

## **Specifications for GeoMIP experiments G1 through G4**

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### **Version 1.0**

### **ABSTRACT**

We provide additional information necessary for climate modeling groups to conduct simulations G1 through G4 under the Geoengineering Model Intercomparison Project (GeoMIP) framework.

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Some of the modeling groups have asked us to provide additional details regarding the GeoMIP simulations G1 through G4 [Kravitz *et al.*, 2011]. We offer these guidelines, which lay out certain specifics.

## Section 1. CMIP5 reference scenarios

The GeoMIP scenarios are based on simulations that will be conducted as part of the CMIP5 suite of experiments [Taylor *et al.*, 2008]. We summarize the relevant CMIP5 experiments here. All four of these are classified as "CORE" experiments, meaning three ensemble members are recommended for experiments 4.1, 6.1, and 6.3. Experiment 3.1 is recommended to have only one ensemble member, but as this is a control run, assuming there is no trend in temperature or radiative forcing, time averaging can serve as an equivalent substitute for ensemble averaging.

**Experiment 3.1: Preindustrial control run.** The model has concentrations of all well mixed gases and, according to the model complexity, emissions or concentrations of short-lived (reactive) species fixed at preindustrial levels. Land use is also fixed at preindustrial levels. This experiment is to be run for 500 years after model spin-up.

**Experiment 4.1: RCP4.5.** This scenario follows prescribed RCP4.5 concentrations of well mixed gases and emissions or concentrations of short-lived species for the years 2000-2100. It is a continuation of the historical run.

**Experiment 6.1: 1% per year CO<sub>2</sub> increase.** Beginning at the preindustrial control (experiment 3.1), CO<sub>2</sub> concentrations increase at 1% per year, up to four times their preindustrial levels. This process will take approximately 140 years. All Earth system components are allowed to respond over this time period. Other forcings of climate change are unchanged.

**Experiment 6.3: 4xCO<sub>2</sub>.** Beginning at the preindustrial control (experiment 3.1), CO<sub>2</sub> concentrations are instantly quadrupled. Other forcings of climate change are unchanged. This experiment is to be run for 150 years.

## Section 2. Details for the two categories of experiments

The experiments G1-G4 can be broadly divided into two categories: reduction of the solar constant and introduction of stratospheric sulfate aerosols. Both of these categories require different treatments in the models, so we discuss the relevant details here.

### Reduction of the solar constant

This discussion applies to Experiments G1, G2, and G3solar (optional, see below). To conduct these experiments, the solar constant should be multiplied by a scalar uniformly across all wavelengths/spectra. The 11-year solar cycle should still be included, and no other changes should be made. We encourage those conducting simulations to remember that these experiments are meant to be simple!

## Introduction of stratospheric sulfate aerosols

This discussion applies to Experiments G3 and G4. These experiments depend upon each model's treatment of the sulfate aerosol processes. We cannot cover every detail, since the models often have quite different treatments, but we provide some guidelines here. *Kravitz et al.* [2011] suggested that each model conduct these experiments in the same manner as they simulate a volcanic eruption. However, this description is insufficient, so we suggest that as an overarching theme, each modeling group should conduct their simulations in the same way that particular model simulated the 1991 eruption of Mount Pinatubo, which injected 20 Tg of SO<sub>2</sub> into the lower stratosphere (16-25 km in altitude) [*Bluth et al.*, 1992].

The models with the most sophisticated sulfur treatment should be able to simulate injections of SO<sub>2</sub> at a single point, allowing the model to convert the SO<sub>2</sub> into sulfate aerosols and transport them via the general circulation. For these models, we recommend continuous injections of SO<sub>2</sub> at a single point on the equator at 0° longitude (although the actual longitude value does not particularly matter due to the zonal circulation), distributed through the altitude range 16-25 km. Models with complex microphysics need no further specification, as they will allow the aerosols to grow and coagulate on their own. However, some models may require further input of parameters, in which case we recommend using the same parameters as in the 1991 eruption of Pinatubo.

For example, the aerosol treatment in GISS ModelE [*Schimdt et al.*, 2006; *Koch et al.*, 2006] requires the input of an aerosol dry radius, and the model will hydrate this aerosol according to ambient humidity values. For their simulations of the 1991 eruption of Mount Pinatubo, *Oman et al.* [2006] used a dry radius of 0.35 μm, which hydrates to a sulfate aerosol size of 0.45-0.52 μm, which is in line with measurements by *Stothers* [1997]. However, according to the data of *Sato et al.* [2006] on which we base our discussion in the next paragraph, this range is slightly too small compared to the realized effective radii from the eruption of Pinatubo, which showed a peak effective radius (globally averaged) of 0.563 in September 1992. Therefore, when conducting GeoMIP simulations with GISS ModelE, we will use a dry radius of 0.38 μm. Other models may require different specifications, in which case the model should use whatever parameter is necessary from the eruption of Pinatubo.

Some modeling groups might use a model with a sophisticated sulfur treatment, but they may have less confidence in the stratospheric dynamics components of their model. In this case, the modeling group can prescribe a uniform distribution of SO<sub>2</sub> and allow the model to then convert the SO<sub>2</sub> into sulfate aerosols. This procedure is straightforward and needs no further description, but we remind the modeling groups proceeding in this fashion to inject an area-weighted amount into each horizontal grid box (i.e., tropical grid boxes should have more SO<sub>2</sub> injected into them than polar grid boxes).

Some other models may require a specification of the aerosol distribution and optical depth. For these models, we recommend using a spatial distribution of the aerosols taken approximately one year after Pinatubo, i.e. a monthly average from May 1992, which is soon after the eruption and a time by which the aerosols were evenly distributed [*Sato et al.*, 2006]. Each modeling group should then calculate the total mass

burden of sulfate aerosols at this particular time and apply a uniform scaling factor until the correct total mass burden for the geoengineering experiment is achieved. If the model can only simulate aerosol optical depth and has no estimate of total mass burden, we refer the modeling group to a webpage we have created which describes the procedure in more detail: <http://climate.envsci.rutgers.edu/GeoMIP/data/geomipaod.html>

Some other models may not have the spatial resolution required to adequately represent the aerosol distribution from the Pinatubo eruption. For these models, we suggest prescription of a uniform aerosol forcing. The peak forcing after the eruption of Pinatubo was in February 1992, with a globally averaged optical depth ( $\lambda=550$  nm) value of 0.149. We suggest the models that fit this category prescribe 1/4 of this value of optical depth, i.e. 0.03725.

### **Section 3. How to run GeoMIP experiments G1 through G4**

This section outlines the steps each modeling group will need to take to run the GeoMIP experiments G1 through G4. In this section, we use the terminology control run to specifically mean CMIP5 experiment 3.1, which is the preindustrial control run. We use the term reference scenario to indicate the specific greenhouse gas forcing that geoengineering is attempting to balance, i.e., CMIP5 experiments 4.1, 6.1, and 6.3.

Experiments G2, G3, G3solar (see below), and G4 should have three ensemble members, in parallel with the CMIP5 experiments upon which they are based. Conducting Experiment G1 with one ensemble member should be sufficient, but modeling groups are welcome to use three if they like. Since all of the CMIP5 experiments on which G1-G4 are based are run with three ensemble members, obtaining three different initial conditions files for the three geoengineering ensembles should not present any problems. However, if three different initial conditions files are not available, we invite each group to create three ensemble members in the way they usually do. Some models may be able to specify a seed for a random number generator. Others may need to choose three different Januaries from a control run. Any modeling group having particular difficulty with creating ensemble members will be handled on a case-by-case basis of consultation with the GeoMIP coordinators.

The iterative process described below for each experiment is imperfect and will undoubtedly result in a net radiation balance (TOA) that is not exactly 0. These simulations are long enough that any imbalance in radiative forcing would result in some temperature perturbations, which we should try to minimize. There could also be a small temperature change even for a perfectly balanced radiative forcing. The arguments here are based on the Goddard Institute for Space Studies Surface Temperature Analysis (GISTEMP) [e.g., Hansen *et al.*, 2006].

The median predicted value of climate sensitivity is 3°C for a doubling of CO<sub>2</sub> [e.g. IPCC, 2007], which corresponds to a radiative forcing at the tropopause of 3.7 W m<sup>-2</sup> [IPCC, 2001]. This gives us a linearized climate sensitivity of 0.81 °C m<sup>2</sup> W<sup>-1</sup>.

It would be reasonable to require our radiation balance error, and subsequent temperature perturbation, to be within the realm of natural variability and measurement error. GISTEMP values in 2000, chosen because an error bar is given, show a globally averaged surface air temperature anomaly of 0.5±0.05°C. Therefore, we would like to

limit our temperature perturbation to no more than 0.05°C in magnitude. By the climate sensitivity argument above, this corresponds to an error in radiative forcing of  $\pm 0.06 \text{ W m}^{-2}$ . Given the potential variability of precision, we round this to  $0.1 \text{ W m}^{-2}$ .

Ideally, the preindustrial control run will be in radiative balance, so there will be no net radiation anomaly (TOA) in this run. However, expecting this would be impractical, so we expect some TOA anomaly to occur in the control run. Therefore, it would not make sense to have geoengineering perfectly balance the net TOA radiation (within  $\pm 0.1 \text{ W m}^{-2}$ ), as this will not take into account the potential trend in the control run. Therefore, we would like the geoengineering run to have a net radiation balance (TOA) of within  $\pm 0.1 \text{ W m}^{-2}$  the net radiation balance of the control run.

Based on past experience, we believe there is a particular order in which the experiments should be run which will make calculations much easier. This order is G1, G2, G4, G3solar, and finally G3. Therefore, we list the experiments in this order below. Each experiment except G1 should be run for 50 years, followed by 20 years of cessation of geoengineering, as described in *Kravitz et al.* [2011]. This 20 years of cessation is not prescribed for Experiment G1, but modeling groups are welcome to include it if they like.

## Experiment G1

This experiment will use CMIP5 experiment 6.3 as the reference scenario, which is a quadrupling of CO<sub>2</sub> concentrations from the preindustrial control. We recommend each modeling group proceed as follows:

1. Evaluate the steady state net radiation (TOA) difference between the reference scenario (4xCO<sub>2</sub>) and the control run (preindustrial control).
2. Using the formula  $\Delta RF = \frac{S_0}{4}(1 - \alpha)$ , where  $\alpha$  is the planetary albedo (specific to the model), set  $\Delta RF$  equal to the value calculated in step 1 and solve for  $S_0$ .
3. Perform a ten year G1 run with CMIP5 experiment 6.3 (4xCO<sub>2</sub>) as the reference and the solar constant reduced by the value found in step 2.
4. Evaluate the net radiation (TOA) in the experiment performed in step 3. If the net radiation balance (TOA) is less than  $0.1 \text{ W m}^{-2}$  different from the net radiation balance of the control run, continue the run. If not, adjust the value of the solar constant reduction and reiterate step 3. Past experimentation has shown that if the model can be balanced for the first 10-15 years, it will stay balanced for the entire 50 year run. However, if the first ten years are in balance (within  $0.1 \text{ W m}^{-2}$ ), any small drifts beyond this are acceptable.

## Experiment G2

This experiment will use CMIP5 experiment 6.1 as the reference scenario, which is a 1% increase in CO<sub>2</sub> concentrations per year from the preindustrial control. The modeling groups should proceed as follows:

1. Using the value obtained in Experiment G1, estimate a linear reduction in the solar constant to compensate for increasing CO<sub>2</sub> concentrations. Recall that even though CO<sub>2</sub> concentrations are increasing exponentially, radiative forcing increases as the log of concentration, so the solar constant should be decreased linearly.
2. Perform a ten year G2 run using this slope. If the net radiation balance (TOA) is within 0.1 W m<sup>-2</sup> of the net radiation balance of the control run, continue the run. If not, adjust the value of the estimated slope and reiterate. Past experimentation has suggested that any temperature drifts in Experiment G2 will be very small until at least year 20.

## Experiment G4

This experiment will use CMIP5 experiment 4.1 as the reference scenario, which is RCP4.5. Unlike the other experiments, Experiment G4 does not seek a zero net change in TOA radiation balance. We recommend simulating 1/4 of a Pinatubo eruption per year, in whatever sense that means for the particular model (see Section 2):

- For models that can handle SO<sub>2</sub> injections: This is equivalent to 5 Tg of SO<sub>2</sub> per year, or 0.0137 Tg SO<sub>2</sub> per day, but with SO<sub>2</sub> injected continuously into the lower stratosphere (16-25 km) on the Equator.
- For models that need to specify an aerosol mass distribution: The *e*-folding lifetime of stratospheric sulfate aerosols is approximately one year [e.g., *Robock et al.*, 2008], meaning 5 Tg of SO<sub>2</sub> injection per year, which becomes 7.5 Tg sulfate aerosols per year, is equivalent to an equilibrium mass burden of 7.5 Tg sulfate aerosols. Therefore, we ask the modeling group to evaluate the June 1992 Pinatubo aerosol distribution (see Section 2) by calculating the total atmospheric mass burden and scaling it to reach a total mass burden of 7.5 Tg.
- For models that need to specify a distribution of aerosol optical depth: Refer to the website specifically prepared for these models: <http://climate.envsci.rutgers.edu/GeoMIP/data/geomipaod.html>
- For models that need to specify a uniform aerosol distribution: Prescribe a uniform aerosol optical depth of 0.03725.

## Experiment G3solar (optional)

This experiment was suggested by Simone Tilmes and Mike Mills. Not only will this experiment be very useful, but it will also alleviate certain difficulties they encountered while conducting their simulations. The idea of this experiment is that it will be conducted in the same manner as experiment G3, but instead of using sulfate aerosols to balance the increase in greenhouse gas radiative forcing, the balance will be obtained via a reduction of the solar constant. Therefore, this too will use CMIP5 experiment 4.1 as the reference scenario, which is RCP4.5.

In the original specification of the four experiments, there was no experiment which prescribed a reduction in the solar constant combined with a present-day climate as opposed to a preindustrial climate. The climate, chemistry, land surface, and important feedbacks, among many other things, are vastly different in a present-day climate than a preindustrial climate. Since most of these processes are interactive in an AOGCM, the usefulness of estimating radiative forcing and efficacy in Experiments G1 and G2 and applying it to Experiments G3 and G4 is quite limited. Therefore, G3solar serves as a useful transition from G1/G2 to G3/G4. Since this experiment was not part of the original suite, and four experiments may already place an unduly large burden upon the modeling groups, we recommend this experiment remain optional, although we stress its usefulness in the context of GeoMIP.

We expect the responses to greenhouse gas forcing to be similar across all models. Moreover, we are interested in keeping this experiment rather simple. Therefore, we suggest all modeling groups who wish to participate in this experiment conduct it as follows:

1. The values of anthropogenic radiative forcing for the reference scenario RCP4.5 are provided in the table here: <http://climate.envsci.rutgers.edu/GeoMIP/data/G3solar.html>. Using the values in Column 4 (TOTAL\_ANTHRO\_RF), calculate  $S_0$  for the individual model's albedo via the formula  $\Delta RF = \frac{\bar{S}_0}{4}(1 - \alpha)$  for each year. The albedo should be an average over the period 2010-2030.
2. Subtract this number from the value calculated for the year 2020.
3. In each year 2020-2069, reduce the value of the solar constant by the number calculated in Step 2.

We note that unlike in experiments G1 and G2, the radiation balance via this method may not be within the  $0.1 \text{ W m}^{-2}$  threshold.

### **Experiment G3**

This experiment will also use CMIP5 experiment 4.1 as the reference scenario, which is RCP4.5. This is the most complicated experiment in the suite, so for ease of simulation and to ensure all modeling groups are performing a similar experiment, we have taken a simple approach to this simulation.

1. Using the results from experiment G4, estimate the sulfate aerosol radiative forcing for a given amount of  $\text{SO}_2$  injection. This can be done with a short simulation involving a double radiation call if such simulation specifications are not automatically included in the model setup. Each group is responsible for obtaining the necessary forcing diagnostics to estimate this quantity. Some of the quantities in the "aero" tab of the CMIP5 standard output (see Section 4 below) will also be useful in diagnosing sulfate aerosol radiative forcing.

2. Using the table provided as in Step 1 of G3solar, determine the amount of sulfate aerosol needed to balance the greenhouse gas forcing given in the table, obtaining a prior estimate time series of SO<sub>2</sub> injection throughout the lifetime of the simulation.

We recognize that these quantities are difficult to estimate, and balancing to within the 0.1 W m<sup>-2</sup> tolerance may not be achieved, although it remains unclear as to how well we can estimate the degree of balance in the first place.

#### **Section 4. Model Output**

CMIP5 has already determined a list of variables to be included as the standard output for that project [CMIP, 2010]. The AOGCMs participating in GeoMIP are likely the same models that would participate in CMIP5, and thus are already set up to output this standard list of variables. We recommend that all participating models conform their output to this list. This would make analysis easier and more uniform. Also, great care was taken to assemble a list of output that would address important scientific questions for the next IPCC report. Therefore, omissions from this list, although innocuous in purpose, may have implications for those who wish to analyze the output from GeoMIP, thus preventing the assessment of certain implications of geoengineering.

That said, the CMIP5 list is rather extensive, and conforming to this list may prove difficult for certain modeling groups who do not plan to participate in CMIP5 and have thus not spent time developing their model to cater to this standardization. Table 1 is a list which we designate as the minimum subset of these variables which we would require from participants in GeoMIP. Any modeling group finding this requirement difficult to meet should contact us for special consideration.

We have also been in discussion with various groups and concerned parties regarding additional variables they would like to be saved. We have included these variables in Table 2, along with the groups that have requested them. These variables are not mandatory but are highly recommended.

All of the model output will be submitted to and archived at PCMDI for public access to the broader scientific community. To assure the intellectual rights of the GeoMIP community, we have requested a temporary embargo on the model output, allowing only the participants to access it for the immediate future, allowing sufficient time for analysis and publications by the parties directly involved. We would like the results of GeoMIP to be included in the IPCC Fifth Assessment Report, to be published in 2013. Therefore, we have included a set of deadlines (Table 3) relevant to GeoMIP to ensure our participation in this report.

#### **Acknowledgments**

We thank Pete Irvine and Andy Jones for their help in initial tests of this protocol, as well as their invaluable suggestions and feedback. We also thank Simone Tilmes and Mike Mills for their suggestion, description, and test runs of Experiment G3solar.



Additionally, we thank the participants (other than the ones previously listed) in the GeoMIP Stratospheric Aerosol Geoengineering Workshop, held at Rutgers University on 10-12 February 2011: May Akrawi, Lauren Baba, Jean-Loup Bertaux, Diana Boukaram, Peter Braesicke, Alexander Chernokulsky, Simon Driscoll, Kathryn Emmerson, Piers Forster, Stephan Fueglistaler, Jim Haywood, Michio Kawamiya, Mark Lawrence, Graham Mann, Ulrike Niemeier, Phil Rasch, Georgiy Stenchikov, Ronald Stouffer, Masahiro Sugiyama, Jean-Paul Vernier, Matt Watson, and Lili Xia.

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**Table 1.** Standard output for GeoMIP. The categories listed are standard categories listed in CMIP [2010]. If a category is not listed, output of variables from that category is not compulsory for GeoMIP, but we encourage the modeling groups to output all CMIP5 variables if possible.

<b>CMIP5 Category</b>	<b>Variables</b>
dims	all
fx	all
amon	all
omon	priority 1 variables only
lmon	priority 1 variables only
limon	all
oimon	all
aero	all
day	all

**Table 2.** Additional variables requested for GeoMIP. These variables are not mandatory but are highly recommended. Some of the variables listed are part of the standard CMIP5 output [CMIP, 2010], but we choose to emphasize them here and highlight the particular groups that have requested them. Fields marked by an asterisk (\*) are included in CMIP5 standard output, but the fields are saved with insufficient frequency. Fields marked by a cross (†) are part of the CFMIP output, which may not be performed by all modeling groups.

Variable	Frequency of output	Group requesting this variable	Already included in CMIP5 standard output
3-D surface area density of aerosols ( $\mu\text{m}^2 \text{cm}^{-3}$ )	monthly	GeoMIP (general)	no
stratospheric aerosol optical depth (550 nm)	monthly	GeoMIP (general)	no
mass and number density for all aerosol size classes	monthly	microphysics	no
photosynthetically active radiation	daily	agriculture	no
UVB	monthly	GeoMIP (general)	no
stratospheric radiative heating rates	monthly	GeoMIP (general)	yes†
aerosol budget terms in the stratosphere (levels)	monthly	GeoMIP (general)	no
maximum temperature	daily	agriculture	yes
minimum temperature	daily	agriculture	yes
average temperature	daily	agriculture	yes
total precipitation	daily	agriculture	yes
total solar radiation (incoming TOA)	daily	agriculture	yes*
surface shortwave radiation (total)	daily	agriculture, ecosystems, solar power	yes*
surface shortwave radiation (diffuse)	daily	agriculture, ecosystems, solar power	yes*
ocean heat content	monthly	oceanography	no
CH <sub>4</sub> , O <sub>3</sub> , OH, NO <sub>x</sub> , ClO <sub>x</sub>	monthly	chemistry	some

**Table 3.** Relevant deadlines for GeoMIP.

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<b>Date</b>	<b>Comments</b>
October 2011	All groups should have completed experiments G1 and G2 by this time.
January 2012	All groups should have completed experiments G3 and G4 by this time.
February 2012	Second GeoMIP workshop (possibly held at UK Met Office Hadley Centre, Exeter)
July 2012	IPCC deadline for submitted papers

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