which over multidecadal scales is larger than other sources in the CMIP context (Lehner et al., 2020), can also be very hard to sample in the GeoMIP context. Moreover, scenario exploration has historically required multiple decades of simulation for each scenario, which limits the number of scenarios that can be explored. Considering multiple, but shorter, simulations could perhaps free up the resources needed to span the scenario dimension but at the cost of perhaps undersampling the long-term climatic response: for future iterations of experiments that are part of CMIP, the community will have to make some choices on this aspect or perhaps distinctly consider short-term process details and long-term response characteristics in separate experiments. A possibility could be to also focus on studies that try to develop better emulators that are applicable in the geoengineering context: some currently exist and may work better for some variables than for others (MacMartin and Kravitz, 2016). These allow researchers to analyze multiple scenarios a posteriori after a lower number of possibly higher signal-to-noise scenarios has been simulated with the full host of climate models and to ultimately verify the emulator with a subset of available climate models afterwards.

There continues to be an important role for GeoMIP in geoengineering research, both scientifically and as a community effort. We recommend that, for activities in GeoMIP, participants carefully evaluate their purpose and participation to ensure that the objectives of GeoMIP continue to be met and support the ongoing development of GeoMIP. We also recommend active coordination with other MIPs, World Climate Research Program activities, core programs such as SPARC, the Earth System Modelling and Observations (ESMO), and the Safe Landings Lighthouse activity, and other geoengineering research efforts to identify synergies that will increase the use of GeoMIP efforts and encourage more participation in GeoMIP. Issues and uncertainties in geoengineering are rarely exclusive to that field – rather, they are often common to climate science research in general. Bringing geoengineering research into the mainstream, perhaps in part through efforts made by GeoMIP, will benefit both geoengineering research and broader climate research efforts.

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