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Temperature and precipitation responses to a stratospheric aerosol geoengineering experiment using the Community Climate System Model 4

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Summary

As the global climate continues to change it may become critical to explore possibilities for climate intervention and remediation to counteract warming by greenhouse gases. One such 'geoengineering solution' proposes to inject reflective aerosol particles into the atmosphere to decrease insolation, the amount of radiation coming from the sun received by the Earth. Given constraints due to a lack of technology and restricted physical experimentation, we study the unintended potential consequences of this experimental solution by examining the temperature and precipitation response to historical scenarios, projected radiative forcing, and idealized geoengineering scenarios to counteract radiative forcing due to human influences, using the Community Climate System Model version 4, CCSM4. The model projects increased temperature globally, increased precipitation in the Tropical Pacific, and decreased precipitation in some semi-arid regions if climate change continues without mitigation. Although these changes are not as severe with geoengineering, global temperature and precipitation are still redistributed globally. This research helps to understand the possible effects of geoengineering on the radiative balance affecting the Earth's temperature and hydrologic cycle.

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Introduction

The study of climate engineering, also known as "geoengineering," explores various potential solutions for counteracting global climate change in case mitigation efforts to reduce carbon dioxide (CO_2) emissions are insufficient. Many geoengineering strategies have been suggested including altering the CO_2 concentration in the atmosphere or reducing insolation, the amount of radiation coming from the sun received by the Earth (1). One of the most discussed geoengineering solutions is to inject sulfate aerosol particles into the stratosphere to counteract the radiative forcing, the change in energy received by the earth and radiated back to space from greenhouse gases.

Low concentrations of sulphate aerosols are typically present in the stratosphere due to the transportation of natural and anthropogenic sulphur-bearing compounds from the troposphere (2). However, when large quantities of sulphate aerosols are added to the stratosphere, planetary albedo, the Earth's reflectivity, increases causing globally-averaged temperatures to decrease. Since we are not sure how the climate will react to this proposed geoengineering strategy, we need to understand all the possible outcomes and uncertainties that may arise from it.

Researchers are hindered in determining the full range of possible effects produced when large quantities of sulfate aerosols enter the atmosphere because there is a lack of technology and restricted physical experimentation. Physical experimentation is limited because we are currently unable to flawlessly replicate the Earth's physical conditions in material or computer models. We are also limited because we cannot conduct experimental trials globally and risk the potential perils associated with such experiments. Another limitation is the lack of an international political framework for geoengineering experiments (3). Although researchers are not able to physically test geoengineering experiments globally, numerical climate models provide a way to explore the unintended consequences that may arise from stratospheric aerosol loading before implementing such a project on a large scale. Global climate modeling provides a method for testing plausible outcomes that may arise from a geoengineering experiment.

The concern of this investigation is the potential stratospheric aerosol loading has to disrupt the hydrologic cycle and global surface temperatures. We are particularly concerned with temperature and precipitation changes due to decreased insolation because large quantities of stratospheric sulfate aerosols, like those emitted though volcanic eruptions, have the potential to increase planetary albedo causing global climate cooling and precipitation changes (4). In the past, these eruptions have resulted in temporary global cooling that dissipates once the aerosols are removed from the atmosphere. Increased stratospheric sulfate aerosols from volcanic eruptions have also impacted river runoff, crop yield, and drought (4).

We explore the possible unintended temperature and precipitation changes as a result of stratospheric aerosol loading by examining the response of the

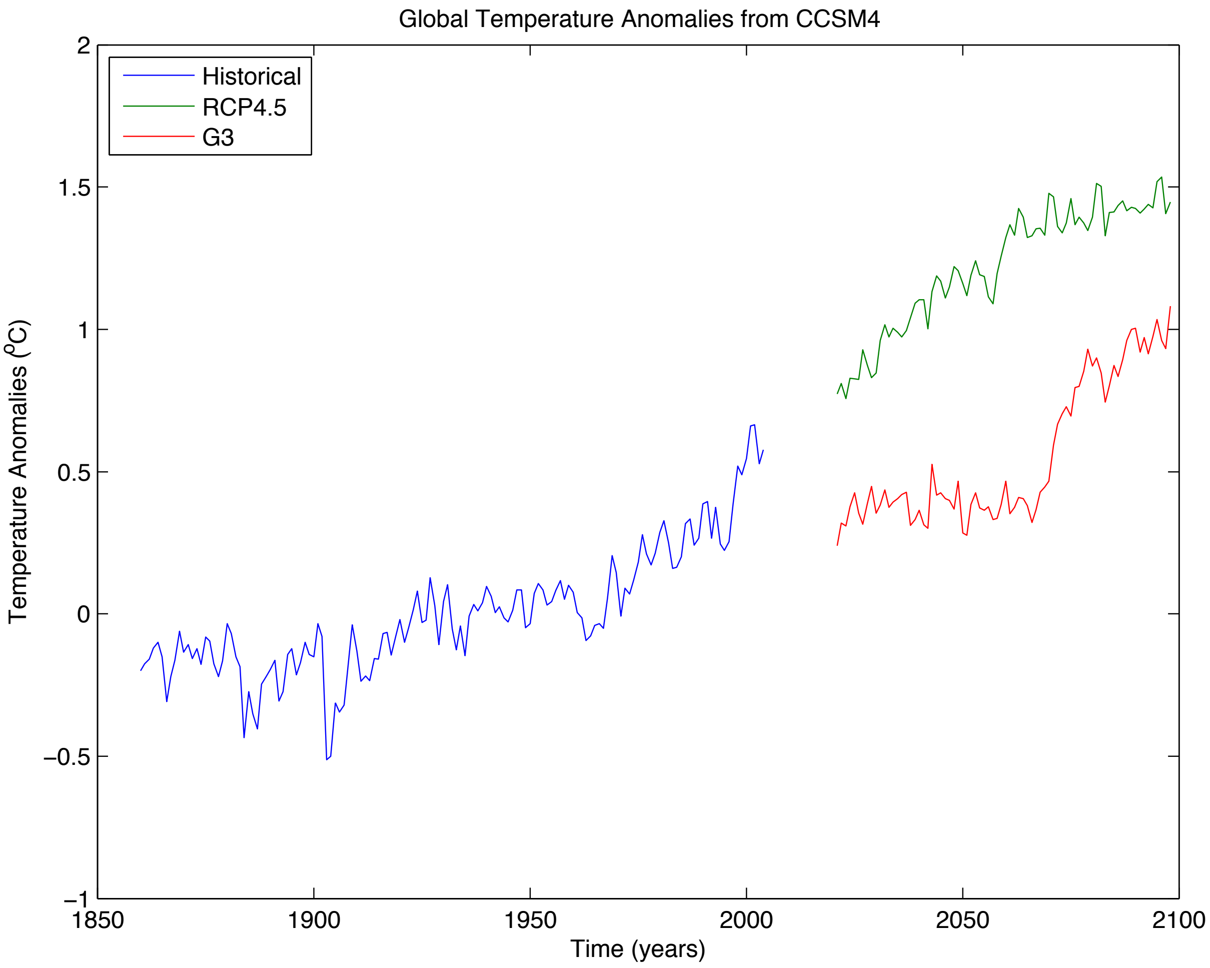

Figure 1. Globally averaged surface temperature anomalies from 1850 to 2100 in CCSM4. The blue line represents temperature anomalies (with respect to the 1850-2005 baseline) due to estimates of historical forcing, the green line represents the projected temperature change due to RCP4.5 forcing, and the red line represents temperature change due to the net forcing after the G3 simulation. The RCP4.5 forcing and the G3 simulation begin in 2020.

Community Climate System Model version 4 (CCSM4) to the computer simulation of the aerosol loading experiment. The CCSM4 is a general circulation model able to numerically simulate possible future outcomes based on forced changes to an initial condition that is prescribed within the model. CCSM4 is one of a number of models currently being used to study climate change as part of international efforts orchestrated by the Intergovernmental Panel in Climate Change (IPCC).

We find that the CCSM4 projects increased temperature globally and a redistribution of global precipitation if climate change is not mitigated.

Results

To understand the radiative balance effecting the Earth's hydrologic cycle and temperature distribution, we generated a CCSM4 output used in three scenarios representative of various alternative stratospheric aerosol loading simulations. The twentieth century scenario, the representative concentrated pathway (RCP) 4.5 scenario, and then Geoengineering Model Intercomparision Project (GeoMIP) scenario were compared using climatologically averaged temperature and precipitation maps (6, 8).

We have investigated the possible unintended consequences of anthropogenic influences on Earth's radiative budget by comparing the G3 Solar scenario to historical scenario. **Figure 1** shows surface temperature anomalies, the average amount any given temperature will be away from the average temperature, modeled in CCSM4 in degrees Celsius. Since 1850, average surface temperatures have risen approximately a degree and a half in the model, which is consistent with reality (9). The variance shown in the graph is due to interannual variability as well as natural phenomena such as volcanic eruptions. The break in the graph between 2011 and 2020 is due the fact that the geoengineering (G3) scenario does not begin until 2020. Once the RCP4.5 scenario begins in 2020, the temperature increases approximately half a degree in the next 40 years. With the G3 counteraction of the projected temperature increase, the net result shows little if any warming until around 2070 when the

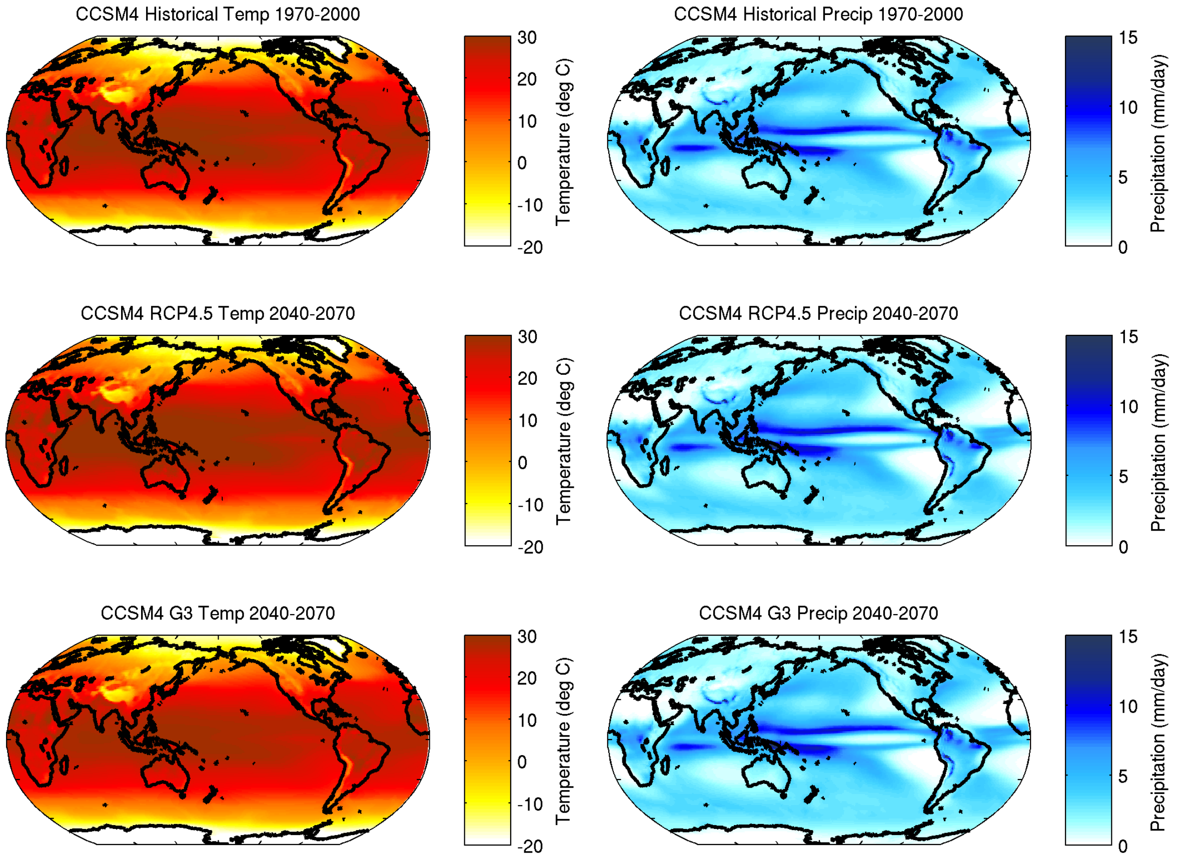

Figure 2. The average temperature (left) and precipitation (right) for the historical simulations from 1970-2000 (top), projected RCP4.5 forcing from 2040-2070 (middle), and net forcing after the G3 simulation from 2040-2070 (bottom), in CCSM4.

G3 forcing is removed and the greenhouse gas forcing of the RCP4.5 scenario dominates. From 2070 to 2100, average surface temperatures increase. During these 30 years, surface temperatures were projected to increase approximately a degree and a half.

We then examined the annually-averaged temperature and precipitation maps for the historical, RCP4.5, and G3 scenarios. **Figure 2** shows the average temperature maps in degrees Celsius (left) and precipitation in millimeters per day (right). The historical scenarios of annually-averaged temperatures from 1970-2000 show warmer temperatures along the tropics with climatologically cooler temperatures in Polar Regions (top left). The coolest regions are the poles, the Himalayan Mountains, and the Andes Mountain Range off the coast of South America. Sea surface temperatures are generally warmer than land surface temperatures. The RCP4.5 and implementation of the G3 scenario show similar pictures.

Average precipitation maps from the historical scenarios show that precipitation is greatest in the tropics, specifically in the Tropical Pacific (**Figure 2**; top right). There is generally less precipitation over land than sea, with the least amount of precipitation in the Sahara Desert and near the North Pole. There tends to be less precipitation in the Eastern Pacific than the Western Pacific. Due to the RCP4.5 forcing from 2040-2070 there is an increase in precipitation at the mid-latitudes (middle right). There is also a slight increase in the Walker Circulation, air flow along tropical regions moving east to west, shown by decreased precipitation in the Eastern Pacific and increased precipitation in the Western Pacific. The net precipitation after the G3 scenario shows only minute changes from the historical scenarios. There is a slight decrease in precipitation along the mid-latitudes (bottom right).

Figure 3 shows the difference between the forcings with regard to temperature in degrees Celsius (left), and precipitation in millimeters per day (right). Due to the RCP4.5 forcing, there is an increase in the average annual temperature between the RCP4.5 projected temperature and the historical temperature (top left). Although the temperature increase is globally distributed, the increase is most prominent over land, specifically in the poles. There is an approximately five-degree average increase near the North Pole, a two-and-a-half-degree average increase over land, and a one degree average increase over the majority of the sea. The G3 model run shows significant temperature redistribution from historical records (middle left). Approximately a one-degree average warming is experienced over land and a five-degree average warming is experienced near the

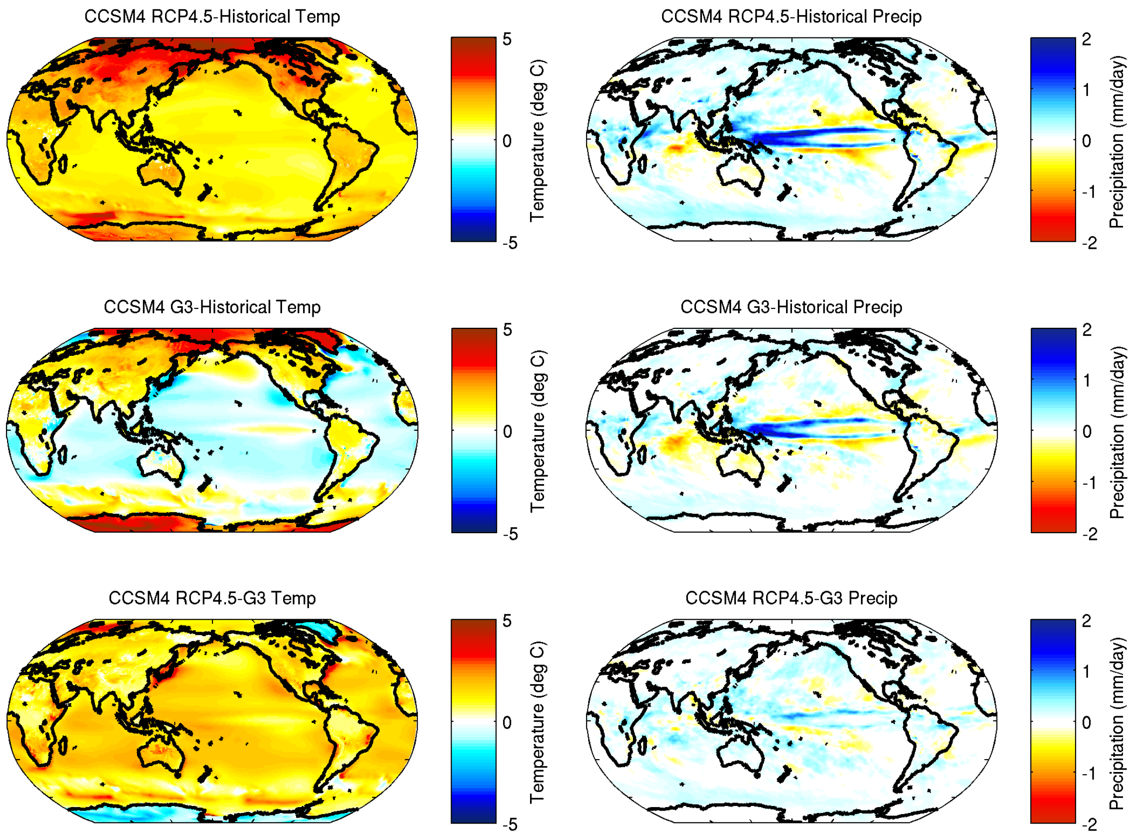

Figure 3. The change in temperature (left) and precipitation (right) between RCP4.5 and historical simulations (top), the G3 simulation and historical simulations (middle), and RCP4.5 and the G3 simulation (bottom), in CCSM4.

poles. There is a one-degree decrease in average temperature over the majority of all oceans, and a two-degree temperature decrease near the mid-latitude coasts. However, the seas located near both poles and in the Tropical Pacific experience approximately one degree of warming. Compared to the RCP4.5 forcing, the amount of warming not experienced because of the decreased solar constant modeled by the G3 scenario (bottom left), is approximately one degree over land and two degrees over the mid-latitude seas.

The difference in mean precipitation between the RCP4.5 projected precipitation and the historical precipitation shows a general increase in precipitation of approximately half a millimeter per day, with the exception of in the tropical oceans and in the southern mid-latitude (**Figure 3**; top right). Along the Tropical Pacific, the increase in precipitation is approximately two millimeters per day. Directly to the north and south of the Tropical Pacific, precipitation decreases due to the RCP4.5 forcing. There is no change in precipitation in the southern mid-latitude. In the G3 scenario, we see only slight increases in precipitation globally (middle right). The Tropical Pacific still experiences increased precipitation with decreases directly to the north, south, and Indian Ocean. The amount of precipitation not experienced due to the G3 scenario is approximately half a millimeter per day along much of the mid-latitudes and approximately one millimeter per day in the Tropical Pacific (bottom right).

Discussion

It is clear from our results that decreasing the solar constant redistributes and reduces warming, yet it does not do so in a spatially uniform way. Moreover, it redistributes precipitation. The top row in **Figure 3** shows the amount of temperature and precipitation increase we will experience, from present, based upon RCP4.5. The middle row represents the amount of temperature and precipitation change experienced with the implementation of the G3 scenario. The bottom row shows the amount of warming and precipitation we will not experience if geoengineering is implemented.

As shown in **Figure 3**, no mitigation, with the assumed RCP4.5 forcing, will result in warmer temperatures. These temperature changes are greatest at the poles. Precipitation will increase in the Tropical Pacific and decrease in certain semi-arid regions of the globe. The 2013 IPCC showed that using geoengineering to counteract atmospheric warming, caused by increased CO_2, will change the atmospheric vertical heating profile. This leads to less cooling in the tropopause, a boundary between the troposphere and the stratosphere. Since precipitation and temperature share a direct relationship, the decrease in cooling from geoengineering corresponds to a decrease in rainfall (10). This decrease in temperature and precipitation is manifested in the spatial patterns represented by the difference between the RCP4.5 and G3 scenarios. Even though temperature and precipitation are predicted to redistribute globally with the G3 scenario, temperature and precipitation changes are more severe without mitigation. A spatial redistribution of temperature and precipitation can impact a region politically, biologically, and socioeconomically. Geoengineering as a form of mitigation has the potential to lessen climate change if the associated consequences are managed.

It is important to note that global climate models exhibit some biases and are not entirely consistent with historical records. The models consistently produce precipitation results that are generally too wet overall (9, 11). Models also tend to reduce precipitation in dry regions and increase precipitation in damp regions (5). Many models do not accurately represent the Tropical Pacific. Models tend to depict this region with a two-band-like pattern of precipitation, as shown in the right column of **Figure 3**. This region should be depicted with a single band of increased precipitation rather than two. This bias is represented in our results shown in the right column of **Figure 3**. These considerations are particularly relevant to the problem of geoengineering because the projected changes look like the biases.

Although the modeled responses are not perfect, global climate models are the best option for exploring the real potential outcomes of deliberately changing insolation because they do not pose actual risks to humans and ecosystems like field experiments might. Moreover, because we have a good idea of what model biases exist, we minimize the effect of the model biases by using multiple models and by looking at overall trends rather than specific spatial patterns. The work here helps to explore possible outcomes in regard to temperature and precipitation, with or without geoengineering, and document the potential benefits of it.

Methods

We generated CCSM4 output from data generated as a part of the internal CMIP5/GeoMIP activities by the Climate Change and Variability Working Group (CCVWG) in the Climate and Global Dynamics Division (CGD) at NCAR, and used this information in three scenarios representative of various alternative stratospheric aerosol loading simulations. These scenarios were compared to understand the effect a stratospheric aerosol loading simulation would have on the Earth's radiative balance, effecting global temperature and the hydrologic cycle. Thirty-year periods were extracted from each of the following scenarios so that they could be compared with each other in a consistent way.

For the first scenario, we examined twentieth century temperature and precipitation simulated by CCSM4 (5). Although the complete scenarios described in Gent *et al*. (5) begin in 1850 and end in 2005, we only examined global temperature and precipitation from 1970-2000. We chose to evaluate 1970-2000 because it represents a typical post-industrial 30-year period and because it allows for comparison with the following scenarios run over 30 years.

We next examined the projected temperature and precipitation during 2040-2070 by using the RCP4.5 (6). The RCP scenarios were designed to provide four plausible radiative forcing trajectories based on a range of socioeconomic, environmental, and technological trends. The four trajectories are RCP 2.6, RCP4.5, RCP 6.0, and RCP 8.5 (6). For this scenario, we used RCP4.5 because it represents an intermediate radiative forcing of 4.5 Wm-2 with stabilization after 2100. The RCP4.5 forcing is a default case against which the GeoMIP models are compared representing a counterfactual case. The 2040-2070 time span is chosen because it is when the RCP4.5 forcing has the greatest increase. For an overview of the response of CCSM4 to this forcing (and other scenarios) see Meehl et al. (7). RCP4.5 data was obtained through NCAR's local mirror of the Earth System Grid Federation (ESGF) CMIP5 data archive.

For the last scenario we used one of the GeoMIP scenarios (8). GeoMIP encompasses 4 options: G1, G2, G3, and G4. G1, G2, and G3 are all designed to produce an annual mean global radiative balance at the top of the atmosphere while G4 involves a constant annual rate of stratospheric injection starting in 2020 (8). For this simulation, we are only using the G3 "Solar" option because it gradually "turns down" the solar constant to counteract RCP4.5 forcing without changing the radiative balance by implementing aerosols. The G3 Solar scenario starts in 2020 by gradually decreasing the solar forcing to balance the anthropogenic forcing, ostensibly keeping the planetary temperature fairly constant. It is therefore representative of an "idealized" geoengineering simulation because it makes no assumptions about what kind of technology (e.g., aerosols, space mirrors, or other mechanisms) would be used to balance the increased radiative forcing from greenhouse gases. We examined the G3 scenario in CCSM4 over 30 years spanning 2040-2070.

We further analyzed these three scenarios by using maps of climatologically-averaged temperature and precipitation from each experiment. We created these maps, using the MathWorks numerical programming language MATLAB, by taking the average value of temperature and precipitation through time at each point in the output from CCSM4 (provided on a 1 x 1 degree latitude x longitude grid). We then performed the following analysis: (1) we subtracted the twentieth century historical model maps from the projected RCP4.5 maps; (2) we subtracted the historical model maps from the G3 maps; and (3) we subtracted the G3 scenario maps from the RCP4.5 model maps.

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The data used in this study is generated as part of the international CMIP5/GeoMIP activities by the NCAR CGD CCVWG. We especially thank Gary Strand for assistance and early access to the data. The simulations are all archived on the ESGF (https://pcmdi9.llnl.gov/esgf-idp/idp/) as follows: for the "historical" and "rcp4.5" scenarios, data were generated using CCSM4 with 1850-2005 and future forcing boundary conditions. Both scenarios were from the "r1i1p1" runs. The G3 scenario is also archived in the ESGF under the GeoMIP project as CCSM4 simulation "G3S_r1i1p1."

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