COVER SHEET FOR PROPOSAL TO THE NATIONAL SCIENCE FOUNDATION

PROGRAM ANNOUNCEMENT/SOLICITATION NO./CLOSING DATE/if not in response to a program announcement/solicitation enter NSF 11-1

NSF 11-1

FOR NSF USE ONLY

NSF PROPOSAL NUMBER

1157525

FOR CONSIDERATION BY NSF ORGANIZATION UNIT(S) (Indicate the most specific unit known, i.e. program, division, etc.)

AGS - GEO/ATM - Climate & Large-Scale Dynamics, (continued)

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NEW BRUNSWICK, NJ. 089018559

NAME OF PRIMARY PLACE OF PERF

Rutgers University New Brunswick

ADDRESS OF PRIMARY PLACE OF PERF, INCLUDING 9 DIGIT ZIP CODE

Rutgers University New Brunswick
14 College Farm Road
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IS AWARDEE ORGANIZATION (Check All That Apply) (See GPG II.C For Definitions)
☐ SMALL BUSINESS ☐ MINORITY BUSINESS
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☐ IF THIS IS A PRELIMINARY PROPOSAL THEN CHECK HERE

TITLE OF PROPOSED PROJECT **Impacts of Geoengineering Using Stratospheric Aerosols**

REQUESTED AMOUNT	PROPOSED DURATION (1-60 MONTHS)	REQUESTED STARTING DATE	SHOW RELATED PRELIMINARY PROPOSAL NO. IF APPLICABLE
$ (b) (4) [redacted]	36 months	03/01/12	

CHECK APPROPRIATE BOX(ES) IF THIS PROPOSAL INCLUDES ANY OF THE ITEMS LISTED BELOW

☐ BEGINNING INVESTIGATOR (GPG I.G.2)
☐ DISCLOSURE OF LOBBYING ACTIVITIES (GPG II.C.1.e)
☐ PROPRIETARY & PRIVILEGED INFORMATION (GPG I.D, II.C.1.d)
☐ HISTORIC PLACES (GPG II.C.2.j)
☐ EAGER* (GPG II.D.2) ☐ RAPID** (GPG II.D.1)
☐ VERTEBRATE ANIMALS (GPG II.D.6) IACUC App. Date ______
PHS Animal Welfare Assurance Number ______
☐ HUMAN SUBJECTS (GPG II.D.7) Human Subjects Assurance Number ______
Exemption Subsection ______ or IRB App. Date ______
☐ INTERNATIONAL COOPERATIVE ACTIVITIES: COUNTRY/COUNTRIES INVOLVED (GPG II.C.2.j)
______
☐ HIGH RESOLUTION GRAPHICS/OTHER GRAPHICS WHERE EXACT COLOR REPRESENTATION IS REQUIRED FOR PROPER INTERPRETATION (GPG I.G.1)

PI/PD DEPARTMENT

Department of Environmental Sciences

PI/PD FAX NUMBER

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CO-PI/PD				
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CERTIFICATION PAGE

Certification for Authorized Organizational Representative or Individual Applicant:

By signing and submitting this proposal, the Authorized Organizational Representative or Individual Applicant is: (1) certifying that statements made herein are true and complete to the best of his/her knowledge; and (2) agreeing to accept the obligation to comply with NSF award terms and conditions if an award is made as a result of this application. Further, the applicant is hereby providing certifications regarding debarment and suspension, drug-free workplace, lobbying activities (see below), responsible conduct of research, nondiscrimination, and flood hazard insurance (when applicable) as set forth in the NSF Proposal & Award Policies & Procedures Guide, Part I: the Grant Proposal Guide (GPG) (NSF 11-1). Willful provision of false information in this application and its supporting documents or in reports required under an ensuing award is a criminal offense (U. S. Code, Title 18, Section 1001).

Conflict of Interest Certification

In addition, if the applicant institution employs more than fifty persons, by electronically signing the NSF Proposal Cover Sheet, the Authorized Organizational Representative of the applicant institution is certifying that the institution has implemented a written and enforced conflict of interest policy that is consistent with the provisions of the NSF Proposal & Award Policies & Procedures Guide, Part II, Award & Administration Guide (AAG) Chapter IV.A; that to the best of his/her knowledge, all financial disclosures required by that conflict of interest policy have been made; and that all identified conflicts of interest will have been satisfactorily managed, reduced or eliminated prior to the institution’s expenditure of any funds under the award, in accordance with the institution’s conflict of interest policy. Conflicts which cannot be satisfactorily managed, reduced or eliminated must be disclosed to NSF.

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Is the organization or its principals presently debarred, suspended, proposed for debarment, declared ineligible, or voluntarily excluded from covered transactions by any Federal department or agency? (b) (6) [redacted]

By electronically signing the NSF Proposal Cover Sheet, the Authorized Organizational Representative or Individual Applicant is providing the Debarment and Suspension Certification contained in Exhibit II-4 of the Grant Proposal Guide.

Certification Regarding Lobbying

The following certification is required for an award of a Federal contract, grant, or cooperative agreement exceeding $100,000 and for an award of a Federal loan or a commitment providing for the United States to insure or guarantee a loan exceeding $150,000.

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The undersigned certifies, to the best of his or her knowledge and belief, that:

(1) No federal appropriated funds have been paid or will be paid, by or on behalf of the undersigned, to any person for influencing or attempting to influence an officer or employee of any agency, a Member of Congress, an officer or employee of Congress, or an employee of a Member of Congress in connection with the awarding of any federal contract, the making of any Federal grant, the making of any Federal loan, the entering into of any cooperative agreement, and the extension, continuation, renewal, amendment, or modification of any Federal contract, grant, loan, or cooperative agreement.

(2) If any funds other than Federal appropriated funds have been paid or will be paid to any person for influencing or attempting to influence an officer or employee of any agency, a Member of Congress, an officer or employee of Congress, or an employee of a Member of Congress in connection with this Federal contract, grant, loan, or cooperative agreement, the undersigned shall complete and submit Standard Form-LLL, ‘‘Disclosure of Lobbying Activities,’’ in accordance with its instructions.

(3) The undersigned shall require that the language of this certification be included in the award documents for all subawards at all tiers including subcontracts, subgrants, and contracts under grants, loans, and cooperative agreements and that all subrecipients shall certify and disclose accordingly.

This certification is a material representation of fact upon which reliance was placed when this transaction was made or entered into. Submission of this certification is a prerequisite for making or entering into this transaction imposed by section 1352, Title 31, U.S. Code. Any person who fails to file the required certification shall be subject to a civil penalty of not less than $10,000 and not more than $100,000 for each such failure.

Certification Regarding Nondiscrimination

By electronically signing the NSF Proposal Cover Sheet, the Authorized Organizational Representative is providing the Certification Regarding Nondiscrimination contained in Exhibit II-6 of the Grant Proposal Guide.

Certification Regarding Flood Hazard Insurance

Two sections of the National Flood Insurance Act of 1968 (42 USC §4012a and §4106) bar Federal agencies from giving financial assistance for acquisition or construction purposes in any area identified by the Federal Emergency Management Agency (FEMA) as having special flood hazards unless the:

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(1) for NSF grants for the construction of a building or facility, regardless of the dollar amount of the grant; and
(2) for other NSF Grants when more than $25,000 has been budgeted in the proposal for repair, alteration or improvement (construction) of a building or facility.

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The undersigned shall require that the language of this certification be included in any award documents for all subawards at all tiers.

AUTHORIZED ORGANIZATIONAL REPRESENTATIVE	SIGNATURE	DATE
NAME **Fana Campbell**	**Electronic Signature**	**Aug 31 2011 3:25PM**

TELEPHONE NUMBER	ELECTRONIC MAIL ADDRESS	FAX NUMBER
732-932-0150	**fanac@grants.rutgers.edu**	

* EAGER - EArly-concept Grants for Exploratory Research
** RAPID - Grants for Rapid Response Research

COVER SHEET FOR PROPOSAL TO THE NATIONAL SCIENCE FOUNDATION

FOR CONSIDERATION BY NSF ORGANIZATION UNIT(S) - continued from page 1
(Indicate the most specific unit known, i.e. program, division, etc.)

CBET - ENVIRONMENTAL SUSTAINABILITY

Impacts of Geoengineering Using Stratospheric Aerosols

Principal Investigator: Alan Robock

Project Summary

The intellectual merit of the proposed activity

Solar radiation management, by means of artificial stratospheric aerosols or brightening marine stratus clouds, has been suggested as a response to global warming. This is sometimes referred to as geoengineering or climate engineering. While volcanic eruptions and ship tracks demonstrate the potential of geoengineering, climate model simulations so far have indicated both potential positive and negative impacts. The work proposed here will examine these impacts for stratospheric geoengineering, particularly impacts on the planet's hydrological cycle. Precipitation changes that would be particularly important for food production, such as a reduction of the Asian and African summer monsoons, will be examined. We have just started the Geoengineering Model Intercomparison Project (GeoMIP), which has been approved as a "CMIP Coordinated Experiment" as part of the Climate Model Intercomparison Project 5 (CMIP5). GeoMIP involves 17 different climate modeling, most participants in the CMIP5 experiments, and will add at least seven Climate Model Validation Activity 3 (CCM-Val3) models. We will coordinate the experiment, conduct two of the GeoMIP sets of runs, prepare forcing for the CCM-Val3 models, and analyze the GeoMIP runs, paying particular attention to their hydrological responses, especially in the summer monsoon regions, and the ocean responses. We will then use GeoMIP results to see how geoengineering climate change will affect food production, by conducting crop simulations with the Decision Support System for Agrotechnology Transfer (DSSAT) and other crop models, taking into account temperature, precipitation, insolation, and other climate changes. We will look at whether reduced temperatures will produce less evapotranspiration, with little effect on soil moisture, or whether increased CO_2 and more diffuse solar radiation will increase crop production enough to compensate for the precipitation reductions. In addition, we will see if there are adaptation strategies that could also help to compensate for any negative impacts of the climate change. We will also conduct climate model simulations to see whether there are strategies of sulfur injection into the stratosphere with particular latitudinal and seasonal patterns that can produce desirable climate changes while avoiding undesirable ones. In addition, we will see if stratospheric injections can be combined with marine cloud brightening in particular regions to produce desired results and use the marine forcing to compensate for stratospheric effects. The work proposed here also evaluates global engineering ideas as to their environmental sustainability.

The broader impacts resulting from proposed activity

Schemes to try to control the climate of the planet clearly have broad impacts. We do not advocate geoengineering in any of the proposed work. Rather we want to understand both the potential positive and negative impacts of geoengineering. We will inform policy makers of the effects of proposed measures and give an estimate of the uncertainty, so that informed decisions can be made in the future. We will continue our participation in the Solar Radiation Management Governance Initiative. We will complete the training of one [redacted] Ph.D. student and train one additional Ph.D. student. We will also involve undergraduate students at Rutgers in the research. We will put our results on a public webpage where other scientists, the public, and policy makers can access the information. The GeoMIP project enhances the international research infrastructure.

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For font size and page formatting specifications, see GPG section II.B.2.

Appendix Items:

*Proposers may select any numbering mechanism for the proposal. The entire proposal however, must be paginated. Complete both columns only if the proposal is numbered consecutively.

Results from Prior NSF Support to Alan Robock

Alan Robock is currently supported by NSF grant ATM-0730452, "Collaborative Research in Evaluation of Suggestions to Geoengineer the Climate System Using Stratospheric Aerosols and Sun Shading," February 1, 2008 – January 31, 2012, $622,275, with co-PIs Georgiy Stenchikov and Martin Bunzl. This proposal is for a continuation of the work begun under the current grant. Georgiy Stenchikov, Martin Bunzl, and Ben Kravitz have agreed to continue to collaborate on the work, but at no cost to this project.

This grant has supported numerous conference presentations, the convening of six conference sessions on geoengineering at AGU, AAAS, EGU, IUGG, and WCRP conferences, and the establishment of the Geoengineering Model Intercomparison Project (GeoMIP). We conducted climate model experiments of the effects of stratospheric aerosol clouds on climate, examined many of the potential risks of stratospheric geoengineering, began work on impacts of stratospheric geoengineering on food production, and worked on ethical and governance issues. [redacted] was supported in his Ph.D. work on this grant, and will be writing one more paper on his dissertation, which examined suggestions of using stratospheric soot aerosols for geoengineering. The grant also trained undergraduate [redacted] with a Research Experience for Undergraduates supplement. [redacted] Ph.D. study supported by the grant, and this proposal asks for funding for [redacted] to complete [redacted] work. So far the grant has supported the following articles on geoengineering:

1. Robock, Alan, 2008: 20 reasons why geoengineering may be a bad idea. *Bull. Atomic Scientists*, **64**, No. 2, 14-18, 59, doi:10.2968/064002006.
2. Bunzl, Martin, 2008: An ethical assessment of geoengineering. *Bull. Atomic Scientists*, **64**, No. 2, 18.,
3. Robock, Alan, 2008: Whither geoengineering? *Science*, **320**, 1166-1167.
4. Robock, Alan, Luke Oman, and Georgiy Stenchikov, 2008: Regional climate responses to geoengineering with tropical and Arctic SO_2 injections. *J. Geophys. Res.*, **113**, D16101, doi:10.1029/2008JD010050.
5. Rasch, Philip J., Simone Tilmes, Richard P. Turco, Alan Robock, Luke Oman, Chih-Chieh (Jack) Chen, Georgiy L. Stenchikov, and Rolando R. Garcia, 2008: An overview of geoengineering of climate using stratospheric sulfate aerosols. *Phil. Trans. Royal Soc. A.*, **366**, 4007-4037, doi:10.1098/rsta.2008.0131.
6. Bunzl, Martin, 2009: Researching geoengineering: Should not or could not? *Environ. Res. Lett.*, **4**, 045104, doi:10.1088/1748-9326/4/4/045104.
7. Kravitz, Ben, Alan Robock, Luke Oman, Georgiy Stenchikov, and Allison B. Marquardt, 2009: Sulfuric acid deposition from stratospheric geoengineering with sulfate aerosols. *J. Geophys. Res.*, **114**, D14109, doi:10.1029/2009JD011918.
8. Robock, Alan, Allison B. Marquardt, Ben Kravitz, and Georgiy Stenchikov, 2009: The benefits, risks, and costs of stratospheric geoengineering. *Geophys. Res. Lett.*, **36**, L19703, doi:10.1029/2009GL039209.
9. Jones, Andy, Jim Haywood, Olivier Boucher, Ben Kravitz, and Alan Robock, 2010: Geoengineering by stratospheric SO_2 injection: Results from the Met Office HadGEM2 climate model and comparison with the Goddard Institute for Space Studies ModelE. *Atmos. Chem. Phys.*, **10**, 5999-6006, doi:10.5194/acp-10-5999-2010.
10. Robock, Alan, Martin Bunzl, Ben Kravitz, and Georgiy Stenchikov, 2010: A test for geoengineering? *Science*, **327**, 530-531, doi:10.1126/science.1186237.

11. Kravitz, Ben, Alan Robock, Olivier Boucher, Hauke Schmidt, Karl Taylor, Georgiy Stenchikov, and Michael Schulz, 2011: The Geoengineering Model Intercomparison Project (GeoMIP). *Atmospheric Science Letters*, **12**, 162-167, doi:10.1002/asl.316.
12. Robock, Alan, 2011: Bubble, bubble, toil and trouble. An editorial comment. *Climatic Change*, **105**, 383-385, doi:10.1007/s10584-010-0017-1.
13. Robock, Alan, Ben Kravitz, and Olivier Boucher, 2011: Standardizing experiments in geoengineering; GeoMIP Stratospheric Aerosol Geoengineering Workshop; New Brunswick, New Jersey, 10-12 February 2011, *EOS*, **92**, 197, doi:10.1029/2011ES003424.
14. Bunzl, Martin, 2011: Geoengineering harms and compensation. *Stanford J. Law, Science & Policy*, **4**, 70-77.
15. Kravitz, Ben, Alan Robock, and Drew Shindell, 2011: Impacts of stratospheric black carbon geoengineering on the ozone layer. Submitted to *J. Geophys. Res.*
16. Kravitz, Ben, and Alan Robock, 2011: Practicality of stratospheric geoengineering with black carbon aerosols. Submitted to *Geophys. Res. Lett.*

Since large volcanic eruptions are the closest natural analog to stratospheric geoengineering with sulfate, we also continued to study their impacts on climate. The grant has also supported the following papers on the effects of volcanic eruptions on climate:

17. Robock, Alan, Caspar M. Ammann, Luke Oman, Drew Shindell, Samuel Levis, and Georgiy Stenchikov, 2009: Did the Toba volcanic eruption of ~74 ka B.P. produce widespread glaciation? *J. Geophys. Res.*, **114**, D10107, doi:10.1029/2008JD011652.
18. Kravitz, Ben, Alan Robock, and Adam Bourassa, 2010: Negligible climatic effects from the 2008 Okmok and Kasatochi volcanic eruptions. *J. Geophys. Res.*, **115**, D00L05, doi: 10.1029/2009JD013525.
19. Robock, Alan, 2010: New START, Eyjafjallajökull, and Nuclear Winter. *Eos,* **91** (47), 444-445, doi:10.1029/ 2010ES003201.
20. Kravitz, Ben, and Alan Robock, 2011: The climate effects of high latitude volcanic eruptions: The role of the time of year. *J. Geophys. Res.*, **116**, D01105, doi:10.1029/ 2010JD014448.
21. Kravitz, Ben, Alan Robock, Adam Bourassa, Terry Deshler, Decheng Wu, Ina Mattis, Fanny Finger, Anne Hoffmann, Christoph Ritter, Lubna Bitar, Thomas J. Duck, and John E. Barnes, 2011: Simulation and observations of stratospheric aerosols from the 2009 Sarychev volcanic eruption. *J. Geophys. Res.*, doi:10.1029/2010JD015501, in press.

Finally, the grant supported the following papers on nuclear winter:

22. Toon, Owen B., Alan Robock, and Richard P. Turco, 2008: Environmental consequences of nuclear war. *Physics Today*, **61**, No. 12, 37-42.
23. Ozdogan, Mutlu, Alan Robock, and Christopher Kucharik, 2011: Consequences of a regional nuclear conflict for crop production in the Midwestern United States. Submitted to *Climatic Change*.

In addition, Alan Robock is currently supported by NSF Arctic System Science, ARC-0908834, “Regional Climate Modeling of Volcanic Eruptions and the Arctic Climate System,” August 1, 2009 – July 31, 2012, $342,401. That grant supports graduate student Mira Losic, who is using WRF to model impacts of large volcanic eruptions on the initiation and decay of ice sheets on Baffin Island.

Alan Robock recently completed work on NSF Water Cycle, ATM-0450334, “Coupled Climatic-Hydrologic Change in the Terrestrial Water Cycle of North America in the 20th and

21st Centuries: Natural Variability and Anthropogenic Impacts," March 1, 2005 – February 28, 2011, $818,564, with co-PIs Ying Fan Reinfelder and Christopher Weaver. That grant supported M. Deniz Kustu to complete her Ph.D., graduate student Anthony DeAngelis, and postdocs Elif Sertel and Richard Anyah, and resulted in the following publications:

24. Fan, Ying, Gonzalo Miguez-Macho, Christopher Weaver, Robert Walko, and Alan Robock, 2007: Incorporating water table dynamics in climate modeling: 1. Water table observations and the equilibrium water table. *J. Geophys. Res.*, **112**, D10125, doi: 10.1029/2006JD008111.
25. Miguez-Macho, Gonzalo, Ying Fan, Christopher Weaver, Robert Walko, and Alan Robock, 2007: Incorporating water table dynamics in climate modeling: 2. Formulation, validation, and soil moisture simulation. *J. Geophys. Res.*, **112**, D13108, doi:10.1029/ 2006JD008112.
26. Anyah, Richard, Christopher P. Weaver, Gonzalo Miguez-Macho, Ying Fan, and Alan Robock, 2008: Incorporating water table dynamics in climate modeling: 3. Simulated groundwater influence on coupled land-atmosphere variability. *J. Geophys. Res.*, **113**, D07103, doi:10.1029/2007JD009087.
27. DeAngelis, Anthony, Francina Dominguez, Ying Fan, Alan Robock, M. Deniz Kustu, and David Robinson, 2010: Observational evidence of enhanced precipitation due to irrigation over the Great Plains of the United States. *J. Geophys. Res.*, **115**, D15115, doi: 10.1029/2010JD013892.
28. Kustu, M. Deniz, Ying Fan, and Alan Robock, 2010: Large-scale water cycle perturbation due to irrigation pumping in the US High Plains: 1. A synthesis of observed stream flow changes. *J. Hydrology*, **390**, 222-244, doi:10.1016/j.jhydrol.2010.06.045.
29. Sertel, Elif, Alan Robock, and Cankut Ormeci, 2010: Impacts of land cover data quality on regional climate simulations. *Internat. J. Climatology*, **30**, 1942-1953, doi:10.1002/ joc.2036.
30. Sertel, E., C. Ormeci, and A. Robock, 2011: Modelling land cover change impact on the summer climate of the Marmara region, Turkey. *International J. Global Warming*, **3**, 194-202.

Introduction

On February 2, 2007, the Intergovernmental Panel on Climate Change (IPCC) Working Group I released the Summary for Policymakers of the Fourth Assessment Report, which stated that "Most of the observed increase in globally averaged temperatures since the mid-20th century is *very likely* due to the observed increase in anthropogenic greenhouse gas concentrations." "Very likely" is defined as with a greater than 90% probability of occurrence, using the expert judgment of the IPCC scientists. Furthermore, they outline the projected global warming, sea level rise, changes in precipitation patterns, increase in tropical storms, and other responses to future anthropogenic pollution with a greater degree of certainty than before.

The United Nations Framework Convention on Climate Change (UNFCCC) was established in 1992. Signed by 194 countries and ratified by 189, including the United States, it came into force in 1994. It says in part, "The ultimate objective of this Convention ... is to achieve ... stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system."

As a means to achieve the UNFCCC objective, the Kyoto Protocol was adopted at the third session of the Conference of the Parties to the UNFCCC in Kyoto, Japan, on 11 December 1997. It has been signed, but not ratified, by the US. The Kyoto Protocol entered into force on

February 16, 2005, after Russia ratified it. The Kyoto Protocol commits developed countries to reduce their greenhouse gas emissions to specific percentages of their 1990 values by 2012. However an analysis by Kintisch (2006) of emissions changes between 1990 and 2002 showed that the US had increased its emissions by 18%, compared to its Kyoto mandate to reduce them by 7%. India and China, while signatories to Kyoto, do not have mandated emissions reductions. During this same 12-year period, China increased its emissions by 49% and India by 70%. Rahmstorf et al. (2007) showed that as of 2006, global greenhouse gas emissions have continued since 1990 above the rate of all the IPCC scenarios, even the business-as-usual ones. “Dangerous anthropogenic interference” was not defined when the UNFCCC was signed, but following the Conference of the Parties in Copenhagen in 2009, the major countries of the world agreed that global warming of 2°C above preindustrial levels should be considered dangerous.

In light of the failure of society to take any concerted actions to deal with global warming in spite of the UNFCCC agreement, two prominent atmospheric scientists published papers five years ago suggesting that society consider geoengineering solutions to global warming (Crutzen, 2006; Wigley, 2006). This suggestion generated much interest in the press and in the scientific community, and there has been an increasing amount of work on the topic since then. Robock et al. (2008) summarized the climate modeling work up until then, and more recent work is discussed in the body of the proposal.

The term geoengineering has come to refer to both carbon dioxide reduction and solar radiation management (Shepherd et al., 2009; Lenton and Vaughan, 2009), and these two different approaches to climate control have very different scientific, ethical and governance issues. This proposal will only deal with solar radiation management, and focus on the suggestion to produce stratospheric clouds to reflect sunlight in the same way large volcanic eruptions do. In addition, in part of the proposed work, we will look at marine cloud brightening, the other scheme that has gotten the most attention recently. Stratospheric aerosols and marine cloud brightening are the only two schemes that seem to have the potential to produce effective and inexpensive large cooling of the planet (Lenton and Vaughan, 2009). Unless otherwise noted, this proposal will use the term geoengineering to refer to solar radiation management.

The American Meteorological Society policy statement on geoengineering (AMS, 2009), which was subsequently adopted by the American Geophysical Union (AGU, 2009), recommends “Enhanced research on the scientific and technological potential for geoengineering the climate system, including research on intended and unintended environmental responses.” Strong recommendations for geoengineering research have recently also come from Keith et al. (2010), Betz (2011), and GAO (2011). This proposal is to continue my work on this topic. While research so far has pointed out both benefits and risks from geoengineering, and that it is not a solution to the global warming problem, at some time in the future, despite mitigation and adaptation measures, society may be tempted to try to control the climate to avoid dangerous impacts. Much more research on geoengineering is needed so that society will be able to make informed decisions. Right now, we do not know whether geoengineering may make the situation even more dangerous. The work proposed here is to take steps toward producing the understanding that will help inform such decisions.

Scientific Questions to be Addressed

We propose to address the following scientific questions:

1) **How would stratospheric geoengineering affect the planet’s hydrological cycle?** We know that if warming from greenhouse gases is countered with reduction of solar radiation to

cancel out the globally-averaged radiative forcing, the planetary temperature can be kept from changing but the hydrological cycle will be weaker, with a reduction of globally-averaged evapotranspiration and precipitation. But will there be patterns of precipitation reduction that will be particularly important for food production, such as a reduction of the Asian and African summer monsoons?

2) **How would stratospheric geoengineering affect the planet's ocean and long-term climate?** Long-term changes of climate forced by stratospheric geoengineering, to a great extent, are controlled by the responses of ocean temperature and circulation. How will the frequencies of El Niño and La Niña change during geoengineering? Will a cooling signal propagate deep into the ocean, as has been observed and modeled after volcanic eruptions, and how will this affect the long-term climate response to geoengineering?

3) **Are there strategies of sulfur injection into the stratosphere with particular latitudinal and seasonal patterns that can produce desirable climate changes while avoiding undesirable ones?** For example, could spring and summer high-latitude injections maximize the cooling effect at high latitudes, while avoiding lower latitude precipitation impacts and wasteful winter injection when there is little sunlight? Could stratospheric injections be combined with marine cloud brightening in particular regions to produce desired results and use the marine forcing to compensate for stratospheric effects?

4) **How would the changes in climate that result from stratospheric geoengineering affect food production?** For example, if there is a reduction of summer precipitation over India and China, accompanied by cooling and less insolation, what would be the net effect on crop production? Would reduced temperatures produce less evapotranspiration, with little effect on soil moisture? Would increased CO_2 and more diffuse solar radiation increase crop production enough to compensate for the precipitation reductions? Are there adaptation strategies that could also help to compensate for any negative impacts of the climate change?

Proposed Research Activities

The proposed research activities to answer each of these questions are discussed below. For each, the past work on the topic is discussed, and the specific work proposed here is described.

1. How would stratospheric geoengineering affect the planet's hydrological cycle?

Robock et al. (2009) pointed 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. (2010a) 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. (2010a) ramped up the anthropogenic greenhouse gas forcing using the IPCC A1B scenario (IPCC, 2007a), while the others conducted equilibrium simulations at $2xCO_2$. Ammann et al.

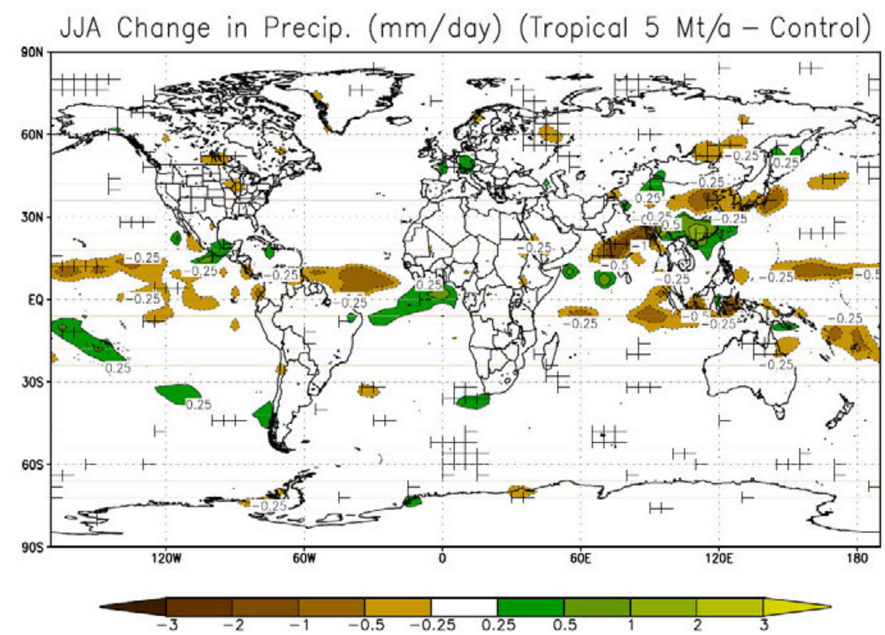

Figure 0. Northern Hemisphere summer precipitation differences from the control climate averaged for the second 10 years of a 20-year geoengineering period emitting 5 Mt SO_2 per year into the tropical lower stratosphere combined with A1B (Robock et al., 2008). Hatch marks indicate changes significant at the 5% level. Note large reductions over India and China.

(2010) gradually balanced a transient increase of anthropogenic forcing with a transient increase of stratospheric aerosols or a transient decrease of the solar constant.

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. Greenhouse gas radiative forcing has a larger impact on precipitation reduction than changes of shortwave radiation do to increase precipitation, since greenhouse gas warming acts throughout the troposphere, making it more stable to convective processes. 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 meant 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 (Figure 0). Jones et al. (2010a) 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.

To address these issues, we recently implemented GeoMIP (Kravitz et al., 2011a). GeoMIP builds on experiments already being conducted as part of the Climate Model

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

G1	Instantaneously quadruple the CO_2 concentration (as measured from pre-industrial 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 sulphate 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 (~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).

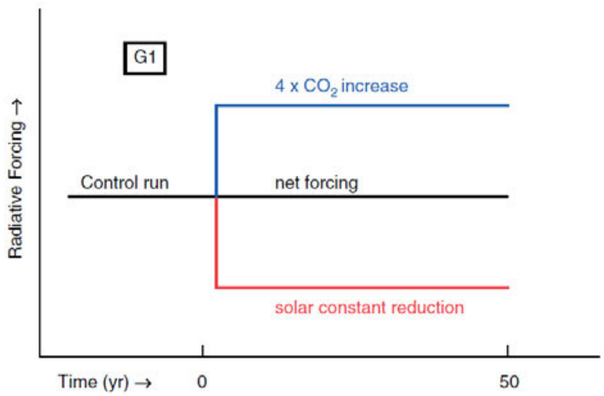

Figure 1. Schematic of experiment G1. The experiment is started from a control run. The instantaneous quadrupling of CO_2 concentration from pre-industrial levels is balanced by a reduction in the solar constant until year 50.

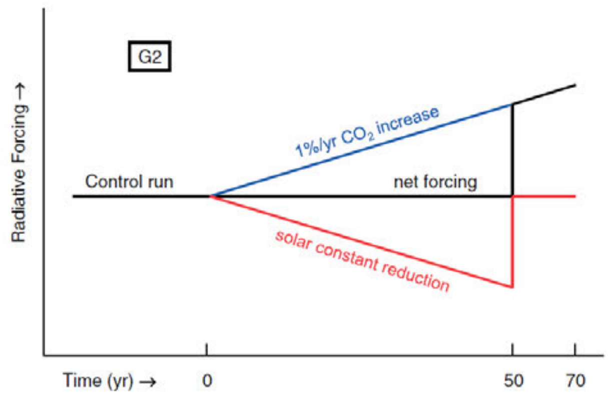

Figure 2. Schematic of experiment G2. The experiment is started from a control run. The positive radiative forcing of an increase in CO_2 concentration of 1% per year is balanced by a decrease in the solar constant until year 50.

Intercomparison Project 5 (CMIP5; Taylor et al., 2008), with four sets of standardized experiments using solar constant reduction or stratospheric aerosol clouds to either balance anthropogenic radiative forcing or reduce it quickly (Table 1). GeoMIP has been approved as a "CMIP Coordinated Experiment" as part of CMIP5. The Program for Climate Model Diagnosis and Intercomparison (PCMDI) is archiving 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 IPCC assessment reports. Initially, largely for practical reasons, the number of simulations to be performed must be kept small because CMIP5 is already stretching the capabilities of the modeling groups.

The four GeoMIP experiments are listed in Table 1, from Kravitz et al. (2011a), and shown in Figures 1-4, also from Kravitz et al. (2011a). They were designed to be easy to implement and to allow the diagnosis of the climate response to stratospheric geoengineering from a number of different models carrying out identical experiments.

GeoMIP formally started with a workshop at Rutgers University in February, 2011 (Robock et al., 2011). The workshop was very successful, with attendance by 30 scientists from seven different countries. Seventeen different climate modeling groups (Table 2), including 11 CMIP5 participants, have already agreed to conduct some or all of the GeoMIP model

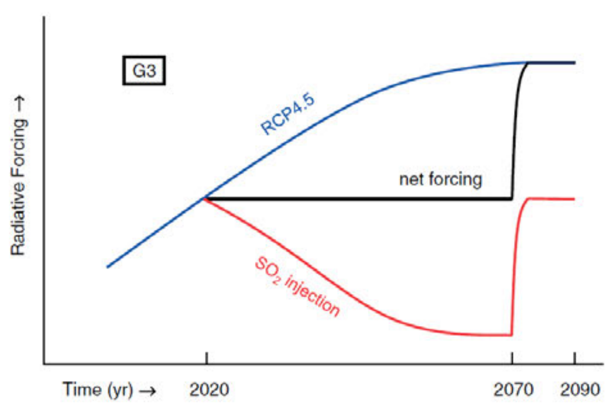

Figure 3. Schematic of experiment G3. The experiment approximately balances the positive radiative forcing from the RCP4.5 scenario by an injection of SO_2 or sulphate aerosols into the tropical lower stratosphere.

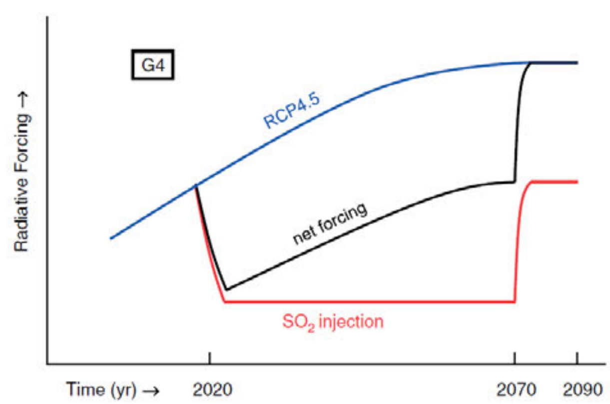

Figure 4. Schematic of experiment G4. This experiment is based on the RCP4.5 scenario, where immediate negative radiative forcing is produced by an injection of SO_2 into the tropical lower stratosphere at a rate of 5 Tg per year.

simulations, and we have an open invitation for more to join the project, which is described at http://climate.envsci.rutgers.edu/GeoMIP/. Different groups are now carrying out the experiments and will be submitting their results to PCMDI over the next year or two. We request money here to support the second GeoMIP Workshop, scheduled for March 30-31, 2012 at the Hadley Centre in Exeter, UK.

In addition, the Chemistry-Climate Model Validation Activity (CCMVal) is part of Stratospheric Processes and their Role in Climate (SPARC), which was created in 1992 by the World Climate Research Programme (SPARC CCM-Val, 2010). Led by Veronika Eyring, a number of modeling groups participating in the next intercomparison project, CCM-Val3, have expressed interest in participating in GeoMIP (Table 2). Typically these models are run with specified surface boundary conditions and do not include an interactive ocean, so they will focus on experiments G3 and G4, and examine the circulation atmospheric chemistry responses to an imposed stratospheric aerosol cloud.

Table 2. GeoMIP participants

AOGCM groups, who are participants in CMIP5:

NASA Goddard Institute for Space Studies (ModelE2)
National Center for Atmospheric Research (NCAR; 3 versions: CESM-CAM5, CESM-CAM4, CESM-WACCM4)
UK Met Office Hadley Centre (HadGEM2-ES)
Max Planck Institute for Meteorology (MPI-ESM/ECHAM6)
Laboratoire des Sciences du Climat et l'Environnement (LSCE; IPSLCM5A)
Japan Agency for Marine-Earth Science and Technology (MIROC-ESM)
Norwegian Met Office (NORESM)
Canadian Centre for Climate Modelling and Analysis (CanESM2)
NOAA Geophysical Fluid Dynamics Laboratory (CM3)

Additional climate groups, who are not participants in CMIP5:

Max Planck Institute for Chemistry (EMAC/ECHAM5)
University of Bristol (HadCM3, perturbed physics ensemble)
Cambridge University (UMUKCA)
Russian Institute of Atmospheric Physics (IAPRASCM)
Beijing Normal University (GCCESM)
Commonwealth Scientific and Industrial Research Organisation (CSIRO Mk3L)

CCM-Val3 models that will participate in GeoMIP:

CAM3.5	CCSRNIES/MIROC3.2	
EMAC (DLR)*	LMDzrepro*	
HadGEM	SOCOL	
ULAQ	UMSLIMCAT	
UMUKCA*	WACCM	*maybe

The specific work proposed here will be conducted with a new graduate student and former graduate student, Ben Kravitz, who just began a postdoc at the Carnegie Institution for Science and will donate his time to collaborate on the project, along with Georgiy Stenchikov, who is now a professor at King Abdullah University of Science and Technology, who also will collaborate at no cost. The work will consist of the following specific activities:

- Complete the NASA GISS Model E2 GeoMIP runs, which are now under way, analyze them, and write at least one paper describing them.
- Conduct the NOAA GFDL GeoMIP runs at the King Abdullah University of Science and Technology. The model is already running there on one of the fastest supercomputers in the world.
- Analyze the CMIP5 set of runs for the CMIP5 models participating in GeoMIP, in particular paying attention to their ability to simulate the climate response to past volcanic eruptions and to simulate summer monsoons, which will allow us to better interpret their results for the GeoMIP runs, in particular G3 and G4, following the recommendations of Knutti et al. (2010).

- Analyze the GeoMIP runs, paying particular attention to their hydrological responses, especially in the summer monsoon regions, and the ocean response.
- Prepare forcing data sets for the CCM-Val3 experiments. Since these models in general do not have the capability to simulate the creation, transport, and removal of stratospheric aerosols (Morgenstern et al., 2010), we will provide a standardized stratospheric aerosol forcing data set, by modifying the SPARC aerosol data set that was used for CCM-Val2 (SPARC CCM-Val, 2010), for them to prescribe for their experiments, which will begin in about a year.
- Analyze the CCM-Val3 experiments, focusing on the stratospheric circulation and ozone loss responses.

While volcanic eruptions are an imperfect analog for continuous aerosol clouds in the stratosphere that might be used for geoengineering, they are the closest natural experiment that we have available. As Andrews et al. (2010) pointed out, there are fast and slow precipitation responses to radiative forcing. But they found that forcing mechanisms that act through modification of shortwave radiation, such as tropospheric sulfate or surface albedo, can be diagnosed through the traditional radiative forcing concept, and only mechanisms acting through the longwave have different short-term and long-term responses. Because the lifetime of volcanic forcing from large tropical eruptions, such as the 1991 Pinatubo eruption, is a couple years, and precipitation processes respond on much shorter time scales, such as the diurnal cycle for convection and the seasonal cycle for monsoons, we think that volcanic eruptions are probably a good analog for stratospheric geoengineering. Trenberth and Dai (2007), looking at the Pinatubo eruption, and Anchukaitis et al. (2010), using tree ring data for a large number of eruptions for the past 750 years, found a pattern of response in the summer monsoon precipitation over Africa and Asia similar to that found by Robock et al. (2008) in a geoengineering simulation averaging over the second decade after an imposed stratospheric cloud (Figure 0). But the details of this response and the mechanisms involved can certainly be studied more in observations and climate model simulations of volcanic eruptions. Therefore, during this project we will continue to take advantage of volcanic eruptions that occur to better understand both the distribution and radiative effects of the resulting aerosol clouds as well as the climate response. Recently we examined the 2008 Okmok and Kasatochi eruptions (Kravitz et al., 2010) and 2009 Sarychev eruption (Kravitz et al., 2011b) and conducted theoretical studies (Kravitz and Robock, 2011) as examples for proposed schemes for Arctic geoengineering. Because the lifetime of stratospheric aerosols in the Arctic is only a few months, volcanic eruptions there serve as a better analog than for tropical eruptions, especially if Arctic geoengineering were implemented with only spring and summer injections, so as to only have the aerosols present when there would be sunlight to reflect.

2. How would stratospheric geoengineering affect the planet's ocean and long-term climate?

Long-term changes of climate forced by stratospheric geoengineering, to a great extent, are controlled by the responses of ocean temperature and circulation. From observations and model simulations (Stenchikov et. al., 2009) we know that stratospheric aerosols associated with explosive volcanic eruptions could affect sea surface temperature, deep ocean temperature, ocean overturning circulation, the hydrological cycle, and sea ice extent, which are crucial for assessing the biospheric and economic consequences of geoengineering. The shorter term impacts are discussed above under question 1. Here we seek to examine the longer term impacts, including after geoengineering might be halted.

Strong explosive volcanic eruptions can produce global stratospheric aerosol clouds that last for 2 to 3 years, reflecting solar radiation and cooling Earth's surface. The climate response to volcanic forcing is a result of interaction of associated thermal and dynamic perturbations with the major modes of climate variability. Analyses of the past 350 years using proxy data even suggest that tropical eruptions could increase the likelihood of El Niño (Adams et al, 2003), but Emile-Geay et al. (2008) show that this could only be expected for very strong eruptions. For example, the strongest explosive events of the 19th and 20th centuries, Tambora in 1815 and Pinatubo in 1991, occurred in El Niño years, but was this just a coincidence? Would geoengineering change the frequency of El Niño and La Niña events, and how would this project onto a global pattern of temperature and precipitation responses?

In addition, Stenchikov et al. (2009) showed that after volcanic eruptions, surface air temperatures relax back to normal with a typical time scale of 7 years, but cooling accumulated in the ocean can be seen for about a century in the sub-thermocline waters. This decrease of deep ocean temperature is associated with negative anomalies of sea level. This provides a mechanism of how short-term volcanic radiative impacts could produce perturbations in the climate system that last for centuries, producing a cumulative cooling effect. The volcanic impact tends to strengthen the meridional overturning circulation. Sea ice appears to be sensitive to volcanic forcing, especially during the warm season.

Thus ocean responses could be significant and play an important role in formation of the geoengineered climate. Therefore in this study we propose to conduct a detailed analysis of ocean responses in the GeoMIP experiments to better understand the modeled ocean responses and associated physical mechanisms. We plan to conduct the analysis in a way similar to that conducted by Stenchikov et al. (2009), to intercompare sea surface temperature responses, the impact of radiative forcing on the overturning circulation, and sea ice. We expect that geoengineering forcing, which would be relatively constant in time, will be less effective than sporadic volcanic eruptions in accelerating ocean vertical mixing and enhancing the overturning circulation, but this has to be thoroughly tested and quantified using model responses.

3. Are there strategies of sulfur injection into the stratosphere with particular latitudinal and seasonal patterns that can produce desirable climate changes while avoiding undesirable ones?

In the past, rather simple strategies for stratospheric aerosol injection or solar radiation reduction have been tested. For example, Robock et al. (2008) used tropical SO_2 injection, which produced a fairly uniform global aerosol cloud and radiative forcing, and also examined Arctic aerosol injection, which produced a cloud that extended south to about 30°N, with fairly uniform coverage. Caldeira and Wood (2008) used idealized solar radiation reductions in the Arctic and globally to counteract doubled CO_2. Ban-Weiss and Caldeira (2010) were the first to try idealized global distributions of stratospheric aerosols to attempt to achieve specified climate responses, but do not claim that it would be possible to engineer those particular distributions. Niemeier et al. (2010) examined slightly different strategies for SO_2 and sulfate emissions in the Tropics, but did not try emissions at different latitudes or specific seasons.

Here we propose to carry out general circulation model (GCM) experiments by actually emitting SO_2 into the stratosphere in various patterns and allowing the model to generate sulfate aerosols, allow them to grow, be advected and interact chemically and radiatively with the atmosphere, and then be removed. We will use both the NASA GISS ModelE2 and NCAR

CESM-WACCM4 models, which have those capabilities. The first experiments will be with Arctic injection, but only in the spring and summer, so as to reduce the amount of injection needed, since the sulfate aerosol lifetime is only about 3 months in the Arctic (Robock et al., 2008) and it would be much less useful to have aerosols in the winter when there would little insolation to block. Furthermore, we will attempt to minimize African and Asian monsoon impacts while still cooling the planet.

It needs to be said here that we are not at all advocating implementation of such a strategy, nor small-scale outdoor testing of it. In fact, Robock et al. (2010) explained why small-scale testing in the stratosphere would be ineffective, due to different microphysics if emitting SO_2 into a pristine atmosphere and due to the impossibility of detecting a climate response from a small forcing in a noisy climate system. Rather we are attempting to see if there are any practical schemes for controlling regional or global climate without severe impacts and risks. If so, that will be very interesting, and if not, it will also be interesting. Equipped with this information, future policy decisions will be much better informed. We understand how difficult it is to satisfy both temperature and precipitation goals at the same time (Rasch et al., 2009; Ricke et al., 2010; Moreno-Cruz et al., 2011), but will examine innovative injection schemes that are not uniform in time or location, such as combinations of tropical, mid-latitude, and high-latitude SO_2 at different times of the year.

Heckendorn et al. (2009) and Hommel and Graf (2010) suggested that the stratospheric sulfate aerosols would grow larger with continuous SO_2 injection, making them less effective per unit mass in producing radiative forcing, both because they would be larger and because their lifetimes would be shorter. Pierce et al. (2010) proposed injection of sulfuric acid directly into the stratosphere to produce smaller aerosols, but if that would work, it would have a larger impact on ozone depletion. We will test both types of aerosols in our experiments.

Jones et al. (2009), in marine cloud brightening experiments, found a remote drying response over the Amazon from south Atlantic cloud brightening. Rasch et al. (2009) found different patterns of response, but in their model there were few clouds in the south Atlantic that could be seeded. Korhonen et al. (2010), on the other hand, found small impacts on clouds of salt injection because of negative feedbacks on cloud dynamics, something also indicated by the high-resolution study of Wang et al. (2011). Jones et al. (2010b) compared the effects of cloud brightening (Jones et al., 2009) and stratospheric aerosols (Jones et al., 2010a) and found both effective at cooling the planet, but that each method produced different patterns of temperature and precipitation response. They also found that both methods reduced global average precipitation if the emissions were such as to cause the temperature anomaly to be zero. They did not attempt a combined geoengineering strategy.

As our work progresses, we will consider the latest work on this topic and try combined patterns of cloud brightening and stratospheric aerosol creation to produce a desirable climate with minimum risks and assess how easy it would be to do this. However minimum risk strategies will be different depending on the objective of the geoengineering, such as to minimize sea level rise or to minimize agricultural impacts.

4. How would the changes in climate that result from stratospheric geoengineering affect food production?

Robock et al. (2008) found global average reductions of precipitation produced by geoengineering, but particular changes in summer monsoon regions of Asia and Africa. The GeoMIP experiment discussed above will determine how robust those changes might be, but assuming that there would be reductions, they will be particularly important if they affect water

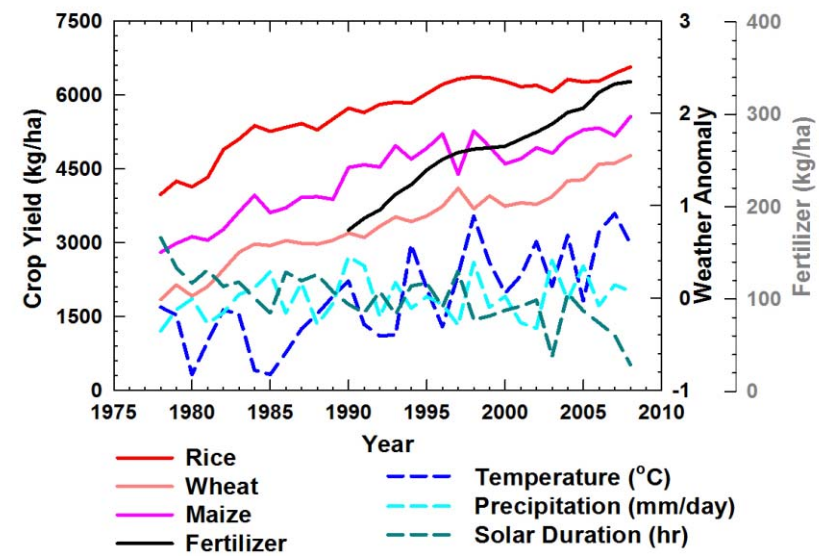

Figure 5. China agricultural production and climate anomalies with respect to the entire period, 1978-2008.

resources and agricultural productivity for a region of more than 2 billion people. It is soil moisture and not precipitation that impacts agriculture. Will reduced evaporative demand compensate for reduced precipitation? Will more CO_2 in the atmosphere and more diffuse radiation both work to stimulate plant growth? Will farmers be able to adapt to changing climate with different agricultural practices, including different planting dates, application of more fertilizer, changes to irrigation, or changes to cultivars? We will address these questions with crop modeling simulations, driven by the climate change scenarios from the GeoMIP project, for the entire world.

Preliminary work with student [redacted] has already begun using the Decision Support System for Agrotechnology Transfer (DSSAT; Jones et al., 2003) crop simulation model, driven by the climate change scenarios of Robock et al. (2008), for China, which is the world's largest producer of rice and wheat, and second only to the U.S. in corn. We will expand this work globally and make use of all the GeoMIP results, after evaluating the models for their fidelity at simulating the current climate, in particular the precipitation, temperature, and other climate elements over the regions of interest. But we will keep in mind the results of Schaller et al. (2011), who found that in some situations the multi-model mean is more useful than trying to pick individual models based on specific metrics.

We obtained agricultural productivity and fertilizer use data from every province in China for 1978-2008, along with daily weather data from weather stations throughout the country for the same period. Figure 5 shows that there has been a strong upward trend in agricultural productivity in China for the past 30 years, with no clear impact of temperature, precipitation, and insolation anomalies. There may be impacts from the upward temperature trend and the downward insolation trend (there has not been a precipitation trend), but those cannot be identified just by examining the figure. Clearly the upward productivity trends are related to agricultural practices, particularly the increased use of fertilizer, as shown on the figure. But is there a limit to how much additional fertilizer can be effective? And additional fertilizer use will have impacts on the atmosphere because of the additional greenhouse gases that would be produced. We will include adaptation strategies in our simulations, including changes to fertilizer use, irrigation, planting and harvest dates, and choice of cultivars. Our preliminary results for China show small impacts of climate changes caused by geoengineering, that would be easy to address with more fertilizer use, but that is with one GCM, one geoengineering scenario, one crop model, and one country. We propose to conduct a comprehensive study to quantify these potential impacts.

Summary

The idea that humans might gain control of our climate system and manipulate the climate on purpose is transformative as it is frightening. Would such a power be used for the benefit of humanity, to enhance environmental sustainability and to improve the lives of people? Or would it be used for selfish purposes, without regard to the potential negative consequences? Research into geoengineering is still in its infancy, and we agree with the AMS (2009) and AGU (2009), who stated "Geoengineering will not substitute for either aggressive mitigation or proactive adaptation, but it could contribute to a comprehensive risk management strategy to slow climate change and alleviate some of its negative impacts. The potential to help society cope with climate change and the risks of adverse consequences imply a need for adequate research, appropriate regulation, and transparent deliberation." The research proposed here will be done transparently, as part of an international collaboration, and the results will be disseminated broadly. Armed with this information, policy makers will be able to make informed decisions that will affect all of us. If the risks of implementing geoengineering appear substantial, this may increase the push for mitigation of greenhouse gas and particle emissions that are causing global warming. If strategies to implement geoengineering appear to be able to temporarily reduce the most dangerous global warming impacts while producing fewer impacts themselves, such potential strategies need to be examined. In any case, we expect the results of this work to add to vital information that will guide global policy in the future.

Broader impacts resulting from proposed activity

Schemes to try to control the climate of the planet clearly have broad impacts. The results produced here will be of great value for policy decisions on these measures. We will inform policy makers of the effects of proposed measures and give an estimate of the uncertainty. Furthermore, we will produce estimates of possible adverse consequences. We will complete the training of one [redacted] Ph.D. student and train an additional Ph.D. student. We will try to recruit a new student from an underrepresented group. We will also involve undergraduate students at Rutgers in the research. We will put our results on a public webpage where other scientists, the public, and policy makers can access the information. We will continue to present results in talks to the public, Congressional testimony (if invited again), and in interviews in the press. We will continue our participation in the Solar Radiation Management Governance Initiative, which is attempting to sort out rules for outdoor geoengineering research. The GeoMIP project enhances the international research infrastructure.

Environmental Sustainability

Geoengineering proposals would involve engineering of the entire planet. While this proposal is written in the disciplinary language of climate system modeling and observations, it is clearly concerned with environmental sustainability. We will examine how engineering approaches to controlling Earth's climate will affect agriculture and water resources, whether life on Earth will be more sustainable because the impacts of global warming will be reduced, or whether the additional impacts of geoengineering will threaten our access to food and water.

Management Approach

The schedule for the main research activities we propose here are presented in a table:

Activity	Year 1	Year 2	Year 3
Complete NASA GISS ModelE2 GeoMIP runs	X		
Complete NOAA GFDL GeoMIP runs	X		
Provide GeoMIP forcing scenarios for use by CCM-Val3	X	X	
Analyze GeoMIP results, in particular to produce scenarios for crop models and to examine monsoon and ocean responses	X	X	X
Analyze CCM-Val3 results		X	X
Conduct GCM simulations with various combinations of cloud brightening and stratospheric aerosols	X	X	X
Conduct crop simulations using GeoMIP output	X	X	X
Organize and conduct GeoMIP meetings	X	X	
Present results in refereed journal articles, at national and international conferences and on our web site.	X	X	X

Personnel

Specific responsibilities for the PIs and the each collaborator are given below.

Alan Robock, PI: Will be in charge of overall coordination of the project, and will work closely with Stenchikov, Kravitz, [redacted] and new student to design and carry out all the proposed work.

Georgiy Stenchikov: At no cost, will conduct the NOAA GFDL GeoMIP runs, analyze GeoMIP output for ocean responses, and consult on other aspects of the work.

Martin Bunzl: At no cost, will analyze ethical and sustainability issues.

Ben Kravitz: At no cost, will conduct the NASA GISS GeoMIP runs, and analyze GeoMIP output for monsoon responses.

[redacted] **graduate student:** Will analyze GeoMIP output, conduct crop model simulations, and help conduct GCM experiments of combined forcings.

Graduate Student (new hire): Will conduct GCM experiments of combined forcings and of the impacts of volcanic eruptions on climate.

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