The Geoengineering Model Intercomparison Project (GeoMIP)

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ABSTRACT

To evaluate the effects of stratospheric geoengineering with sulfate aerosols, we propose standard forcing scenarios to be applied to multiple climate models to compare their results and determine the robustness of their responses. Thus far, different modeling groups have used different forcing scenarios for both global warming and geoengineering, complicating the comparison of results. We recommend four experiments to explore the extent to which geoengineering might offset climate change projected in some of the Climate Model Intercomparison Project 5 experiments. These experiments focus on stratospheric aerosols, but future experiments under this framework may focus on different means of geoengineering.

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Introduction

Since the idea of geoengineering was thrust back into the scientific arena by Crutzen (2006) and Wigley (2006), many have wondered whether it could reduce global warming as mitigation measures are implemented. Several methods of geoengineering have been discussed, but Lenton and Vaughan (2009) argue that among the most feasible is through stratospheric sulfate aerosols. Analyses by Robock et al. (2009) indicate that such a scenario would be relatively inexpensive, especially in comparison to the cost of mitigation as determined by the Intergovernmental Panel on Climate Change (IPCC, 2007b), potentially making this idea attractive to policy makers.

However, Robock et al. (2009) point out that stratospheric geoengineering with sulfate aerosols could have unintended and possibly harmful consequences, including potential impacts on the hydrologic cycle and ozone depletion. For policymakers to be able to make informed decisions, the strength and patterns of these climate system responses need to be understood, and climate modeling will play an important part in this analysis. So far, several groups have conducted experiments, but these largely cannot be directly compared. For instance, Robock et al. (2008) and Rasch et al. (2008a) used a 5 Tg SO_2 per year injection rate into the tropical lower stratosphere, while Jones et al. (2010) injected the same amount, but uniformly globally. In contrast, Govindasamy and Caldeira (2000), Govindasamy et al. (2002, 2003), Matthews and Caldeira (2007), and Bala et al. (2008) reduced the solar constant to approximate the net effects of stratospheric aerosols on the planetary energy balance. Robock et al. (2008) and Jones et al. (2010) ramped up the anthropogenic greenhouse gas forcing using the IPCC A1B scenario (IPCC, 2007a), while the others conducted equilibrium simulations at $2xCO_2$.

Bala et al. (2008) explained why globally averaged precipitation would be reduced if the solar constant is reduced to balance the radiative forcing from increased greenhouse gas concentrations. However, simulation of the spatial patterns of such a reduction would likely be model-dependent. The results of Robock et al. (2008) indicate that stratospheric geoengineering in order to compensate for increased greenhouse gas concentrations would reduce summer monsoon rainfall in Asia and Africa, potentially threatening the food supply for billions of people. Jones et al. (2010) got similar results, but Rasch et al. (2008a) found different regional patterns. Past large volcanic eruptions have disrupted the summer monsoon (Oman et al., 2005; Trenberth and Dai, 2007) and even produced famine (Oman et al., 2006), but direct comparisons between geoengineering with stratospheric sulfate aerosols and large volcanic eruptions are limited by the differences in forcing. Some unanswered questions include whether a continuous stratospheric aerosol cloud would have the same effect as a transient one and to what extent regional changes in precipitation would be compensated by regional changes in evapotranspiration. A consensus has yet to be reached on these, as well as other, important issues.

To answer these questions, we propose a suite of standardized climate modeling experiments to be performed by interested modeling groups. We also propose to establish a coordinating framework for performing such experiments, which will be known as the Geoengineering Model Intercomparison Project (GeoMIP). Aside from coordinating the experiments described here, GeoMIP may consider additional geoengineering experiments in response to interest from climate modeling groups and the broader community. The particular experiment suite outlined in this document consists of four experiments, all of which are relevant to the geoengineering strategy of injecting stratospheric sulfate aerosols in an attempt to offset greenhouse gas warming. The Program for Climate Model Diagnosis and Intercomparison (PCMDI) has consented to archive results from these experiments, so they can be openly studied. We anticipate this set of standardized experiments will permit the level of intercomparison necessary to achieve confidence in the results, similar to the level of scientific consensus that is published in the assessment reports of the IPCC. Initially, largely for practical reasons, the number of simulations to be performed must be kept small because the Climate Model Intercomparison Project 5 (CMIP5; Taylor et al., 2008) is already stretching the capabilities of the modeling groups.

Experiment Design

We use the codes G1, G2, G3, and G4 to refer to the four simulations that will be conducted in this suite of experiments. We summarize these four experiments in Table 1. G1, G2, and G3 are designed to produce an annual mean global radiative balance at the top of the atmosphere. We seek to determine commonalities and differences among climate model responses to these particular schemes of geoengineering. G1 and G2 are the simplest possible explorations of balancing increased longwave forcing with reduced shortwave forcing, i.e., through a reduction of the solar constant. These idealized experiments are expected to reveal the basic model responses to this forcing balance without the added complication of differing treatments of stratospheric aerosols in the various models. The idealized specification of forcing also makes it especially easy to implement. In all of these experiments, we define radiative forcing to be the “adjusted forcing," which applies after so-called “fast” radiative responses (e.g., stratospheric adjustment) occur, as discussed, for example, in Hansen et al. (2005). We note that we will unlikely be able to attain a perfect balance in radiative forcings, but we are aiming for a net balance as close to zero as possible. Included in CMIP5 is a historical run, which will include simulation of past volcanic eruptions. We will use the results of these simulations to validate the models as part of our interpretation of the GeoMIP runs.

The G1 experiment will be initiated from a model control run and will build on a CMIP5 simulation in which the CO_2 concentration is instantaneously quadrupled. We choose this experiment to ensure a high signal-to-noise ratio of the climate response to radiative forcing from CO_2. In G1, the global average radiative forcing from the CO_2 will be balanced by a reduction of the solar constant. The CO_2 radiative forcing will be measured during the CMIP5 quadrupled CO_2 run, and the reduction in solar constant needed to compensate for this forcing will be based on a simple calculation using global average planetary albedo. A correction to this first estimate of solar constant change can be made after simulating a few years and monitoring the radiative balance. If a correction is necessary, the simulation will be restarted from the control run. In each model, a different solar constant change may be needed since both the CO_2 radiative forcing and the planetary albedo may differ from one model to the next. The tuning procedure described above also determines the change in solar constant that will be applied in the G2 experiment. Figure 1 illustrates the net radiative balance that would result from G1.

Similar to G1, the G2 experiment will involve a reduction in solar forcing to counteract the additional forcing due to increasing CO_2 concentration. However, the G2 experiment will build on the CMIP5 run specifying a 1% per year increase in CO_2, starting from a model control run. In G2, the global average radiative forcing from increases in CO_2 concentration will be balanced by gradually reducing the solar constant. Since we prescribe an exponentially increasing CO_2 concentration, and the radiative forcing scales with the logarithm of CO_2 concentration, the solar constant will be prescribed to decrease linearly over time, with the scaling for the solar constant changes inferred from G1. Figure 2 illustrates the radiative balance that would result from G2.

Experiment G3 is similar to G1 and G2 but more realistic, in the sense that it will provide a scenario of possible implementation of stratospheric geoengineering (Figure 3). It assumes an RCP4.5 scenario (Representative Concentration Pathway, with a radiative forcing of 4.5 W m^{-2} in the year 2100; Moss et al., 2008), but with additional stratospheric aerosol added starting in the year 2020, which is a reasonable estimate of when the delivery systems needed to inject the aerosols might be ready. Stratospheric aerosols will be added gradually, balancing the anthropogenic forcing to keep the planetary temperature nearly constant. The aim of this experiment is to achieve an ongoing radiative balance, which will likely require differing amounts of aerosol, with a time-varying size distribution, to be added in the various models. Ideally, the models will create, grow, and transport sulfate aerosols from an equatorial injection of SO_2. If a model does not have this capability, aerosols can be added at the Equator or globally in a way similar to each model's treatment of volcanic aerosols. If the model is capable, inclusion of O_3 chemistry or the carbon cycle, as well as the relevant couplings with the physical climate system, will allow additional scientific issues to be addressed, but the models should be run in concentration-driven rather than emission-driven mode for the carbon cycle. The G2 and G3 results will differ from each other from model to model, which will inform us of the effects of different treatments of stratospheric aerosols.

The radiative forcing due to anthropogenic greenhouse gases and aerosols has already been estimated in preparing the RCP4.5 runs. Therefore, in the G3 simulations, this forcing simply needs to be balanced by aerosol forcing. Hansen et al. (2005) found that the radiative forcing at the tropopause due to a large tropical volcanic eruption such as Pinatubo, after allowing stratospheric temperatures to adjust, is -24τ W m^{-2}, where τ is the sulfate aerosol optical depth at 550 nm. In their geoengineering simulations, Jones et al. (2010) report an increase in sulfate aerosol optical depth of 0.05 after 3-4 years, by which time the aerosol layer has reached an equilibrium thickness. By the formula of Hansen et al. (2005), this should correspond to a radiative forcing of –1.2 W m^{-2}, which is consistent with the results found in Jones et al. Therefore, the amount of aerosol injected to achieve the desired radiative forcing can use the formula by Hansen et al. (2005) as a rough guide. However, each modeling group likely will need to fine-tune this calculation.

Experiment G4 (Figure 4), similar to experiment G3, simulates a stratospheric sulfate aerosol layer. However, instead of achieving radiative balance, G4 involves injection of stratospheric aerosols at a specific constant annual rate, turned on abruptly in the year 2020. Results from this experiment will be helpful in assessing the uncertainties that can arise in estimating the impact of geoengineering when models are used to transform emission rates into concentrations. The sudden start of the aerosol injection in 2020 is meant to approximate the kind of action that might result from society's sudden perception of a climate warming "emergency" (e.g., an immediate imperative to stop ice sheet melting).

We base the proposed rate of aerosol injection of 5 Tg SO_2 per year on several considerations. Several estimates (e.g., Robock et al., 2008; Rasch et al., 2008b) have indicated that 3-5 Tg per year of SO_2 injected into the lower stratosphere would offset a doubling of CO_2 concentration. An injection rate of 5 Tg SO_2 per year translates into 0.0137 Tg SO_2 per day, as in Crutzen (2006), Wigley (2006), and Robock et al. (2008). Rasch et al. (2008a) suggest 1.5 Tg of sulfur (approximately 3 Tg SO_2) per year would be sufficient, but we propose using 5 Tg SO_2 per year, to reduce the global average temperature to about 1980 values. We choose to err on the larger side of this interval to maximize the signal-to-noise ratio of the climate response to geoengineering. Additionally, according to Heckendorn et al. (2009), previous studies used too small of an aerosol effective radius, meaning the amounts used in prior experiments will be less effective in cooling the planet than previously thought, bolstering our argument for the larger 5 Tg SO_2 per year injection.

An ensemble of simulations will be performed for each geoengineering experiment. The suggested method of generating each ensemble and the recommended sizes of the ensembles will closely align with the protocol set by CMIP5 for the simulations without geoengineering, but if our results show the size of an ensemble is insufficient to obtain statistically significant results, additional ensemble members will be generated. In experiments G2, G3, and G4, the geoengineering will be applied for only the first 50 years, but with the runs extended an additional 20 years to examine the response to a cessation of geoengineering.

In the RCP4.5 scenario, as outlined by Moss et al. (2008), the total radiative forcing in 2100 reaches and subsequently stabilizes at 4.5 W m^{-2} (relative to preindustrial levels). This stabilized forcing reflects a CO_2 equivalent concentration of 650 ppm. We have selected this scenario because, as noted by Taylor et al. (2008), “RCP4.5 is chosen as a ‘central’ scenario...[and] is chosen for the decadal prediction experiments.” Using a more optimistic scenario in which rapid mitigation is implemented would result in less robust results and is thus not likely to be as illuminating. Conversely, choosing a scenario with higher radiative forcing would reflect an irrational and unsustainable path, since if society cannot effectively mitigate greenhouse gas emissions, then geoengineering would be needed on a massive scale for a long period of time, due to the long atmospheric lifetime of CO_2 (Solomon et al., 2009).

Wigley (2006), Matthews and Caldeira (2007), and Robock et al. (2008) performed simulations in which, after a period of time, they stopped geoengineering and then evaluated the resulting rapid warming. Since this response has been fairly well established, it could be argued that further investigation of the results of stopping geoengineering at this time would not be particularly interesting. However, it will likely be very easy to continue experiments G2, G3, and G4 for an additional 20 years after a 50-year geoengineering period, so we suggest that this recovery period be part of the experiments and analyses.

The intended audience of this paper is much broader than the climate scientists who will actually perform the experiments. For that reason, we have omitted many of the details which are somewhat incidental to understanding the design and aims of the experiments. We refer the reader to a technical report (Kravitz et al., 2010) which more thoroughly describes the specifications under which the simulations should be run. This technical report is also expected to serve as a working document, which will discuss problems encountered and modifications to the protocol if that should become necessary.

Model Specifications

The models used should be the same as those used in the CMIP5 simulations. A fully coupled atmosphere and ocean general circulation model (AOGCM) is necessary for these experiments to properly assess the dynamic responses of the climate.

Each of the models will undoubtedly treat chemistry differently. Rasch et al. (2008b) provide a thorough discussion of the chemistry of stratospheric injection of sulfate aerosols. If a model cannot handle photochemical conversion of sulfate aerosol precursors into sulfate aerosols, an aerosol size distribution should be used. Some models will be able to inject SO_2 and calculate the resulting aerosols. Others will require the injection of aerosols, which they will then transport, or the complete specification of the aerosol distribution and radiative properties, which will be provided by the GeoMIP project team. In the G3 experiment, some models will specify a time-invariant sulfate aerosol size distribution while others (e.g., Heckendorn et al., 2009) will allow the aerosols to grow over time, which, in a realistic model, will lead to a reduction of the aerosol backscattering efficiency and an increase in the sedimentation rate. The differences between model results arising from different aerosol treatments will need to be evaluated and understood.

Models with detailed treatment of stratospheric chemistry (SPARC CCMval, 2010) typically are run with a specified seasonal cycle of the ocean. Their participation in GeoMIP, running the first 50 years of G1, G2, and G3 with a specified ocean, but particularly G3, will provide us with additional evaluation of the effects of stratospheric geoengineering on ozone chemistry.

The specifications outlined here may exclude certain modeling groups from participating in this complete suite of proposed experiments. However, we encourage these groups to participate in whatever capacity they are capable and to adhere to the experiment protocol as closely as possible. Although their results may not be directly comparable, they will undoubtedly be interesting and useful to this study.

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Table 1. A summary of the four experiments included in this proposal.

G1	Instantaneously quadruple the CO_2 concentration (as measured from preindustrial levels) while simultaneously reducing the solar constant to counteract this forcing (Figure 1).
G2	In combination with a 1% increase in CO_2 concentration per year, gradually reduce the solar constant to balance the changing radiative forcing (Figure 2).
G3	In combination with RCP4.5 forcing, starting in 2020, gradual ramp-up the amount of SO_2 or sulfate aerosol injected, with the purpose of keeping global average temperature nearly constant (Figure 3). Injection will be done at one point on the Equator or uniformly globally. The actual amount of injection per year can be based on Hansen et al. (2005) but may need to be fine tuned to each model.
G4	In combination with RCP4.5 forcing, starting in 2020, daily injections of a constant amount of SO_2 at a rate of 5 Tg SO_2 per year at one point on the Equator through the lower stratosphere (approximately 16-25 km in altitude) or the particular model's equivalent. These injections would continue at the same rate through the lifetime of the simulation (Figure 4).

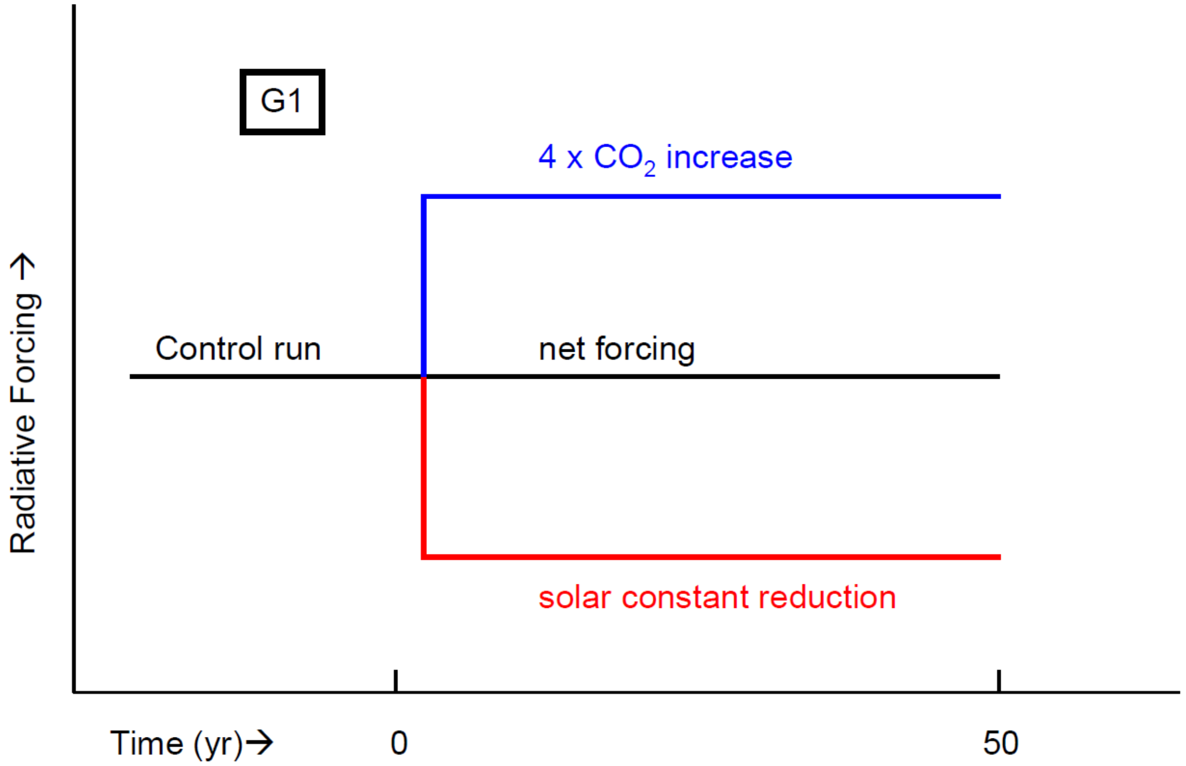

Figure 1. Schematic of experiment G1. The experiment is started from a control run. The instantaneous quadrupling of CO_2 concentration from preindustrial levels is balanced by a reduction in the solar constant until year 50.

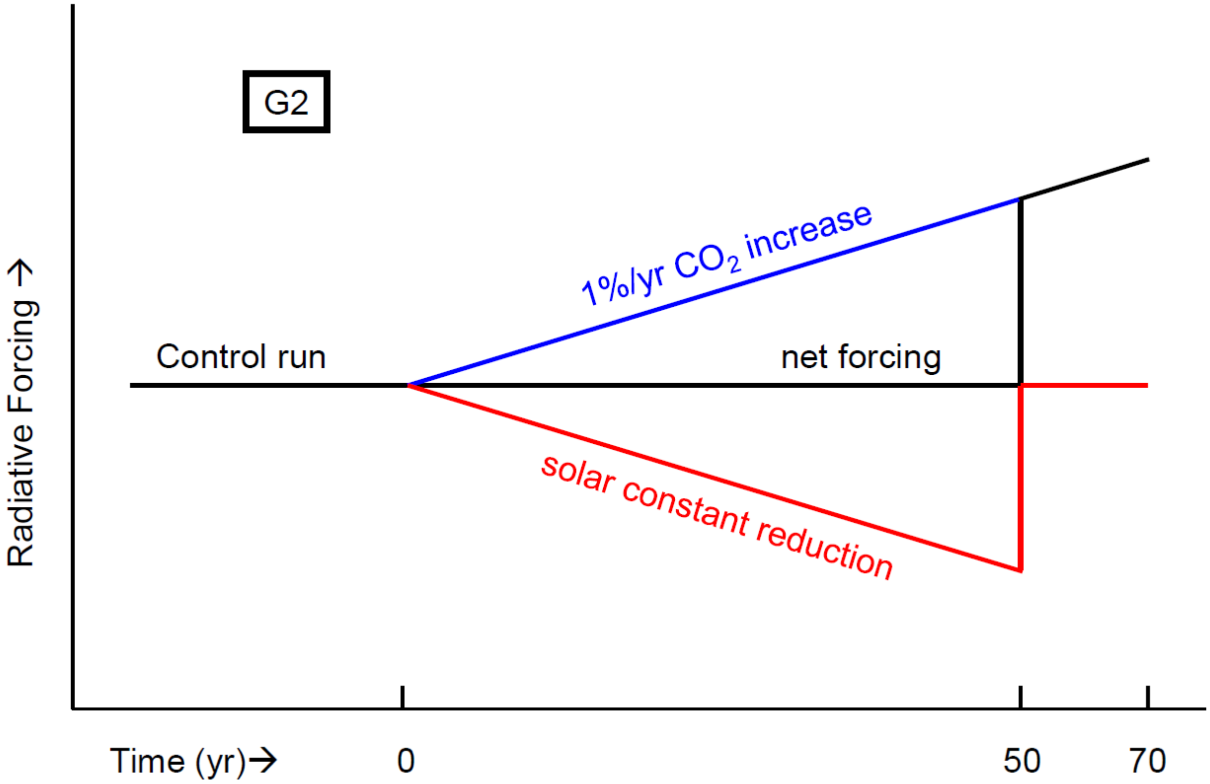

Figure 2. Schematic of experiment G2. The experiment is started from a control run. The positive radiative forcing of an increase in CO_2 concentration of 1% per year is balanced by a decrease in the solar constant until year 50.

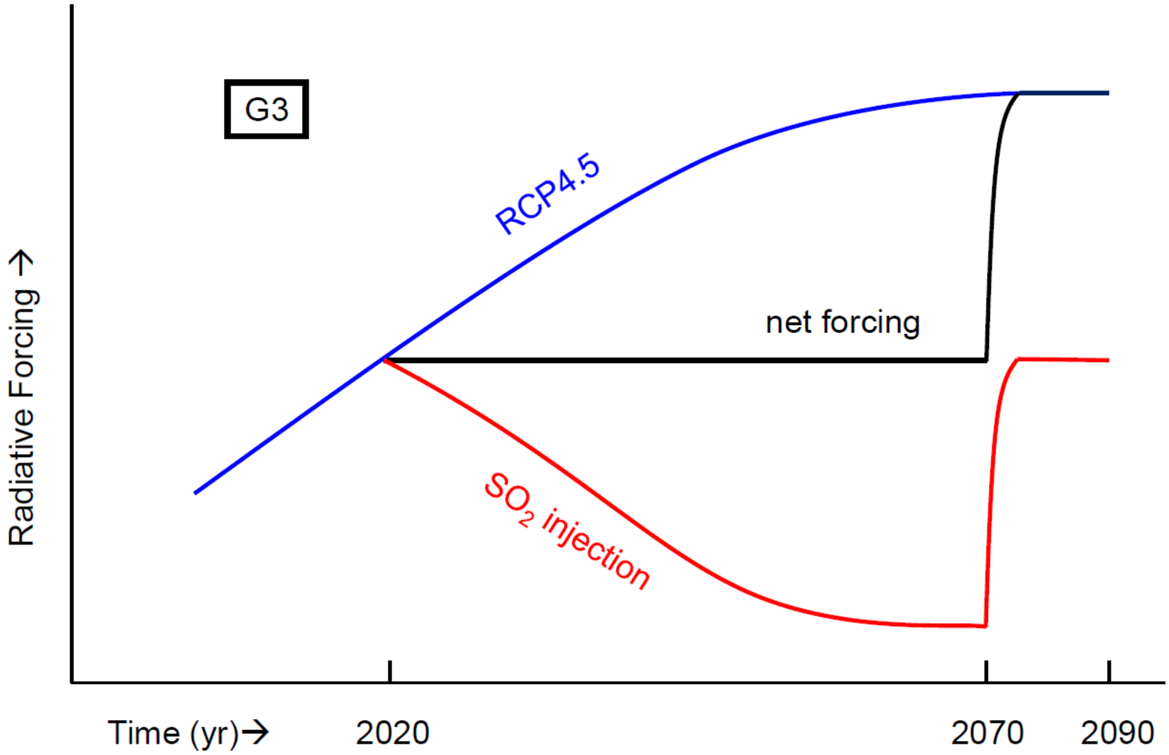

Figure 3. Schematic of experiment G3. The experiment approximately balances the positive radiative forcing from the RCP4.5 scenario by an injection of SO_2 or sulfate aerosols into the tropical lower stratosphere.

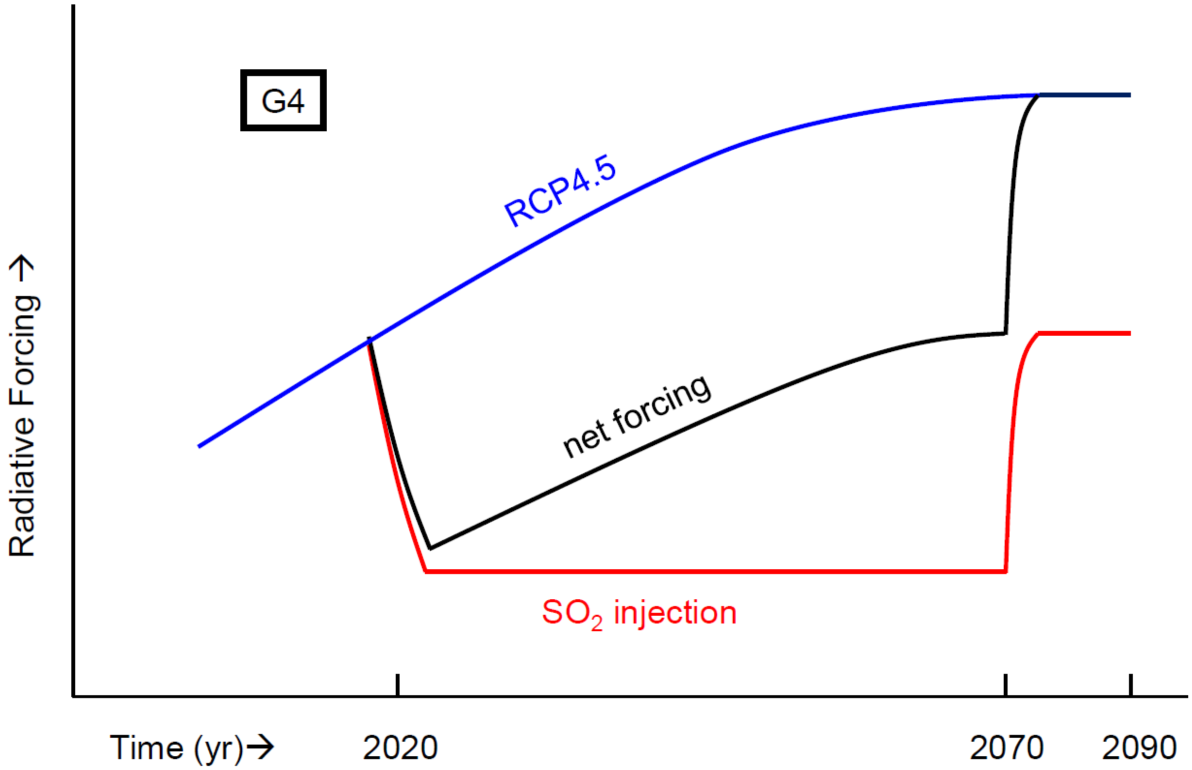

Figure 4. Schematic of experiment G4. This experiment is based on the RCP4.5 scenario, where immediate negative radiative forcing is produced by an injection of SO_2 into the tropical lower stratosphere at a rate of 5 Tg per year.