

TESTIMONY

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House Committee on Science and Technology Hearing
 “Geoengineering: Assessing the Implications of Large-Scale Climate Intervention”
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| 8. Kravitz, Ben, Alan Robock, Luke Oman, Georgiy Stenchikov, and Allison B. Marquardt, 2009: Sulfuric acid deposition from stratospheric geoengineering with sulfate aerosols. <i>J. Geophys. Res.</i> , 114 , D14109, doi:10.1029/2009JD011918. | S99 |
| 9. Robock, Alan, Allison B. Marquardt, Ben Kravitz, and Georgiy Stenchikov, 2009: The benefits, risks, and costs of stratospheric geoengineering. <i>Geophys. Res. Lett.</i> , 36 , L19703, doi:10.1029/2009GL039209. | S106 |

Summary of testimony by Alan Robock

Observations throughout the world make it clear that climate change is occurring, and rigorous scientific research demonstrates that the greenhouse gases emitted by human activities are the primary driver. Moreover, there is strong evidence that ongoing climate change will have broad impacts on society, including the global economy, national security, and the environment. Therefore, it is incumbent on us to address the threat of climate change.

Three proactive strategies could reduce the risks of climate change: 1) *mitigation*: reducing emissions; 2) *adaptation*: moderating climate impacts by increasing our capacity to cope with them; and 3) *geoengineering*: deliberately manipulating physical, chemical, or biological aspects of the Earth system.

Geoengineering proposals can be separated into solar radiation management (by producing a stratospheric cloud or making low clouds over the ocean brighter) or carbon capture and sequestration (with biological or chemical means over the land or oceans). My expertise is in the first area. In particular, my work has focused on the idea of emulating explosive volcanic eruptions, by attempting to produce a stratospheric cloud that would reflect some incoming sunlight, to shade and cool the planet to counteract global warming. In this testimony, except where indicated, I will confine my remarks to this specific idea, and use the term “geoengineering” to refer to only it. I do this because it is the suggestion that has gotten the most attention recently, and because it is the one that I have addressed in my work.

My personal view is that we need aggressive mitigation to lessen the impacts of global warming. We will also have to devote significant resources to adaptation to deal with the adverse climate changes that are already beginning.

If geoengineering is ever used, it should be as a short-term emergency measure, as a supplement to, and not as a substitute for, mitigation and adaptation. And we are not ready to implement geoengineering now.

The question of whether geoengineering could ever help to address global warming cannot be answered at this time. In our most recent paper, we have identified six potential benefits and 17 potential risks of stratospheric geoengineering, but a vigorous research program is needed to quantify each of these items, so that policy makers will be able to make an informed decision, by weighing the benefits and risks of different policy options.

Furthermore, there has been no demonstration that geoengineering is even possible. No technology to do geoengineering currently exists. The research program needs to also evaluate various suggested schemes for producing stratospheric particles, to see whether it is practical to maintain a stratospheric cloud that would be effective at blocking sunlight.

For geoengineering ever to be tested, and for monitoring future large volcanic eruptions anyway, we need to rebuild our capacity to observe particles in the stratosphere, using satellites and ground-based observations.

Alan Robock Biographical Sketch

Dr. Alan Robock is a Professor II (Distinguished Professor) of climatology in the Department of Environmental Sciences at Rutgers University and the associate director of its Center for Environmental Prediction. He also directs the Rutgers Undergraduate Meteorology Program. He graduated from the University of Wisconsin, Madison, in 1970 with a B.A. in Meteorology, and from the Massachusetts Institute of Technology with an S.M. in 1974 and Ph.D. in 1977, both in Meteorology. Before graduate school, he served as a Peace Corps Volunteer in the Philippines. He was a professor at the University of Maryland, 1977-1997, and the State Climatologist of Maryland, 1991-1997, before moving to Rutgers in 1998.

Prof. Robock has published more than 250 articles on his research in the area of climate change, including more than 150 peer-reviewed papers. His areas of expertise include geoengineering, the effects of volcanic eruptions on climate, the impacts of climate change on human activities, detection and attribution of human effects on the climate system, regional atmosphere-hydrology modeling, soil moisture, and the climatic effects of nuclear weapons.

Professor Robock is currently supported by the National Science Foundation to do research on geoengineering. He has published five peer-reviewed journal articles on geoengineering, in 2008 and 2009. He was a member of the committee that drafted the July 2009 American Meteorological Society Policy Statement on Geoengineering the Climate System. He has convened sessions on geoengineering at two past American Geophysical Union Fall Meetings, and is the convener of sessions on geoengineering to be held at meetings of the American Association for the Advancement of Science and European Geosciences Union in 2010.

His honors include being a Fellow of the American Meteorological Society, a Fellow of the American Association for the Advancement of Science (AAAS), and a participant in the Intergovernmental Panel on Climate Change, which was awarded the Nobel Peace Prize in 2007. He was the American Meteorological Society/Sigma Xi Distinguished Lecturer for the academic year 2008-2009.

Prof. Robock was Editor of the *Journal of Geophysical Research – Atmospheres* from April 2000 through March 2005 and of the *Journal of Climate and Applied Meteorology* from January 1985 through December 1987. He was Associate Editor of the *Journal of Geophysical Research – Atmospheres* from November 1998 to April 2000 and of *Reviews of Geophysics* from September 1994 to December 2000, and is once again serving as Associate Editor of *Reviews of Geophysics*, since February, 2006.

Prof. Robock serves as President of the Atmospheric Sciences Section of the American Geophysical Union and Chair-Elect of the Atmospheric and Hydrospheric Sciences Section of the American Association for the Advancement of Science. He has been a Member Representative for Rutgers to the University Corporation for Atmospheric Research since 2001, and serves on its President's Advisory Committee on University Relations. Prof. Robock was a AAAS Congressional Science Fellow in 1986-1987, serving as a Legislative Assistant to Congressman Bill Green (R-NY) and as a Research Fellow at the Environmental and Energy Study Conference.

Detailed Answers to Questions from Committee

Introduction

In the October 28, 2009, letter from Chairman Gordon inviting me to testify at the House Committee on Science and Technology Hearing, “Geoengineering: Assessing the Implications of Large-Scale Climate Intervention,” I was asked to address a number of specific issues, which I do below. But first I would like to give a brief statement of the framework within which we consider the issue of geoengineering.

I agree with the October 21, 2009, statement from the leaders of 17 U.S. scientific societies to the U.S. Senate (Supplementary Material 1), partially based on my own research, that, “Observations throughout the world make it clear that climate change is occurring, and rigorous scientific research demonstrates that the greenhouse gases emitted by human activities are the primary driver.” I also agree with their statement that “Moreover, there is strong evidence that ongoing climate change will have broad impacts on society, including the global economy and on the environment.” Therefore, it is incumbent on us to address the threat of climate change.

I also agree with the recent policy statement of the American Meteorological Society on geoengineering (Supplementary Material 2). I was a member of the committee that wrote this statement. As the statement explains, “Three proactive strategies could reduce the risks of climate change: 1) *mitigation*: reducing emissions; 2) *adaptation*: moderating climate impacts by increasing our capacity to cope with them; and 3) *geoengineering*: deliberately manipulating physical, chemical, or biological aspects of the Earth system.”

Before discussing geoengineering it is necessary to define it. As the American Meteorological Society statement says, “Geoengineering proposals fall into at least three broad categories: 1) reducing the levels of atmospheric greenhouse gases through large-scale manipulations (e.g., ocean fertilization or afforestation using non-native species); 2) exerting a cooling influence on Earth by reflecting sunlight (e.g., putting reflective particles into the atmosphere, putting mirrors in space, increasing surface reflectivity, or altering the amount or characteristics of clouds); and 3) other large-scale manipulations designed to diminish climate change or its impacts (e.g., constructing vertical pipes in the ocean that would increase downward heat transport).”

My expertise is in category 2, sometimes called “solar radiation management.” In particular, my work has focused on the idea of emulating explosive volcanic eruptions, by attempting to produce a stratospheric cloud that would reflect some incoming sunlight, to shade and cool the planet to counteract global warming. In this testimony, except where indicated, I will confine my remarks to this specific idea, and use the term “geoengineering” to refer to only it. I do this because it is the suggestion that has gotten the most attention recently, and because it is the one that I have addressed in my work.

My personal view is that we need aggressive mitigation to lessen the impacts of global warming. We will also have to devote significant resources to adaptation to deal with the adverse climate changes that are already beginning. If geoengineering is ever used, it should be as a short-term emergency measure, as a supplement to, and not as a substitute for, mitigation and adaptation. And we are not ready to implement geoengineering now.

The question of whether geoengineering could ever help to address global warming cannot be answered at this time. In our most recent paper (Supplementary Material 9) we have identified six potential benefits and 17 potential risks of stratospheric geoengineering, but a vigorous research program is needed to quantify each of these items, so that policy makers will

be able to make an informed decision, by weighing the benefits and risks of different policy options.

Furthermore, there has been no demonstration that geoengineering is even possible. No technology to do geoengineering currently exists. The research program needs to also evaluate various suggested schemes for producing stratospheric particles, to see whether it is practical to maintain a stratospheric cloud that would be effective at blocking sunlight.

Introduce the key scientific, regulatory, ethical, legal and economic challenges of geoengineering.

In Robock (2008a; Supplementary Material 4) I identified 20 reasons why geoengineering may be a bad idea. Subsequent work, summarized in Robock et al. (2009; Supplementary Material 9), eliminated three of these reasons, determined that one is still not well understood, but added one more reason, so I still have identified 17 potential risks of geoengineering. Furthermore, there is no current technology to implement or monitor geoengineering, should it be tested or implemented. Robock (2008b; Supplementary Material 5) described some of these effects, particularly on ozone.

Key challenges of geoengineering related to the side effects on the climate system are that it could produce drought in Asia and Africa, threatening the food and water supply for billions of people, that it would not halt continued ocean acidification from CO₂, and that it would deplete ozone and increase dangerous ultraviolet radiation. Furthermore, the reduction of direct solar radiation and the increase in diffuse radiation would make the sky less blue and produce much less solar power from systems using focused sunlight. Any system to inject particles or their precursors into the stratosphere at the needed rate would have large local environmental impacts. If society lost the will or means to continue geoengineering, there would be rapid warming, much more rapid than would occur without geoengineering. If a series of volcanic eruptions produced unwanted cooling, geoengineering could not be stopped rapidly to compensate. In addition, astronomers spend billions of dollars to build mountain-top observatories to get above pollution in the lower troposphere. Geoengineering would put permanent pollution above these telescopes.

Another category of challenges is unexpected consequences. No matter how much analysis is done ahead of time, there will be surprises. Some will make the effects less damaging, but some will be more damaging. Furthermore, human error is likely to produce problems with any sophisticated technical system.

Ethical challenges include what is called a moral hazard – if geoengineering is perceived to be a solution for global warming, it will lessen the current gathering consensus to address climate change with mitigation. There is also the question of moral authority – do humans have the right to control the climate of the entire planet to benefit them, without consideration of all other species? Another ethical issue is the potential military use of any geoengineering technology. One of the cheapest approaches may even be to use existing military airplanes for geoengineering (Robock et al., 2009; Supplementary Material 9). Could techniques developed to control global climate forever be limited to peaceful uses? Other ethical considerations might arise if geoengineering would improve the climate for most, but harm some.

Legal and regulatory challenges are closely linked to ethical ones. Who would end up controlling geoengineering systems? Governments? Private companies holding patents on proprietary technology? And whose benefit would they have at heart? Stockholders or the general public welfare? Eighty-five countries, including the United States, have signed the U.N. Convention on the Prohibition of Military or Any Other Hostile Use of Environmental

Modification Techniques. It will have to be modified to allow geoengineering that would harm any of the signatories. And whose hand would be on the thermostat? How would the world decide on what level of geoengineering to apply? What if Canada or Russia wanted the climate to be a little warmer, while tropical countries and small island states wanted it cooler? Certainly new governance mechanisms would be needed.

As far as economic challenges go, even if our estimate (Robock et al., 2009; Supplementary Material 9) is off by a factor of 10, the costs of actually implementing geoengineering would not be a limiting factor. Rather, the economic issues associated with the potential damages of geoengineering would be more important.

Major strategies for evaluating different geoengineering methods.

Evaluation of geoengineering strategies requires determination of their costs, benefits, and risks. Furthermore, geoengineering requires ongoing monitoring. As discussed below, a robust research program including computer modeling and engineering studies, as well as study of historical, ethical, legal, and social implications of geoengineering and governance issues is needed. Monitoring will require the reestablishment of the capability of measuring the location, properties and vertical distribution of particles and ozone in the stratosphere using satellites.

Broadly evaluate the geoengineering strategies you believe could be most viable based on these criteria.

I know of no viable geoengineering strategies. None have been shown to work to control the climate. None have been shown to be safe. However, the ones that have the most potential, and which need further research, would include stratospheric aerosols and brightening of marine tropospheric clouds, as well as carbon capture and sequestration. Carbon capture has been demonstrated on a very small scale. Whether it can be conducted on a large enough scale to have a measurable impact on atmospheric CO₂ concentrations, and whether the CO₂ can be sequestered efficiently and safely for a long period of time, are areas that need to be researched.

Identify the climate circumstances under which the U.S. or international community should undertake geoengineering.

For a decision to actually implement geoengineering, it needs to be demonstrated that the benefits of geoengineering outweigh the risks. We need a better understanding of the evolution of future climate both with and without geoengineering. We need to know the costs of implementation of geoengineering and compare them to the costs of not doing geoengineering. Geoengineering should only be implemented in response to a planetary emergency. However, there are no governance mechanisms today that would allow such a determination. Governance would also have to establish criteria to determine the end of the emergency and the ramping down of geoengineering.

Examples of climate circumstances that would be candidates for the declaration of a planetary emergency would include rapid melting of the Greenland or Antarctic ice sheets, with attendant rapid sea level rise, or a catastrophic increase in severe hurricanes and typhoons. Even so, stratospheric geoengineering should only be implemented if it could be determined that it would address these specific emergencies without causing worse problems. And there may be local means to deal with these specific issues that would not produce the risks of global geoengineering. For example, sea level rise could be addressed by pumping sea water into a new

lake in the Sahara or onto the cold Antarctic ice sheet where it would freeze. There may be techniques to cool the water ahead of approaching hurricanes by mixing cold water from below up to the surface. Of course, each of these techniques may have its own unwelcome side effects.

Right now there are no circumstances that would warrant geoengineering. This is because we lack the knowledge to evaluate the benefits, risks, and costs of geoengineering. We also lack the requisite governance mechanisms. Our policy right now needs to be to focus on mitigation, while funding research that will produce the knowledge to make such decisions about geoengineering in five or ten years.

Recommendations for first steps, if any, to begin a geoengineering research and/or governance effort.

In 2001, the U.S. Department of Energy issued a white paper (Supplementary Material 3) that called for a \$64,000,000 research program over five years to look into a variety of suggested methods to control the climate. Such a coordinated program was never implemented, but there are now a few research efforts using climate models of which I am aware. In addition to my grant from the National Science Foundation, discussed below, I know of one grant from NASA to Brian Toon for geoengineering research and some work by scientists at the National Center for Atmospheric Research, funded by the Federal Government. In addition, there have been some climate modeling studies conducted at the United Kingdom Hadley Centre, and there is a new three-year project, started in July 2009, funded by the European Union for €1,000,000 (\$1,500,000) for three years called “IMPLICC - Implications and risks of engineering solar radiation to limit climate change,” involving the cooperation of 5 higher educational and research institutions in France, Germany and Norway.

In light of the importance of this issue, as outlined in Robock (2008b; Supplementary Material 5), I recommend that the U.S., in collaboration with other countries, embark on a well-funded research program to “consider geoengineering’s potential benefits, to understand its limitations, and to avoid ill-considered deployment” (as the American Meteorological Society says in Supplementary Material 2). In particular the American Meteorological Society recommends:

- 1) Enhanced research on the scientific and technological potential for geoengineering the climate system, including research on intended and unintended environmental responses.
- 2) Coordinated study of historical, ethical, legal, and social implications of geoengineering that integrates international, interdisciplinary, and intergenerational issues and perspectives and includes lessons from past efforts to modify weather and climate.
- 3) Development and analysis of policy options to promote transparency and international cooperation in exploring geoengineering options along with restrictions on reckless efforts to manipulate the climate system.

I support all these recommendations. Research under item 1) would involve state-of-the-art climate models, which have been validated by previous success at simulating past climate change, including the effects of volcanic eruptions. They would consider different suggested scenarios for injection of gases or particles designed to produce a stratospheric cloud, and evaluate the positive and negative aspects of the climate response. So far, the small number of studies that have been conducted have all used different scenarios, and it is difficult to compare the results to see which are robust. One such example is given in the paper by Rasch et al. (2008; Supplementary Material 7). Therefore, I am in the process of organizing a coordinated

experiment among the different climate modeling groups that are performing runs for the Coupled Model Intercomparison Project, Phase 5, which will inform the next Intergovernmental Panel on Climate Change report. Once we agree on a set of standard scenarios, participation will depend on these different groups from around the world volunteering their computer and analysis time to conduct the experiments. Financial support from a national research program, in cooperation with other nations, will produce more rapid and more comprehensive results.

Another area of research that needs to be supported under topic 1) is the technology of producing a stratospheric aerosol cloud. Robock et al. (2009; Supplementary Material 9) calculated that it would cost several billion dollars per year to just inject enough sulfur gas into the stratosphere to produce a cloud that would cool the planet using existing military airplanes. Others have suggested that it would be quite a bit more expensive. However, even if SO₂ (sulfur dioxide) or H₂S (hydrogen sulfide) could be injected into the stratosphere, there is no assurance that nozzles and injection strategies could be designed to produce a cloud with the right size droplets that would be effective at scattering sunlight. Our preliminary theoretical work on this problem is discussed by Rasch et al. (2008; Supplementary Material 7). However, the research program will also need to fund engineers to actually build prototypes based on modification of existing aircraft or new designs, and to once again examine other potential mechanisms including balloons, artillery, and towers. They will also have to look into engineered particles, and not just assume that we would produce sulfate clouds that mimic volcanic eruptions.

At some point, given the results of climate models and engineering, there may be a desire to test such a system in the real world. But this is not possible without full-scale deployment, and that decision would have to be made without a full evaluation of the possible risks. Certainly individual aircraft or balloons could be launched into the stratosphere to release sulfur gases. Nozzles can be tested. But whether such a system would produce the desired cloud could not be tested unless it was deployed into an existing cloud that is being maintained in the stratosphere. While small sub-micron particles would be most effective at scattering sunlight and producing cooling, current theory tells us that continued emission of sulfur gases would cause existing particles to grow to larger sizes, larger than volcanic eruptions typically produce, and they would be less effective at cooling Earth, requiring even more emissions. Such effects could not be tested, except at full-scale.

Furthermore, the climatic response to an engineered stratospheric cloud could not be tested, except at full-scale. The weather is too variable, so that it is not possible to attribute responses of the climate system to the effects of a stratospheric cloud without a very large effect of the cloud. Volcanic eruptions serve as an excellent natural example of this. In 1991, the Mt. Pinatubo volcano in the Philippines injected 20 Mt (megatons) of SO₂ (sulfur dioxide) into the stratosphere. The planet cooled by about 0.5°C (1°F) in 1992, and then warmed back up as the volcanic cloud fell out of the atmosphere over the next year or so. There was a large reduction of the Asian monsoon in the summer of 1992 and a measurable ozone depletion in the stratosphere. Climate model simulations suggest that the equivalent of one Pinatubo every 4 years or so would be required to counteract global warming for the next few decades, because if the cloud were maintained in the stratosphere, it would give the climate system time to cool in response, unlike for the Pinatubo case, when the cloud fell out of the atmosphere before the climate system could react fully. To see, for example, what the effects of such a geoengineered cloud would be on precipitation patterns and ozone, we would have to actually do the experiment. The effects of smaller amounts of volcanic clouds on climate can simply not be detected, and a diffuse cloud produced by an experiment would not provide the correct environment for continued emissions of sulfur gases. The recent fairly large eruptions of the Kasatochi volcano in 2008 (1.5 Mt SO₂)

and Sarychev in 2009 (2 Mt SO₂) did not produce a climate response that could be measured against the noise of chaotic weather variability.

Some have suggested that we test stratospheric geoengineering in the Arctic, where the cloud would be confined and even if there were negative effects, they would be limited in scope. But our experiments (Robock et al., 2008; Supplementary Material 6) found that clouds injected into the Arctic stratosphere would be blown by winds into the midlatitudes and would affect the Asian summer monsoon. Observations from all the large high latitude volcanic eruptions of the past 1500 years, Eldgjá in 939, Laki in 1783, and Katmai in 1912, support those results.

Topics 2) and 3) should also be part of any research program, with topic 3) dealing with governance issues. This is not my area of expertise, but as I understand it, the U.N. Convention on the Prohibition of Military or Any Other Hostile Use of Environmental Modification Techniques prohibits geoengineering if it will have negative effects on any of the 85 signatories to the convention (which include the U.S.). International governance mechanisms, probably through the United Nations, would have to be established to set the rules for testing, deployment, and halting of any geoengineering. Given the different interests in the world, and the current difficulty of negotiating mitigation, it is not clear to me how easy this would be. And any abrogation of such agreements would produce the potential for conflict.

How much would a geoengineering research program cost? Given the continued threat to the planet from climate change, it is important that in the next decade policy makers be provided with enough information to be able to decide whether geoengineering can be considered as an emergency response to dangerous climate change, given its potential benefits, costs, and risks. If the program is not well-funded, such answers will be long in coming. The climate modeling community is ready to conduct such experiments, given an increase in funding for people and computers. Funding should include support for students studying climate change as well as to existing scientists, and would not be that expensive. It should certainly be in the range of millions of dollars per year for a 5-10 year period. I am less knowledgeable of what the costs would be for engineering studies or for topics 2) and 3).

A geoengineering research program should not be at the expense of existing research into climate change, and into mitigation and adaptation. Our first goal should be rapid mitigation, and we need to continue the current increase in support for green alternatives to fossil fuels. We also need to continue to better understand regional climate change, to help us to implement mitigation and adapt to the climate change that will surely come in the next decades no matter what our actions today. But a small increment to current funding to support geoengineering will allow us to determine whether geoengineering deserves serious consideration as a policy option.

Describe your NSF-funded research activities at Rutgers University.

I am supported to conduct geoengineering research by the following grant:

National Science Foundation, ATM-0730452, "Collaborative Research in Evaluation of Suggestions to Geoengineer the Climate System Using Stratospheric Aerosols and Sun Shading," February 1, 2008 – January 31, 2011, \$554,429. (Includes \$5000 Research Experience for Undergraduates supplement.)

I conduct research with Professors Georgiy Stenchikov and Martin Bunzl and students Ben Kravitz and Allison Marquardt at Rutgers, in collaboration with Prof. Richard Turco at UCLA, who is funded on a collaborative grant by NSF with separate funding. We conduct climate model simulations of the response to various scenarios of production of a cloud of particles in the stratosphere. We use a NASA climate model on NASA computers to conduct our

simulations. We also have investigated the potential cost of injecting gases into the stratosphere that would react with water vapor to produce a cloud of sulfuric acid droplets. We calculated how much additional acid rain and snow would result when the sulfuric acid eventually falls out of the atmosphere. Prof. Turco focuses on the detailed mechanisms in the stratosphere whereby gases convert to particles. Prof. Bunzl is a philosopher. Together we are also examining the ethical dimensions of geoengineering proposals.

We have published five peer-reviewed journal articles on our research so far, attached as Supplementary Material items 5-9, and Prof. Bunzl has published one additional peer-reviewed paper supported by this grant.

Delineate the precautionary steps that might be needed in the event of large scale testing or deployment.

First of all, there is little difference between large-scale testing and deployment. To be able to measure the climate response to a stratospheric cloud above the noise of chaotic weather variations, the injection of stratospheric particles would have to be so large as that it would be indistinguishable from deployment of geoengineering. And it would have to last long enough to produce a measurable climate response, at least for five years. One of the potential risks of this strategy is that if it is perceived to be working, the enterprise will develop a constituency that will push for it to continue, just like other government programs, with the argument that jobs and business need to be protected.

The world will have to develop a governance structure that can decide on whether or not to do such an experiment, with detailed rules as to how it will be evaluated and how the program will be ended. The current U.N. Convention on the Prohibition of Military or Any Other Hostile Use of Environmental Modification Techniques will have to be modified.

Any large-scale testing or deployment would need to be first be evaluated thoroughly with climate model simulations. Climate models have been validated by simulating past climate change, including the effects of large volcanic eruptions. They will allow scientists to test different patterns of aerosol injection and different types of aerosols, and to thoroughly study the resulting spatial patterns of temperature, precipitation, soil moisture, and other climate responses. This information will allow the governance structure to make informed decisions about whether to proceed.

Any field testing of geoengineering would need to be monitored so that it can be evaluated. While the current climate observing system can do a fairly good job of measuring temperature, precipitation, and other weather elements, we currently have no system to measure clouds of particles in the stratosphere. After the 1991 Pinatubo eruption, observations with the Stratospheric Aerosol and Gas Experiment II (SAGE II) instrument on the Earth Radiation Budget Satellite showed how the aerosols spread, but it is no longer operating. To be able to measure the vertical distribution of the aerosols, a limb-scanning design, such as that of SAGE II, is optimal. Right now, the only limb-scanner in orbit is the Optical Spectrograph and InfraRed Imaging System (OSIRIS), a Canadian instrument on Odin, a Swedish satellite. SAGE III flew from 2002 to 2006, and there are no plans for a follow on mission. A spare SAGE III sits on a shelf at a NASA lab, and could be used now. There is one Canadian satellite in orbit now with a laser, but it is not expected to last long enough to monitor future geoengineering, and there is no system to use it to produce the required observations of stratospheric particles. Certainly, a dedicated observational program would be needed as an integral part of any geoengineering implementation.

These current and past successes can be used as a model to develop a robust stratospheric observing system, which we need anyway to be able to measure the effects of episodic volcanic eruptions. The recent fairly large eruptions of the Kasatochi volcano in 2008 and Sarychev in 2009 produced stratospheric aerosol clouds, but the detailed structure and location of the resulting clouds is poorly known, because of a lack of an observing system.

Identify the aspects of geoengineering you believe present the greatest risks.

Our recent article (see box at right) lists 17 potential risks, but without further research to evaluate the magnitude of each, my answer will just be a subjective judgment.

Nevertheless, I would say that the potential weakening of the Asian and African summer monsoon, with a reduction in precipitation and threat to the food and water supply for more than two billion people, should be at the top of the list. So far different climate model experiments give different amounts of precipitation change, and even if precipitation changes, reduced evapotranspiration, enhanced growth from diffuse radiation and increased CO₂ may compensate. This is an area of research that deserves detailed study with many different climate models.

Other important potential risks include continued ocean acidification and ozone depletion (with enhanced ultraviolet radiation). And if society ever lost the will or means to continue geoengineering, rapid warming would be more dangerous than the gradual warming we are now experiencing.

Even if governance issues were completely addressed before any geoengineering takes place, international conflict could result if there are perceived negative consequences for some nations, and geoengineering continues due to the perceived advantages for those conducting the geoengineering.

With regard to another suggested geoengineering technique, brightening of marine clouds, there is also a threat to precipitation in other locations, such as the Amazon, and a possible large impact on the oceanic food chain due to less solar energy needed for plankton at the base of the food chain to grow. Again, these potential risks need to be evaluated.

| Risks |
|---|
| 1. Drought in Africa and Asia |
| 2. Continued ocean acidification from CO ₂ |
| 3. Ozone depletion |
| 4. No more blue skies |
| 5. Less solar power |
| 6. Environmental impact of implementation |
| 7. Rapid warming if stopped |
| 8. Cannot stop effects quickly |
| 9. Human error |
| 10. Unexpected consequences |
| 11. Commercial control |
| 12. Military use of technology |
| 13. Conflicts with current treaties |
| 14. Whose hand on the thermostat? |
| 15. Ruin terrestrial optical astronomy |
| 16. Moral hazard – the prospect of it working would reduce drive for mitigation |
| 17. Moral authority – do we have the right to do this? |

Potential risks of geoengineering [Table 1 from Robock et al., 2009; Supplementary Material 9]

October 21, 2009

American Association for the
Advancement of Science

American Chemical Society

American Geophysical Union

American Institute of
Biological Sciences

American Meteorological
Society

American Society of
Agronomy

American Society of Plant
Biologists

American Statistical
Association

Association of Ecosystem
Research Centers

Botanical Society of America

Crop Science Society of
America

Ecological Society of America

Natural Science Collections
Alliance

Organization of Biological
Field Stations

Society for Industrial and
Applied Mathematics

Society of Systematic
Biologists

Soil Science Society of
America

University Corporation for
Atmospheric Research

Dear Senator:

As you consider climate change legislation, we, as leaders of scientific organizations, write to state the consensus scientific view.

Observations throughout the world make it clear that climate change is occurring, and rigorous scientific research demonstrates that the greenhouse gases emitted by human activities are the primary driver. These conclusions are based on multiple independent lines of evidence, and contrary assertions are inconsistent with an objective assessment of the vast body of peer-reviewed science. Moreover, there is strong evidence that ongoing climate change will have broad impacts on society, including the global economy and on the environment. For the United States, climate change impacts include sea level rise for coastal states, greater threats of extreme weather events, and increased risk of regional water scarcity, urban heat waves, western wildfires, and the disturbance of biological systems throughout the country. The severity of climate change impacts is expected to increase substantially in the coming decades.¹

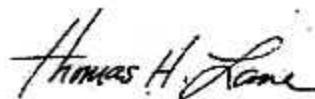
If we are to avoid the most severe impacts of climate change, emissions of greenhouse gases must be dramatically reduced. In addition, adaptation will be necessary to address those impacts that are already unavoidable. Adaptation efforts include improved infrastructure design, more sustainable management of water and other natural resources, modified agricultural practices, and improved emergency responses to storms, floods, fires and heat waves.

We in the scientific community offer our assistance to inform your deliberations as you seek to address the impacts of climate change.

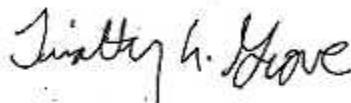
¹ The conclusions in this paragraph reflect the scientific consensus represented by, for example, the Intergovernmental Panel on Climate Change and U.S. Global Change Research Program. Many scientific societies have endorsed these findings in their own statements, including the [American Association for the Advancement of Science](#), [American Chemical Society](#), [American Geophysical Union](#), [American Meteorological Society](#), and [American Statistical Association](#).



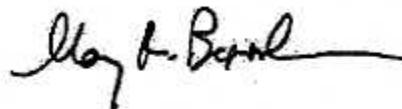
Alan I. Leshner
Executive Director
American Association for the
Advancement of Science



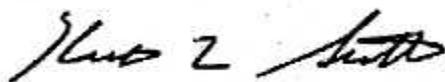
Thomas Lane
President
American Chemical Society



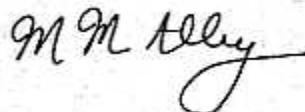
Timothy L. Grove
President
American Geophysical Union



May R. Berenbaum
President
American Institute of Biological
Sciences



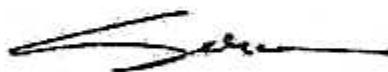
Keith Seitter
Executive Director
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President
American Society of Agronomy



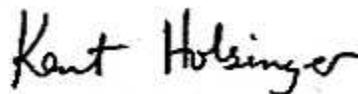
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Lucinda Johnson
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Centers



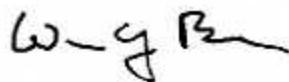
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Kenneth Quesenberry
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Crop Science Society of America



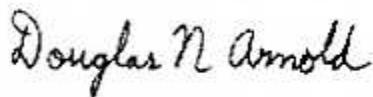
Mary Power
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William Y. Brown
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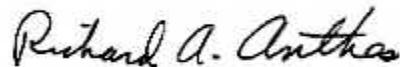
Douglas N. Arnold
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Society for Industrial and Applied
Mathematics



John Huelsenbeck
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Society of Systematic Biologists



Paul Bertsch
President
Soil Science Society of America



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Research

AMS Policy Statement on Geoengineering the Climate System

A Policy Statement of the American Meteorological Society
(Adopted by the AMS Council on 20 July 2009)

Human responsibility for most of the well-documented increase in global average temperatures over the last half century is well established. Further greenhouse gas emissions, particularly of carbon dioxide from the burning of fossil fuels, will almost certainly contribute to additional widespread climate changes that can be expected to cause major negative consequences for most nations¹.

Three proactive strategies could reduce the risks of climate change: 1) *mitigation*: reducing emissions; 2) *adaptation*: moderating climate impacts by increasing our capacity to cope with them; and 3) *geoengineering*: deliberately manipulating physical, chemical, or biological aspects of the Earth system². This policy statement focuses on large-scale efforts to geoengineer the climate system to counteract the consequences of increasing greenhouse gas emissions.

Geoengineering could lower greenhouse gas concentrations, provide options for reducing specific climate impacts, or offer strategies of last resort if abrupt, catastrophic, or otherwise unacceptable climate-change impacts become unavoidable by other means. However, research to date has not determined whether there are large-scale geoengineering approaches that would produce significant benefits, or whether those benefits would substantially outweigh the detriments. Indeed, geoengineering must be viewed with caution because manipulating the Earth system has considerable potential to trigger adverse and unpredictable consequences.

Geoengineering proposals fall into at least three broad categories: 1) reducing the levels of atmospheric greenhouse gases through large-scale manipulations (e.g., ocean fertilization or afforestation using non-native species); 2) exerting a cooling influence on Earth by reflecting sunlight (e.g., putting reflective particles into the atmosphere, putting mirrors in space, increasing surface reflectivity, or altering the amount or characteristics of clouds); and 3) other large-scale manipulations designed to diminish climate change or its impacts (e.g., constructing vertical pipes in the ocean that would increase downward heat transport).

Geoengineering proposals differ widely in their potential to reduce impacts, create new risks, and redistribute risk among nations. Techniques that remove CO₂ directly from the air would confer global benefits but could also create adverse local impacts. Reflecting sunlight would likely reduce Earth's average temperature but could also change global circulation patterns with potentially serious consequences such as changing storm tracks and precipitation patterns. As with inadvertent human-induced climate change, the consequences of reflecting sunlight would almost certainly not be the same for all nations and peoples, thus raising legal, ethical, diplomatic, and national security concerns.

Exploration of geoengineering strategies also creates potential risks. The possibility of quick and seemingly inexpensive geoengineering fixes could distract the public and policy makers from critically needed efforts to reduce greenhouse gas emissions and build society's capacity to deal with unavoidable climate impacts. Developing any new capacity, including geoengineering, requires resources that will possibly be drawn from more productive uses. Geoengineering

technologies, once developed, may enable short-sighted and unwise deployment decisions, with potentially serious unforeseen consequences.

Even if reasonably effective and beneficial overall, geoengineering is unlikely to alleviate all of the serious impacts from increasing greenhouse gas emissions. For example, enhancing solar reflection would not diminish the direct effects of elevated CO₂ concentrations such as ocean acidification or changes to the structure and function of biological systems.

Still, the threat of climate change is serious. Mitigation efforts so far have been limited in magnitude, tentative in implementation, and insufficient for slowing climate change enough to avoid potentially serious impacts. Even aggressive mitigation of future emissions cannot avoid dangerous climate changes resulting from past emissions, because elevated atmospheric CO₂ concentrations persist in the atmosphere for a long time. Furthermore, it is unlikely that all of the expected climate-change impacts can be managed through adaptation. Thus, it is prudent to consider geoengineering's potential benefits, to understand its limitations, and to avoid ill-considered deployment.

Therefore, the American Meteorological Society recommends:

- 1) Enhanced research on the scientific and technological potential for geoengineering the climate system, including research on intended and unintended environmental responses.
- 2) Coordinated study of historical, ethical, legal, and social implications of geoengineering that integrates international, interdisciplinary, and intergenerational issues and perspectives and includes lessons from past efforts to modify weather and climate.
- 3) Development and analysis of policy options to promote transparency and international cooperation in exploring geoengineering options along with restrictions on reckless efforts to manipulate the climate system.

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.

[This statement is considered in force until July 2012 unless superseded by a new statement issued by the AMS Council before this date]

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¹ For example, impacts are expected to include further global warming, continued sea level rise, greater rainfall intensity, more serious and pervasive droughts, enhanced heat stress episodes, ocean acidification, and the disruption of many biological systems. These impacts will likely lead to the inundation of coastal areas, severe weather, and the loss of ecosystem services, among other major negative consequences.

² These risk management strategies sometimes overlap and some specific actions are difficult to classify uniquely. To the extent that a geoengineering approach improves society's capacity to cope with changes in the climate system, it could reasonably be considered adaptation. Similarly, geological carbon sequestration is considered by many to be mitigation even though it requires manipulation of the Earth system.

White Paper

Response Options to Limit Rapid or Severe Climate Change

ASSESSMENT OF RESEARCH NEEDS

**Prepared For President Bush's
National Climate Change Technology Initiative**

October 2001



**U.S. Department of Energy
Washington DC**

Acknowledgment

In June 2001, President Bush announced the National Climate Change Technology Initiative (NCCTI), and directed the Secretary of Energy, in cooperation with other Agencies and Departments to formulate an implementation plan for the initiative. To discharge this responsibility, an interagency process was initiated, led by the Deputy Secretary of Energy, and organized into four thematic groups: Energy, Other Greenhouse Gases and Related Technologies, Offsets, and Monitoring and Measurement. These were further organized into subgroups. The Deputy Secretary appointed Dr. Robert Marlay, Director of the Office of Science and Technology Policy Analysis, to head this activity. Dr. Ari Patrinos, Director of the Office of Biological and Environmental Research, was also instrumental in support of this activity.

This White Paper is one of a series of such White Papers to serve as a resource for developing the NCCTI plan. A steering committee was formed to prepare this White Paper. The steering committee members consist of:

- Dr. Ehsan Khan, DOE (Lead)
- Dr. Wanda Ferrell, DOE (Co-Lead)
- Dr. Michael C. MacCracken, USGCRP
- Dr. Stephen E. Schwartz, BNL
- Dr. Philip B. Duffy, LLNL
- Dr. Starley Thompson, LLNL
- Dr. Gregory H. Marland, ORNL

A preliminary version of the White Paper was discussed at a workshop held on October 9, 2001, at the Department of Energy in Germantown, Maryland. More than 25 people participated in this workshop either in person or via videoconference from the West Coast (Sandia National Laboratory at Livermore, and The Scripps Institution of Oceanography). Participants included prominent scientist and engineers from the National Laboratories, universities, industry, and NASA. Appendix C provides the agenda for the workshop, and a list of participants. Additionally, comments were received from several other individuals who were unable to participate. This White Paper has taken into consideration presentations, comments, concerns and issues that were discussed at the workshop. The steering committee thanks all participants for their contributions and insights.

DISCLAIMER

This White Paper is a working document prepared as an account of work sponsored by an agency of the United States Government. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof.

Response Options to Limit Rapid or Severe Climate Change

ASSESSMENT OF RESEARCH NEEDS

Executive Summary

The Framework Convention on Climate Change recognizes that it is essential to provide the food, energy, and amenities to sustain the quality of life and to enhance the standard of living of the growing population of the 21st century. With fossil fuels providing more than 80 percent of the world's energy, the low cost and extensive investment in this energy resource will necessitate their continued large-scale use for many decades. As a result of ongoing and past emissions, continued changes in the climate are inevitable, and there is a significant risk of rapid and disruptive climate change in the decades ahead.

These climate changes and their causes are the subject of intense scientific study. The results of these studies are being used to make projections of expected future climate change in response to past and projected future activities. It is generally accepted that the equilibrium warming that would result from a doubling of the atmospheric CO₂ concentration from present levels is likely to be within the range 1.5 to 4.5°C; however, analysis of climate model studies and of the historic record allows for an even higher upper limit. During the last century, global average temperature increased by about 0.6 °C, whereas projections for the 21st century range up to about five-to-ten times this amount. There is a possibility for this warming to induce extreme weather events and major climate variations, which could lead to severe adverse consequences. Typical examples of such consequences that might require moderation or amelioration are rapid climate change in the Arctic, persistent development of exceptionally powerful storms (e.g., super hurricanes) affecting major population centers, and sustained droughts in key agricultural regions.

These events could have a significant impact on our way of life, especially the economy and the environment. The possibility of such events then raises the question of whether it is possible to avert these severe consequences through deliberate actions. Clearly any effort to deliberately moderate or ameliorate threats that may arise or become more likely as a result of climate change should be undertaken only in extraordinary circumstances. One needs to ensure that there are no unacceptable or irreversible consequences from any such effort. In view of the risk of significant consequences to society and the environment from either inaction or poorly understood actions, research should be initiated now to examine possible options to moderate adverse climate threats; to ensure that these options are effective, affordable, reversible and sustainable.

This document presents an initial assessment of technical approaches that may be feasible for moderating or ameliorating particularly severe weather and climatic threats, and examines the knowledge gaps that preclude informed decision-making for their implementation. A full feasibility assessment of these approaches and their design cannot be done at present because of lack of knowledge of the requirements of the several approaches, of their engineering requirements, of their climate response, their environmental impacts and other problems. This document presents an assessment of the research that is required to provide the information and understanding that will permit design and evaluation of potential activities that can ultimately better inform decision-makers regarding the implementation of these activities, should they become necessary.

Types of activities that are considered include increasing the reflectivity of marine stratus clouds, using stratospheric scatterers to reduce incoming solar radiation, altering Arctic ocean salinity by controlling river or ocean flows, increasing wintertime heat loss from high-latitude oceans, and use of ocean coatings to weaken or divert severe storms. Assessing the feasibility of the identified approaches requires scoping studies, examination of engineering feasibility, additional climate monitoring capabilities, improving and validating geophysical and economic models, and conducting benchmark, pilot scale and field tests. This White Paper outlines the required research and presents a preliminary plan to conduct this research. The proposed research would require approximately \$64 million over 5 years.

RESPONSE OPTIONS TO LIMIT RAPID OR SEVERE CLIMATE CHANGE

1.0 Introduction and Scope

In June 2001, President Bush announced the National Climate Change Technology Initiative (NCCTI), and directed the Secretary of Energy, in cooperation with other Agencies and Departments to formulate an implementation plan for the initiative. The Department of Energy commissioned a series of technical White Papers to serve as a resource for developing the NCCTI plan. The objective of the NCCTI is to develop and apply technologies to reduce the build up of greenhouse gases in the atmosphere, with the ultimate goal of stabilizing the climate and concentrations of greenhouse gases in the atmosphere.

This White Paper complements other White Papers as it addresses a contingency plan to limit severe consequences of climate change that could occur while in the process of stabilizing the build up of greenhouse gases. Because of the low cost and extensive investment in fossil energy resources around the world, there will continue to be large-scale use of these energy sources for many decades. There is wide scientific agreement that the resulting emissions of CO₂ and other greenhouse gases will contribute to significant climate change during the 21st century, although the timing, magnitude, and pattern remain uncertain. This is due to the limited understanding of the climate system and of future global emissions. Figure 1 shows that even if there is total elimination of emissions in Organization for Economic Cooperation and Development (OECD) countries beginning in 1990, such total elimination does not significantly reduce global mean temperature rise over the next century. This is because Asia as well as Africa, Latin America and Middle Eastern nations are projected to have a rapidly growing energy generation sector in the 21st century, that will result in a rapid increase in greenhouse gas emissions (Special Report on Emission Scenarios (SRES), Marker scenario A1, Nakicenovic et al. 2000), and global mean temperature rise.

It is important to note that the global economy and global environment are interlinked, and countries around the world are concerned about the effect of global warming on their economy. However, the degree of urgency with which the international community has embraced the challenge of climate change cannot be easily explained in terms of economics alone: the more compelling motivations to act stem more likely from concerns about possible foreseen and undesirable climate surprises, and from fears that certain natural ecosystems will be seriously disrupted and that some species and ecosystems may disappear entirely.

Continuing global emissions of CO₂ and other greenhouse gases, certain to be well above today's level through the 21st century, will lead to significant changes that, coupled with the natural variations of the climate, are very likely to lead to occurrence of severe and disruptive weather and climate situations. Estimates vary as to the climatic consequences of doubling the pre-industrial concentration of CO₂ in the atmosphere, but almost all climate researchers conclude that the global mean temperature will rise between 1.5 and 4.5 degrees C. This uncertainty is caused predominantly by uncertainties in climate feedback effects, and to a lesser extent by an uncertainty in predictions of greenhouse gas emissions, as discussed in the next paragraph. Interestingly, in spite of extensive research, this range of estimates in the projected increase has not narrowed in more than a decade.

A change in the greenhouse gas concentrations affect the fraction of infrared radiation that leaves the Earth and reaches the top of the atmosphere, resulting in a change of the average temperature of the earth and the atmosphere adjacent to the Earth. The change in temperature affects the ice, snow, and cloud cover, cloud height, the water vapor in the atmosphere, ocean temperature and evaporation rate, and other climatic variables. Changes in these variables cause further changes in the average surface temperature of the earth. If changes in these variables increase the temperature of the Earth and its adjacent atmosphere, it is called a positive feedback effect, otherwise a negative feedback effect.

An increase in surface temperature of the Earth results in an increase of water vapor content of the atmosphere, increasing the infrared absorption, trapping more infrared radiation that would otherwise leave the system, thereby further increasing the surface average temperature. The uncertainty associated

with water- vapor feedback is much less than that associated with the effects of clouds – the cloud feedback. In the current climate conditions, clouds have a net cooling effect, as they reflect more sunlight than they absorb infrared radiation. If cloudiness changes with temperature, the nature, height, and changes in the geographical location of the clouds would then determine if these changes result in a positive or negative feedback. Surface snow and ice cover change provide a positive feedback with temperature increase, because a decrease in ice and snow cover decreases the albedo. In fact, a major concern is that continued global warming could lead to positive feedbacks due to thinning of clouds (- see DelGenio, 2000), melting of ice, and increase in the water vapor (a greenhouse gas) content of the atmosphere. This positive feedback could result in a relatively rapid rise of the world’s average temperature, with potentially a further increase in positive feedback. Thus global warming may trigger further global warming, leading to a rapid rise in global temperature (the extreme limit of this positive feedback, the so-called ‘runaway’ global warming is thought not likely to occur on Earth, but has been postulated to have occurred on Venus (see Philander, 1998)). However, the consequences of a rapid rise in global temperature could be severe and consequently the risk of this climate event cannot be ignored. In addition, there are a number of other severe climate change issues (Table 1) that could be triggered by an increase in global warming.

The White Paper considers deliberate steps that might be taken to monitor the onset of such rapid or severe situations and explores options for limiting their outcomes. The paper then summarizes the major R&D elements necessary to develop an emergency response strategy for moderating the severe consequences that could result from the climate change issues of Table 1. The scope of this White Paper does not extend to a greenhouse gas mitigation plan as a means of limiting overall global warming – such a greenhouse gas mitigation plan is being developed by the other White Papers on this initiative.

This White Paper will be provided to the NCCTI Integration Group. A final integrated plan will be prepared between December 2001, and February 2002.

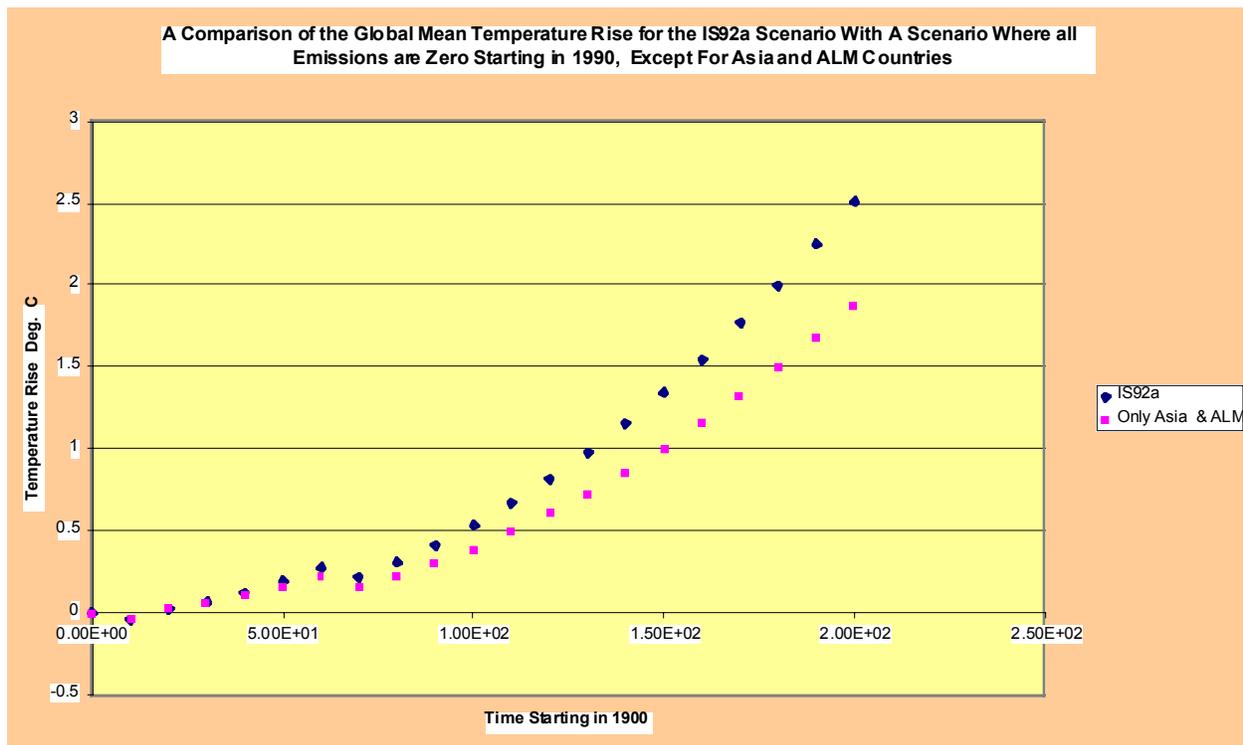


Fig. 1 Comparison of global mean temperature rise for the IPCC IS92a emissions scenario, with that for a reference scenario for which emissions starting in 1990 are assumed zero for the OECD countries but includes emissions from Asia, Africa, Latin America, and Middle East (unpublished work by Dr. Ehsan Khan)

| Table 1. POTENTIAL CONSEQUENCES OF GLOBAL WARMING |
|--|
| <p>1. Onset of Non-linear Processes- Rapid Rise in Temperature</p> <p>Prevailing projections are that the temperature will rise of order 0.2-0.3 °C per decade during the 21st century. However, warming at the upper limit of projections or the onset of unexpected non-linear processes (for example, rapid deterioration of the Arctic ice sheet) could cause the warming rate to increase by a factor of two or more.</p> |
| <p>2. Rapid Sea Level Rise</p> <p>While not believed likely, there have been a number of studies indicating the potential for sudden collapse of parts of the West Antarctic Ice Sheet. A rare episode of rainfall atop the Greenland ice sheet recently provided an indication of how it's melting might be accelerated. Sea level rise during the 21st century is projected to range from about 10 to 100 cm, with estimates of about 30 to 50 cm being considered most likely. Any accelerated melting of Greenland and Antarctica would be on top of these estimates. Once started, the rate of sea level rise could reach 1 to 3 m per century (counting contributions from ocean thermal expansion, melting of mountain glaciers, etc.), headed toward a total of perhaps 5 to 10 m sea level rise over 1000 years.</p> |
| <p>3. Very Intense Storms and Other Extreme Events</p> <p>With a warmer and moister atmosphere, more intense storms can develop because of the greater energy content of the atmosphere. This trend was evident for some types of storms during the 20th century and this is expected to continue. The potential also exists (confirmed by some model simulations) for an intensification of hurricanes and typhoons. For example, recent calculations with the US national hurricane model indicated that a 2 °C warming could lead to peak wind increases of 6 to 7 percent and an increase in peak 6-hr rainfall of more than 25 percent (for reference Hurricane Mitch delivered 48 inches of rain to Honduras in 48 hours, and a weaker storm delivered 30 inches of rain to Houston over 2 days). It is not just the power of storms that is the issue. Many major cities sit exposed to serious damage from storm surges created by a major hurricane (e.g., storm surge height in NY harbor for a Category 4 hurricane is more than 20 feet).</p> |
| <p>4. Modified Variability of the Climate</p> <p>There is increasing evidence that the frequency and intensity of the natural variations of the climate around the mean state may be affected by changes in climate. Warming up from the last glacial maximum, large fluctuations in climate occurred, indicating for major changes in the future. In addition, even if warming causes lower variability, the climate may become locked into a particular pattern that would severely impact some regions. For example, a persistent El Niños would have severe consequences for southeast Asia, Australia, and many Pacific islands, whereas a persistent La Niña, might lead to sequences of high hurricane activity in the Atlantic basin that could have devastating effects on the United States.</p> |
| <p>5. Collapse of Key Ecosystems</p> <p>Climate change may lead to serious disruption of key ecosystems. For example, coral reefs, which are essential to the existence of many islands, are already intensely stressed by warming and are likely to become further stressed by the rising CO₂ concentration, which leads to weaker structures. Increases in temperature and shifts in precipitation patterns may also seriously impact the Amazon rain forest and other regions.</p> |

6. Sudden and Intense Ozone Depletion

Sharp ozone depletion could arise as a result of the cooling of the stratosphere occurring due to the rising concentrations of greenhouse gases or due to a major volcanic eruption. Severe declines in the Northern Hemisphere springtime could lead to high UV doses for large numbers of people living in North America and Eurasia as well as for key ecosystems.

7. Rapid Loss of Arctic Sea Ice

Observations indicate that there is a loss of thickness of Arctic sea ice in the last 40 years, and that reduction of sea ice extent has already begun. Opening Arctic waters would lower the surface reflectivity and allow more solar radiation to be absorbed, further reducing sea ice and contributing to more rapid global warming. In addition to dramatic effects on resident and migrating Arctic wildlife, an open Arctic might provide moisture for excessive winter snowfall on surrounding regions and might alter global ocean currents. Preserving the sea ice would help to slow global warming and limit the amplified temperature increases in the high latitudes that are already inducing disruptive permafrost melting and may in the future prompt rapid release of methane to the atmosphere from soils and coastal sediments.

8. Sudden Change in Large-Scale Ocean Circulation

Both paleoclimatic (historical) evidence and results from a number of climate models suggest the possibility of the relatively rapid collapse of the thermohaline circulation (THC) that provides vital winter warmth for Europe and the rest of the North Atlantic Basin.

2.0 Vision

Increasing or decreasing the amount of solar radiation absorbed by the Earth has the potential to affect the global climate. Such modulation exerts a strong influence on climate as illustrated in both the historic and geological records of the Earth's history, where variation in the distribution of sunlight and the reflectivity of the planet are the major determinants of glacial-interglacial cycling. The great sensitivity of the Earth's climate to absorbed solar radiation suggests that the inadvertent changes in the climate that may arise from increasing concentrations of greenhouse gases could, if necessary, be offset by reducing the amount of sunlight reaching the lower atmosphere or increasing the amount of the Sun's radiation reflected by clouds.

A National Academy of Sciences (NAS) study of 1992 suggested that, "engineered countermeasures need to be evaluated that would at least counter the effects of global warming in case other mitigation options prove to be insufficient in achieving a stabilization and eventual reduction in atmospheric greenhouse gas concentrations. These options should possess the potential of being 'turned off' should unintended and adverse effects occur." In its concluding section the NAS report states:

"Several schemes depend on the effect of additional dust in the stratosphere or very low stratosphere screening out sunlight. Such dust might be delivered to the stratosphere by various means, including being fired by large rifles or rockets or being lifted by hydrogen or hot-air balloons. These possibilities appear feasible, economical and capable of mitigating the effect of as much CO₂ equivalent per year as we care to pay for. Such systems could probably be put into full effect within a year or two of a decision to do so, and mitigation effects would begin immediately. Because dust falls out naturally, if the delivery were stopped, mitigation effects would cease within about six months for dust delivered to the tropopause and within a couple of year for dust delivered to the mid-stratosphere."

This White Paper identifies several promising ways to reduce the amount of heating of the Earth by solar radiation. However, before implementation of any such approaches, improved understanding is required about their influence on the climate system, and if there are adverse consequences on the environment, on atmospheric chemistry and on the surface environment, including the effects on various species, ecosystems, and the cycles of carbon and water. This view is expressed clearly in the above-cited NAS study:

"---Such dust would have a visible effect particularly on sunsets and sunrises and would heat the stratosphere at the altitude of the dust. The heating would have an effect on the chemistry of the stratospheric ozone layer, and this possibility must be considered before major use of such a mitigation system. The amount of dust to be added is within the range of that added from time to time by volcanic eruptions, so the effect on climate would not be expected to go beyond those experienced naturally. However, under conditions of increased CFC chlorine in the stratosphere better specification of dust characteristic and size and improved data on the fallout rate of dust from various altitudes as well as on chlorine chemistry are needed."

This White Paper identifies key research and development needs for evaluating the potential viability and consequences of employing approaches to prevent, forestall, or mitigate disastrously rapid onset of severe or rapid climate change that could have severe consequences.

Several climate change situations have been identified which would widely be viewed as adverse and for which there is a plausible risk based on analogues drawn from history and variations in the climate or from model simulations. Although indicated separately in Table 1, many of these adverse outcomes are interrelated, with global warming as a general common denominator. For example, rapid warming of the Arctic would likely rapidly enhance global warming, and reducing the formation of salty water during sea ice formation reduces the intensity of the global thermohaline (i.e., deep ocean overturning) circulation and contributes to an accelerated rate of rise of sea level. Or an alteration in the normal variability of the climate would likely be a primary contributor to the loss of some key ecosystems.

In view of the interdependence of events in Table 1, and in consideration of relative likelihood and importance of the identified climate changes, three important actions to protect against impending threats to the global economy and environment are:

- Slowing the rapid climate change in the Arctic; this would have the further benefit of reducing the rate of global sea level rise.
- Protecting highly populated coastal areas from direct hits by large hurricanes and typhoons.
- Alleviating sustained droughts in agricultural regions.

These actions are described in detail in Appendix A.

It is important to emphasize that only a modest scale research program has been advocated in this White Paper – to evaluate the initial feasibility of preventing rapid or severe climate changes, and avoiding its adverse consequences. Considerable more work would have to be done to engineer and deploy such a system. However, there are a number of ethical and societal, if not legal, issues that would need to be addressed by the international climate community before any steps might be taken to deploy a full-scale system. In face of a true climate crisis it would not be difficult to get an international consensus, but it is important to be prepared well in advance of a crisis. Central to that preparation is research to fully understand the issues surrounding possible deployment of any such system.

“The paleoclimate (historical) record shouts to us that, far from being self-stabilizing, the Earth’s climate system is an ornery beast which overreacts even to small changes”.

-W.S. Broecker

3.0 Proposed Technical Approaches for Limiting Severe or Rapid Climate Change

3.1 Introduction

The Earth's climate has, quite fortunately, been uncharacteristically stable over the past several thousand years, as civilization has developed around the world. However, the warming of the past several decades and variations in earlier times that are evident in the climate record make clear that relatively small modifications of the large fluxes of energy that drive the climate system can have large influences on the climate. This section considers how some of these fluxes can be modified and the issues relating to their further development and consideration as viable options for limiting severe and deleterious consequences of climate change.

The categories of technical approaches for modifying the Earth's climate are fundamentally of two types:

A. Modification of Absorbed Sunlight: In that sunlight drives the climate, altering the amount of sunlight reaching the Earth or absorbed by the atmosphere and surface will directly modify the temperature, amount of precipitation, and other variables. Determining the extent of modification, of what portion of the incoming solar radiation, in what geographical regions and seasons, and at what levels of the atmosphere, and to what degree it would effect the ecosystems and climate (on both its mean state and spatial and temporal variations) remain important research questions. Section 3.2 presents three examples of how the modification of solar radiation might be achieved and indications of the types of issues requiring consideration.

B. Modification of Non-Solar Fluxes of Energy: Once the sunlight is absorbed by the Earth system, it is transformed into heat energy. As this energy accumulates and warms a particular region, it causes the atmosphere and oceans to move, thereby moving the energy around, warming colder regions and cooling warmer ones, evaporating and precipitating moisture, driving ocean currents, melting snow and ice, and more. Finally, the heat energy is radiated out to space, with as much energy being emitted as is incoming from solar radiation so that there is, at equilibrium, no net energy gain by the Earth as a system. Each of the various transfers of energy provides an opportunity for altering its flow, thereby altering the climate. Appendix B provides some examples of the types of intervention in these flows of energy that should be considered as possible means for avoiding or limiting the most adverse potential consequences of climate variability and change.

Neither of these sections is exhaustive in its consideration—rather the approaches described are intended to be illustrative of the types of approaches and scales of intervention that would be necessary were these approaches to be pursued as complements to reduction in global emissions.

This chapter concludes with a very brief summary of the types of research needed to evaluate the types of information that would likely be needed were implementation of deliberate modification of the climate to be considered, over-and-above that occurring by greenhouse gas emissions. These tend to tie back to the types of information needed to understand how the climate system is operating, which is the major focus of the US Global Change Research Program, so that efforts proposed here are generally quite complementary with ongoing research.

3.2 Technical Approaches for Directly Modifying Solar Radiation

Approaches for modulating either the quantity or the quality of incoming solar radiation have received considerable investigation over the past few decades (e.g., see NAS, 1992). Approaches range from the lofting of mirrors into Earth orbit or the positioning of mirrors at a quasi-stable point located between the Earth and the Sun, to injecting scattering materials into the stratosphere or changing the reflectivity

of the Earth's surface or atmosphere. As a general rule, lofting materials into space requires far more investment than the effort required to loft materials into the atmosphere, but at the same time, modifying the solar radiation before it reaches the Earth tends to have fewer environmental side effects than modifying solar radiation within the Earth system. The following three approaches seek to minimize both potential costs and potential adverse consequences, and so are presented here as worthy of further investigation beyond the conceptual evaluations undertaken to date.

3.2a. Deliberately Introduced Stratospheric Aerosol

Brief Description: Small air-suspended particles (aerosols) scatter solar radiation. Some of the scattered radiation is scattered back into space, preventing absorption at the Earth's surface or in the atmosphere and thereby reducing net solar heating of the planet. Stratospheric aerosols are long-lived (1-5 years, depending on injection altitude and latitude) compared to tropospheric aerosols (ca. 1 week), and hence require a far lower injection rate to sustain a given aerosol loading and scattering capacity. Also, because tropospheric aerosols are most often scavenged by precipitation, the much lower injection rate for stratospheric aerosols leads to a correspondingly lower deposition rate toward the surface and thus much less potential for modifying precipitation processes and cloud characteristics. Aerosol composition might be liquid or solid (e.g., metal oxide or metal); spherical or non-spherical; or even specially shaped to confer special scattering characteristics. Stratospheric aerosols might be directly injected (e.g., dielectric or metallic particles by ground-based projectile-launcher or by high-altitude aircraft, or within a thermal plume originating on the Earth's surface) or may be injected as a precursor gas (e.g., SO₂ at altitude; COS at the surface).

Feasibility: Major volcanic eruptions (e.g., Mt. Pinatubo in 1991) have demonstrated that stratospheric aerosols can reduce solar radiation and lead to a global cooling. Such eruptions loft tens of millions of tons of sulfur, for example, and the corresponding aerosol scattering has been observed to lead to the reduction of solar radiation by about 1%. Eruption of other tropical volcanoes in historic times have had even larger effects; Mt. Tambora's eruption late in 1814 resulted in European crop failures and July frosts in New England, and caused 1815 to become known as "the year without a summer." [Volcanic aerosols are relatively large in size, and their Mie scattering of the majority of solar radiation causes the sky to whiten. The sky is fundamentally blue because nitrogen molecules, acting as molecular-scale aerosols, Rayleigh-scatter the bluer portion of the solar spectrum, thereby reducing the extreme blueness of direct sunlight by tens of percent.] To sustain any given level of aerosol in the mid-stratospheric tropical reservoir would require lofting somewhat less than a fifth of the total amount each year, as the aerosol half-life in this stratospheric region is about five years. Aerosols injected at toward the bottom of the stratosphere or at high latitudes have smaller residence half-lives and would need to be replenished at higher rates.

Potential Side Effects: Some types of aerosol (e.g., chlorine-contaminated sulfate particles of volcanic origin) are known, under some circumstances, to contribute to decomposition of stratospheric ozone and so to ozone depletion; however, "clean" man-made aerosols wouldn't be expected to pose such issues. Depending on their density, size, shape and composition, aerosols might change sky color, e.g., causing it to become either whiter or bluer, and sunsets and sunrises could become somewhat more intense. Modulating the ground-level intensity of solar radiation could either reduce or increase by ~1% the amount of photosynthetically-active sunlight available to plants; use of some aerosol types (e.g., Rayleigh-scatterers) would dramatically reduce the ground-level intensity of the portion of the solar spectrum that causes sunburns, crop damage and skin cancer. Absorption of solar radiation by "dirty" aerosols would modify stratospheric heating and thus circulation patterns (and so potentially ozone concentrations), and use of "clean" aerosols therefore likely would be preferable. The entire aerosol scattering approach is inherently reversible, as aerosols have residence times in the stratosphere of 1-5 years (depending on altitude) before being returned to the troposphere and removed, mainly in precipitation at high latitudes.

Key Issues Requiring Research:

Understanding the action mechanisms of man-made stratospheric aerosols will require significant additional research focused on optimizing the desired insolation modulation while minimizing undesired side-effects. Thus, the following types of investigations need to be considered:

- Optimal material, composition, size distribution, etc. of aerosols, given the stratospheric environment (e.g., ozone distribution, UV radiation, temperatures, etc.);
- Optical properties of aerosols, primarily their complex dielectric functions (e.g., vs. optical frequency) as a function of size, shape and composition;
- Optimal altitude and latitude of aerosol injection, in terms of insolation modulation effects and the means and costs of injection;
- Aerosol amount, lifetime, and replenishment requirements for a given insolation modulation effect;
- Aerosol modulation of radiative forcing of the Earth's fluid envelopes and land-surface and consequences for diurnal, latitudinal, and seasonal variabilities;
- Climatic response to long-term changes in radiative forcing, including effects on temperature, precipitation, etc.;
- Aerosol-induced changes in stratospheric circulation and chemistry, including effects on stratospheric ozone and aerosol lifetime;
- Interactions with background aerosols (quiescent; intense volcanic episodes);
- Ecological effects of various types of aerosols as they are removed from the stratosphere (e.g., possible animal inhalation of insoluble aerosols when returned to the troposphere; incremental pH reduction of precipitation by sulfate aerosols);
- Human health effects, e.g., reduction of sunburn and skin cancer, if Rayleigh scattering aerosols are employed;
- Agricultural impacts, e.g., reduction of photodamage to crops, if Rayleigh scattering aerosols are used;
- Aesthetic effects, e.g., daytime and sunrise/sunset sky color changes;
- All other potential influences

3.2b. Engineered Stratospheric Scatterers

Brief Description: Mass-, shape- and size-optimized particles of a single chemical composition (e.g., sulfate) are one end of a spectrum of increasing sophistication of engineered scatterers that may be placed at various levels and locations in the stratosphere in order to modify the radiative forcing of the climate. With increasing engineering effort (and unit cost), the radiation-forcing properties of such objects may be made significantly more effective, per unit of mass deployed, than the reference case of simple aerosols particles (described above). Such improvements offer the important benefits of greatly reducing the total lifetime cost of insolation modulation, as well as the total mass to be deployed, and also offer a much richer spectrum of choices with respect to just how the modulation is to be accomplished. For example, solar radiative inputs and terrestrial re-radiation both may be scattered in spectrally-selective manners: e.g., attenuation of solar UV-A, UV-B, UV-C, visible, or infrared spectra in order to induce net terrestrial cooling, and preferential attenuation of re-radiation from the Earth's surface and troposphere, so as to induce net terrestrial heating. Examples of possible materials for achieving these effects include 1- and 2-D metallic chaff, particles with spatially-varying compositions, and both single- and multiply-connected macroscopic structures, such as balloons with spatially- and spectrally-varying radiative properties (Teller et al., 1997).

Several of the scatterers of interest may be stratospherically positioned from ground stations. The most obvious example of such auto-positioning would occur with use of radiatively active small super-pressure balloons, which could be designed to auto-position from a ground-release point at whatever stratospheric pressure altitude may be chosen to provide the longest operational lifetime (i.e., at least 5 years at approximately 25-30 km altitude), although wind fields would control their latitudinal and longitudinal distributions. Even the simplest spherical aerosol scattering materials might be injected from ground level, for example using a well-engineered "volcano simulator" positioned at high elevation

at the Equator. Such an injection process could be designed to provide an aerodynamically optimized particulate-loaded plume via carefully-executed combustion-with-expansion of sulfur or aluminum to generate a multi-gigawatt thermal column directed toward the relatively 'transparent' equatorial tropopause. Alternatively, NAS (1992) suggested a relatively inexpensive technique using large artillery; more modern types of projectile-launching systems (e.g., electromagnetic 'guns') might offer significant advantages with respect to cost and collateral environmental impacts.

Of the order of 0.1 million tons/year of sophisticated engineered scatterers are predicted to have the same radiative forcing consequences of as much as 10 millions tonnes/year of volcanic sulfate. More sophisticated scattering systems that use even lower tonnages of scatterers of higher unit costs may also be possible. Associated deployment costs across most of the classes of engineered scatterers appear to be of the order of one billion dollars per year to achieve a 1% change in effective solar insolation

Feasibility: Reducing incoming solar radiation undeniably will cool the planet, in the space- and time-average. However, there are several issues requiring investigation in order to better understand how best to optimize the amount, location(s) and timing of the injection of each of the several different kinds of these scattering materials, the details of the estimated response of the climate system, and the significance of unwanted changes that could result.

Potential Side Effects: In addition to engineering the scatterers to be more effective radiatively than use of the simple aerosols described in Section 3.2a, such scatterers could also be designed to minimize various of the inadvertent consequences facing natural aerosols. Thus, in evaluating this approach, it is essential to consider the pertinent portions of the potential consequences of Section 3.2a, and in addition consider the following:

- Fates of engineered scatterers (likely mostly in polar latitudes), e.g., auto-degradation or deposition on the Earth's surface;
- Attenuation or enhancement of concentrations of other atmospheric constituents due, for example, to (photo)chemical interactions with engineered scatterers in the stratosphere or to changes in the various spectral components of the solar flux available to drive tropospheric chemistry;
- For engineered scatterers which are strongly wavelength-selective, consideration is needed of effects of changes in radiative flux on incidence of worldwide human dermal dysplasia/skin cancer rates (e.g., UV-scatterers may sharply reduce these rates), on crop productivity (e.g., UV reductions may reduce air pollution and enhance agricultural productivity), and on natural ecosystems (e.g., some species may depend on some components of UV-radiation, while others may be damaged by them).

Key Issues Requiring Research: To supplement the types of research required for evaluation of simple stratospheric aerosols, some aspects of engineered stratospheric scatterers merit additional research attention. These include:

- Stratospheric lifetime of various types of engineered scatterers, as functions of deployment altitude, latitude (and longitude?)
- Scattering properties of various classes of engineered scatterers, in the lab and after sustained stratospheric exposure;
- (Photo)chemical interactions of engineered scatterers of various types with stratospheric constituents and consequent effects on lower atmospheric chemistry and atmospheric deposition of nutrients and other compounds;
- Detailed climatic response to the presence of engineered scatterers on the mean climate and its spatial and temporal variations and patterns, including atmospheric circulation and structure;
- Optimal properties, injection pattern and timing of various types of engineered scatterers to achieve the desired climatic response;
- Crop productivity, human health and macroeconomic consequences (both impacts and benefits) of modification of solar radiation in over various spectral intervals;
- Aesthetic and other effects, including changes in sky color and sunset/sunrise vividness, etc.

3.2c. Deliberately Introduced Aerosol in Marine Troposphere To Increase Cloud Albedo

Brief Description: Incoming solar radiation can be reduced by increasing the loading of aerosols in the lower atmosphere (the troposphere). As with stratospheric aerosols, some of the incoming solar radiation will be scattered back into space, preventing absorption at the Earth's surface or in the atmosphere and thereby directly reducing net solar heating of the planet; this is another aspect of direct aerosol forcing. Aerosol particles injected into the troposphere also can serve as nuclei for cloud droplets (cloud condensation nuclei, CCN). As a result, increased concentrations of aerosol particles generally lead to increased concentrations of cloud droplets, enhancing the reflectivity of clouds of intermediate optical thickness (e.g., marine stratiform clouds), thereby indirectly reducing the amount of solar energy absorbed (indirect aerosol forcing). Such aerosols are thought also to increase the lifetimes of clouds, especially for clouds that lead to precipitation. Both of these effects would decrease short-wave radiation absorbed by the surface-atmosphere system, leading to a cooling influence on climate. Because tropospheric aerosols are scavenged by precipitation and filtered by vegetation and thus are short-lived, their lifetimes in the atmosphere are about 1 week (as compared to stratospheric aerosols, which have mean lifetimes of years). As a result, continuous replenishment at relatively high rates is required to sustain a given aerosol loading and reflective effect. However, this short residence time is particularly suitable for finely-targeted application, for example use over oceans, because it would minimize issues associated with decreased solar radiation or aerosol deposition over land.

Feasibility: The whitish haze that extends over and downwind of many industrialized areas provides an indication of the cooling influence caused by tropospheric aerosols. Numerous studies have exhibited direct and indirect effect of aerosols, locally. Present global influence of anthropogenic tropospheric aerosol is quite uncertain, largely because of uncertainty in aerosol loading. Cost of sustained release of aerosols (or aerosol precursor gases) is anticipated to be comparatively high, especially given relatively very short residence times, but the approach should be evaluated.

Potential Side Effects: Aerosols tend to scatter solar radiation in all directions, which increases the diffuse sky radiation and brightens the sky during the day, with possible coloration depending on the nature (primarily the particle-size) of the aerosol. Just as is the case also for stratospheric aerosols, reducing direct solar radiation may also affect a variety of terrestrial ecosystems, some positively and others negatively. Deposition of large amounts of the aerosol on the land or ocean surface might affect superficial chemistry and biology, depending upon the aerosol used. Nevertheless, the approach may have significant value, as it is swiftly reversible due to the relatively very short atmospheric residence time of tropospheric aerosols.

Key Issues Requiring Research: There is a wide variety of issues requiring consideration if beneficial outcomes are to significantly outweigh potential adverse consequences. Among the areas meriting study are the following:

- Optimal material, composition, size distribution, etc. of tropospheric aerosols;
- Optical properties of tropospheric aerosols, including index of refraction, phase function, wavelength dependence;
- Optimal altitude, longitude and latitude of injection, in terms of effects on radiation and the means and cost of injection;
- Amount, lifetime, and replenishment requirements for a given radiative effect;
- Pattern of effects on the radiative forcing as a function of latitude, longitude and season;
- Weather and very short-term climatic response to change in radiative forcing, including effects on temperature, precipitation, etc.;
- Influence of aerosols on atmospheric chemistry and on marine chemistry and biology;
- Aesthetic effects, such as brightening of daytime sky.

The range of technical approaches for reducing incoming solar radiation raises a number of important questions that will provide the focus of the research and development effort. Within each of these key questions, there are a range of issues to be investigated, ranging from investigating aspects of the implementation of an approach (e.g., the characteristics of a material, how it will spread in the

atmosphere, etc.) to issues relating to associated impacts of pursuing an approach (e.g., thinning the ozone layer, etc.).

3.3 Research Needs for Evaluating the Need for Intervention At the Onset of Climate Change

Before one of the suggested technical approaches would be considered for implementation, not only must it be clear that the approach would have the desired effect, but it also must be clear that the climatic consequence it is designed to address is occurring or imminent. Such knowledge can only be developed through research and observation and may build upon efforts already planned as part of the US Global Change Research Program. Some of the important work that needs to be done as part of this Program includes:

- Additional observations needed to monitor key variables that would give a clear indication of the onset of rapid or severe climatic changes;
- Improvements to the ability to predict the onset of changes that might be considered rapid and severe;
- Improvements to the ability to predict the consequences of rapid or severe change that might in themselves trigger additional rapid and severe change (i.e., major climatic non-linearities);
- Improvements needed to provide a more comprehensive integrated evaluation of the relative merits of proceeding with deliberate climate modification (this would include, for example, improving integrated assessment model treatments of such events and biological, social, and economic responses).

It therefore may be desirable to conduct *ad hoc* observational studies aimed at developing and documenting a very detailed, exceedingly well-quantified baseline for the present-day climate and its natural variability, so as to constitute the scientific base for the earliest possible detection of rapid climate change.

4.0 Generic Research and Development Needs Applicable to All Approaches

4.1 Introduction

As indicated in Sections 2 and 3, there are many specific research issues that must be addressed for each technical approach, if understanding is to be developed about the potential effectiveness of each approach to limit rapid and severe changes in the climate, thereby moderating changes in global and regional climate conditions.

This section provides a description of the generic research needs applicable to all the technical approaches to ensure that these approaches would be effective, feasible and cost-effective, while also not creating a new set of problems.

As a general rule, candidate approaches need to be evaluated using a hierarchy of methodologies. To accomplish this, research would be pursued at the level needed to proceed through a sequence of evaluation steps of the various approaches. The steps would be undertaken in the order listed below, proceeding until they are all completed or until a limitation is uncovered that would cause the approach no longer to be considered. Thus, for example, if step 1 revealed that side effects of an approach would be more severe than the threat being addressed, then steps 2, 3, and 4 would not be performed for that candidate approach.

The sequences of steps that is proposed is as follows:

- (1) **Scoping calculations:** Such calculations would be used to assess feasibility, effectiveness, and approximate costs. For many of the candidate approaches, these calculations can be found in the published literature. For other approaches, some laboratory or other experimental determination of key parameters or variables may be needed. Similar scoping calculations would be used for initial quantification of potential side-effects.
- (2) **Evaluation of historical analogs:** Analysis and understanding of data from relevant natural events such as volcanic eruptions and past changes in the climate would be used to gain additional insight about the potential viability of the approach and relevant side-effects. For example, injection of some types of aerosols could be evaluated to significant extents by assessing the effects of volcanic aerosols on radiative forcing, temperature, and perhaps even ozone chemistry.
- (3) **Comprehensive climate modeling:** Available and improved models would be used to assess the potential climatic influence of the candidate approach, both intended and otherwise. An important aspect of these studies would be to work to optimize the design of the approach (e.g., refine the timing and intensity of an application, etc.). These studies would also examine other sorts of impacts (e.g., effects on stratospheric ozone in the case of stratospheric aerosol). For all candidate options, modeling studies would be used to assess effects on radiative forcing, temperature, and the hydrological cycle, both globally and with some regional resolution. For those options that may significantly affect atmospheric chemistry, other relevant processes (e.g., catalysis of ozone decomposition, including gas phase and heterogeneous reactions) would also be simulated. Modeling studies would also be used to compare the effectiveness and feasibility of the candidate approach with alternative approaches to addressing the issue, including comparison to, for example, alteration of the carbon cycle (e.g., by reforestation, sequestration) or specially limiting soot and methane concentrations. This is discussed in detail in the later parts of this section.
- (4) **Benchmark and pilot scale tests:** For candidate approaches that continue to appear promising after steps (1) to (3) have been completed, small-scale laboratory and field tests would be performed to further evaluate model assessments, to consider engineering aspects of potentially implementing the approach, and to further reduce uncertainties.

In association with each stage of analysis considering the environmental feasibility and potential effectiveness of candidate approaches, an evaluation of the economic cost impacts and societal implications of implementing the strategy would be conducted. Such studies would include a

comparison of the cost/benefit analyses being carried out for alternative approaches to limiting rapid and severe changes in climate. This will require advancements in integrated assessment models which explicitly represent complex climate dynamics, and which allow for a non-linearly behaved simulation of a rapid or severe climate change.

The balance of this section presents examples of research pertinent to examining potential approaches by evaluation of historical analogs and by comprehensive modeling. Specific benchmark and pilot scale tests will need to be developed during the course of this project.

4.2 Evaluation of climatological or historical analogs

For many of the candidate approaches there are analogs in the climatological or historical record that can serve as proxies to examine the efficacy and/or side-effects of approaches that are being considered. A highly relevant example is the radiative forcing of climate that resulted from the June 1991 eruption of Mount Pinatubo in the Philippines, which injected large amounts of SO_2 gas into the stratosphere. Over the succeeding few months, this SO_2 converted into sulfuric acid aerosol, which spread poleward from the low latitude (17°N) of the eruption. The resultant optical depth was well characterized by satellite observations (McCormick et al., 1995). Figure 2 shows the zonal mean optical depth of this aerosol,

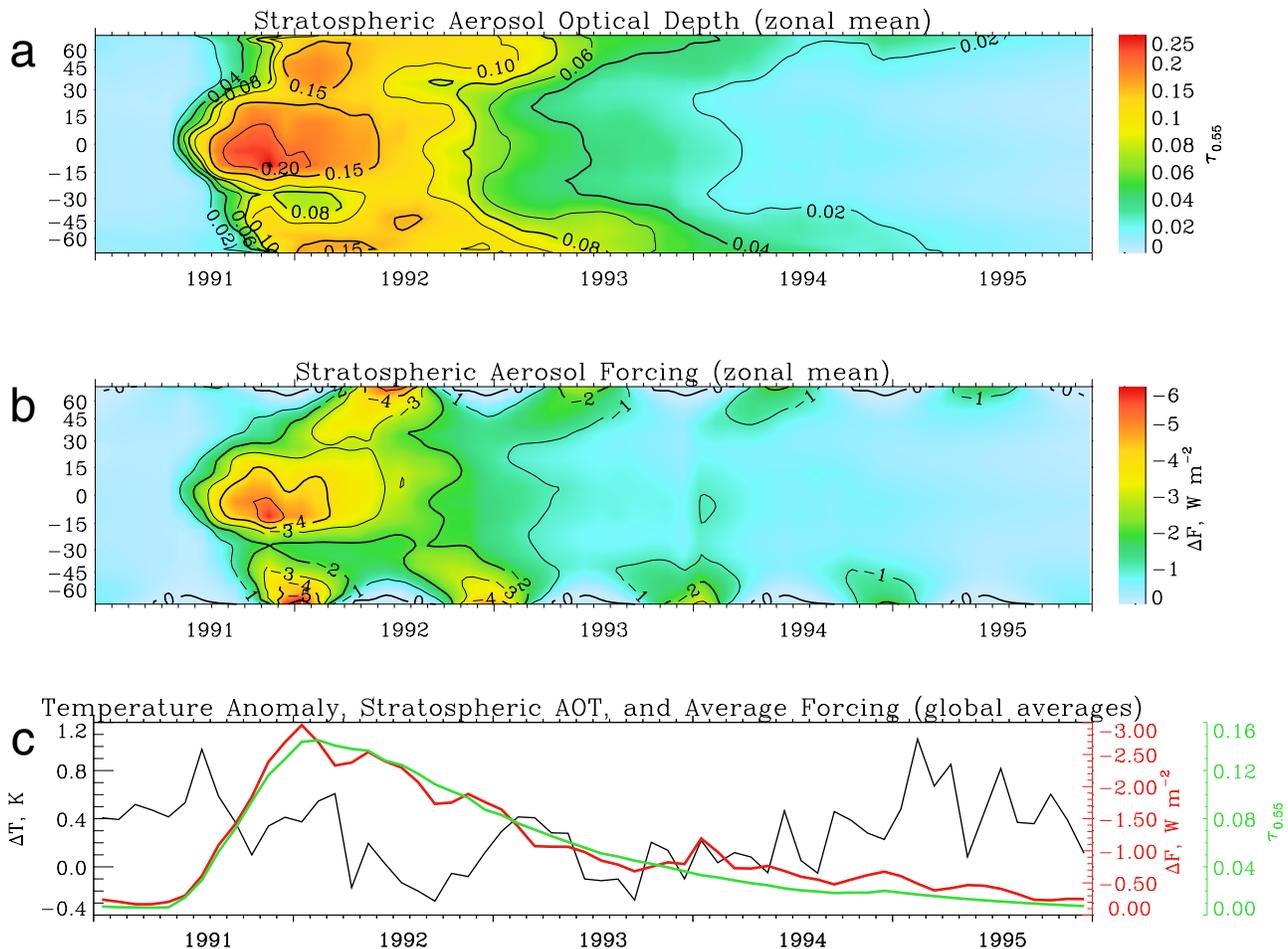


Figure 2. *a*) Zonal average optical thickness of stratospheric aerosol following eruption of Mount Pinatubo, in the Philippines in June 1991; *b*) zonal average shortwave radiative forcing due to light scattering by aerosol in *a*); *c*) global average optical thickness of stratospheric aerosol, shortwave radiative forcing due to light scattering by this aerosol, and monthly mean temperature anomaly. Aerosol optical depth and monthly mean temperature anomaly from GISS; forcing, unpublished calculations by S. Nemesure and S. E. Schwartz, Brookhaven.

which at its peak approached 0.16 in global mean. Also shown in the figure is the zonal average radiative forcing. Note the alternation of forcing, which is maximal in high latitudes in the summer hemisphere, as a consequence of the poleward spreading of the aerosol due to stratospheric circulation and the greater length of sunlight at the poles in summer. The maximum global-average radiative forcing (cooling influence) was about 3 W m^{-2} . Over the several year interval shown, the aerosol optical depth decreased as the material was removed from the stratosphere, largely by downward transport at high latitudes. The lower panel also shows the monthly mean global temperature anomaly over this period. Despite the noise arising from inherent variations in temperature, the signal of global mean temperature reduction due to the radiative forcing by the Pinatubo aerosol is readily discerned. Observations such as these both give confidence in the efficacy of a given approach and provide a quantitative measure of the perturbation that would be required to achieve a given effect.

A further concern with any given approach is side-effects. Again the Pinatubo eruption serves as a valuable analog. The presence of incremental aerosol in the stratosphere modifies the chemistry of inorganic chlorine in the stratosphere, giving rise to enhanced concentrations of ClO (chlorine monoxide) free radical, which serves as a catalyst for ozone decomposition; to be sure, the eruption itself also injected substantial amounts of chloride into the stratosphere, so that it's not straightforward to disentangle the effects of particulate and chloride injections. Figure 3 shows a comparison of satellite-

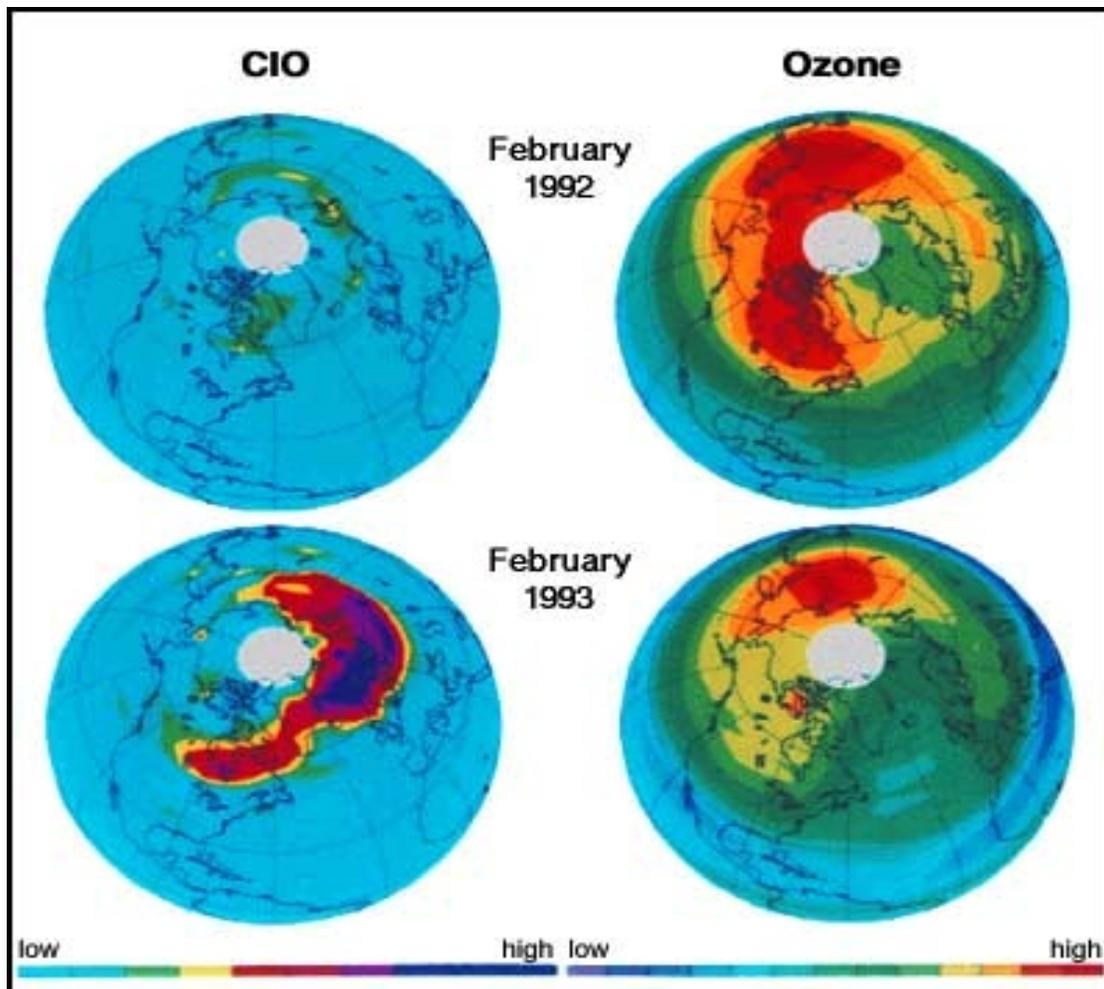


Figure 3. Monthly mean column burden of stratospheric chlorine monoxide and ozone in the Northern Hemisphere for February 1992 and 1993 as determined by satellite observations. Note strong increase in ClO (chlorine monoxide) and decrease in O₃ for 1993. These are attributed to surface reactions on sulfuric acid aerosol resulting from eruption of Mount Pinatubo (Fig. 2) in the Philippines in June 1991 (Fig. 3 from Doug Rotman, LLNL).

observed column burden of stratospheric ClO and ozone for February 1992, which preceded the presence of substantial Pinatubo-derived aerosol at North polar latitudes, and February 1993. Note the strong increase in ClO amount and the resulting depletion of ozone in 1993 compared to 1992. Observations such as these provide stringent tests of models, which would be used to evaluate side-effects of potential approaches, lending confidence in the application of these models to those approaches.

4.3 Needed Climate Model Simulations and Related Model Development

Simulation using numerical models is an essential step in the evaluation of any proposed approach to modify or ameliorate severe and deleterious consequences of climate change. Many pertinent questions can be addressed using today's climate, carbon cycle, and atmospheric chemistry models. Additional climate model development, particularly using higher spatial and time resolution and coupling to carbon cycle and atmospheric chemistry models, will also be needed to more thoroughly understand proposed options that being considered.

An essential means of evaluating potential activities that might be used to moderate or ameliorate severe consequences of climate change will be to simulate their effects (intended and otherwise) using numerical climate models. If the climatic consequences are unsatisfactory, or poorly understood, there is little point in evaluating other aspects such as cost and feasibility. These climate-model evaluations will generally, if not always, require full-fidelity, two- or three-dimensional models. Simplified models are useful for exploring parameter space after the fundamental physics has been understood well enough to be parameterized; for most issues related to deliberate modification of components of the climate system, however, present understanding of fundamental issues is not yet good enough to allow reliable parameterizations to be devised. In addition, higher-dimensional models are needed to understand the geographical variations in the impacts of climate modification, as well as to evaluate schemes that applied locally or regionally. As described below, many important questions can be addressed using existing climate models. Others will require new tools. Chief among these are 3-dimensional coupled climate/chemistry and 3-D coupled climate/carbon cycle models, all with high-resolution. Improved representation of the role of the interactions of surface vegetation and climate are also needed, including particularly effects relating to surface albedo, the hydrologic and carbon cycles, and the daily temperature cycle. This section describes issues which could be addressed at least preliminarily using currently available models; model development needed to address these questions with more confidence, and to address additional related questions, are also described.

4.3a Reductions in Solar Flux

A number of proposed approaches involve reducing the net solar flux at the ground. As described in several recent reviews (NAS, 1992; Keith and Dowlatabadi, 1992; Keith, 2000), this can be accomplished via deliberately introducing stratospheric scatterers, altering cloud microphysical properties, and increasing surface albedos. Climate models can be used to address several important questions that arise, no matter what method is used to reduce solar fluxes.

In any consideration of offsetting one forcing with another, an immediate question is the geographical distribution of the forcings and of the climatic response. Figure 4a shows the geographical distribution of the forcing that would result from a uniform doubling of the atmospheric CO₂ concentration, which results in a global and annual average forcing of about 4 W m⁻². The modeled forcing is more or less uniform but with discernible spatial and temporal gradients, influenced mainly by surface temperature and cloudiness, being somewhat greater at low latitudes than at high latitudes. In contrast, the forcing of the same global and annual average magnitude that would result from a change in the solar constant, Figure 4b, exhibits much greater spatial and seasonal variation, being greatest near the equator and in summer months at high latitudes. Figure 5a shows the annual average temperature change that would result from the 2 × CO₂ forcing of Figure 4a, calculated with a coupled ocean-atmosphere climate model. Note the high spatial variation of temperature change. Because the pattern of temperature change

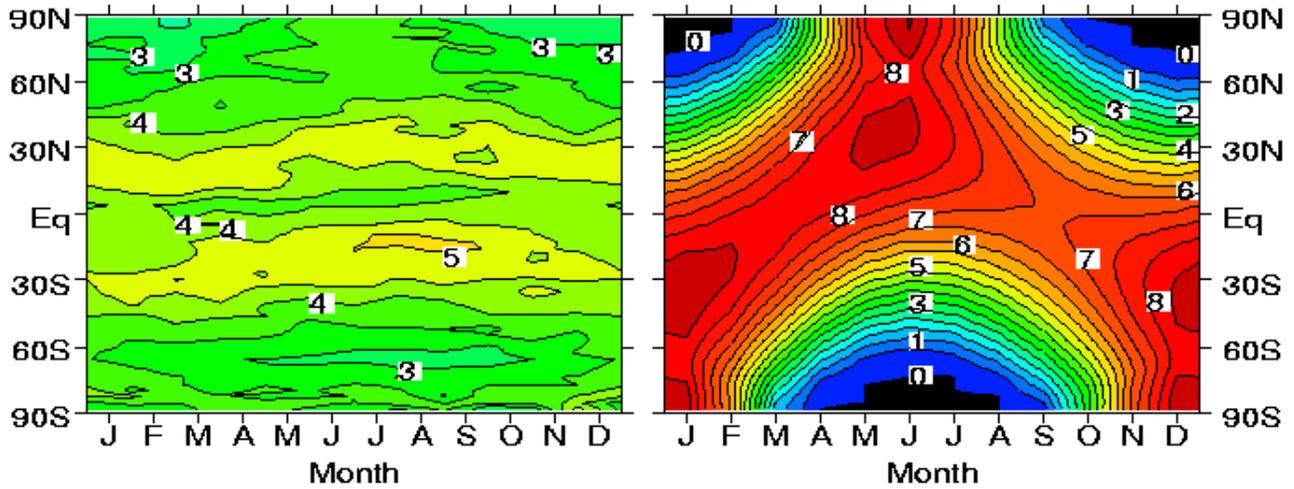


Figure 4. *a)* Change in net long wave radiative flux at the tropopause when CO₂ is doubled with respect to the control case and *b)* the pattern resulting from the global reduction in incoming solar radiation needed to compensate a doubling of the CO₂ concentration. Both quantities (W m⁻²) are zonally averaged as a function of time of year. Govindasamy and Caldeira, 2000.

exhibits little or no coherence with the spatial pattern of the forcing, this response must be considered a characteristic of the Earth climate system, rather than of the forcing. Figure 5*b* shows the temperature change calculated for spatial forcing given by the difference between Figure 4*a* and Figure 4*b*, that is to say, a forcing that is zero in global annual average, but which exhibits strong spatial gradients. The overall magnitude of temperature response is quite small, as might be expected for a net zero forcing, but perhaps more importantly, the spatial variation in the response is quite small, despite the strong

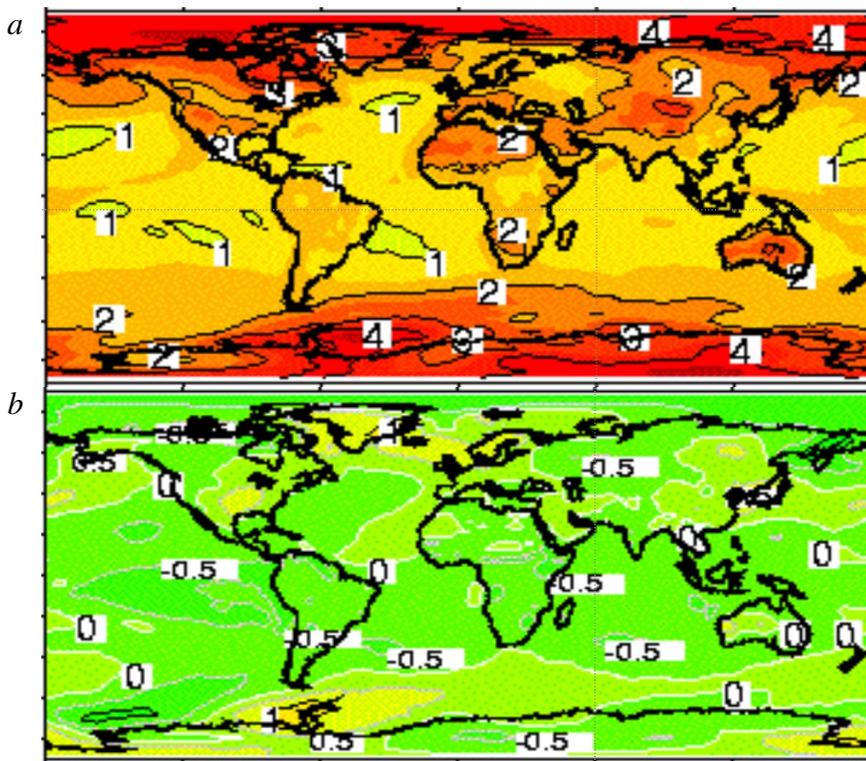


Figure 5. Surface temperature changes *a)* for the doubled-CO₂ forcing (Figure 4*a*) and *b)* for the forcing given as the sum of doubled CO₂ and decreased solar constant (Figure 4*b*). Govindasamy and Caldeira, 2000.

gradients in forcing. These model results suggest that any approach to reduce warming, would be distributed globally rather than be manifested locally in the region where the forcing is applied. Results such as these, while not definitive, being based on a single model, suggest directions of future modeling and analysis of patterns of prior climate change.

An important research question is whether a solar flux reduction would trigger feedbacks related to carbon cycles, which would counteract the cooling effect of reducing the solar flux. In principle, reducing the photosynthetically-active portion of the solar flux would reduce photosynthesis in both terrestrial and marine plants, and thus could reduce uptake of carbon by both the ocean and terrestrial biosphere. This would tend to increase atmospheric CO₂ and to reduce the cooling effect produced by reducing the solar flux. This effect could be quantified using coupled climate/carbon cycle models to simulate how increased atmospheric greenhouse gases, combined with reduced solar flux, would affect terrestrial and oceanic carbon uptake. To be sure, several of the stratospheric scattering approaches discussed in Section 3 do not significantly perturb the fraction of present insolation, which drives photosynthesis, so that these concerns simply don't arise.

4.3b Deliberate Introduction of Stratospheric Aerosols

Previous assessments (e.g. NAS, 1992) have identified deliberate introduction of stratospheric aerosols as a potentially effective and affordable climate-modification option. A major concern, however, is the potential for additional stratospheric aerosol to accelerate chemical reactions that destroy stratospheric ozone. This concern is aggravated by the fact that adding aerosols to the stratosphere may reduce temperatures there, which further accelerates ozone loss (Figure. 6); on the other hand, other types of aerosols may increase stratospheric temperatures (thereby decreasing ozone losses below the levels which occur naturally), and aerosol combinations – or a single specifically-tailored aerosol – may be employed to give zero temperature change. Quantitative assessment of these issues is needed. Concern about ozone loss arises because addition of particles to the stratosphere would alter the path-length of incoming radiation, which affects chemistry and ozone loss cycles. Assessment of the effects of these alterations requires consideration of surface reactions and re-partitioning of radical pools and loss cycle components. Improvement in modeling capability is needed for calculating photolytic reaction rates and aerosol interactions. These phenomena need to be modeled initially in a 3-D off-line chemistry model. Ultimately, however, these issues need to be treated in 3-D coupled climate/chemistry model, because addition of stratospheric particles could influence the thermal (radiative) balance of the atmosphere, thus influencing atmospheric dynamics. Perturbation in the atmospheric dynamics would in turn influence the chemical balance and could lead to colder lower stratosphere, increased water vapor and related consequent effects; on the other hand, effects of the opposite sign could occur, and finally it might be possible to arrange for no net effect at all. Possibly these various effects on stratospheric chemistry could be minimized by optimizing particle sizes or placement within the stratosphere. In any case, we need to understand whether particle sizes or locations can be found which will minimize high-latitude ozone loss while providing the desired cooling effect. Sensitivity to both latitude and altitude of introduced particles should be explored.

Ideally, these questions would be investigated using a 3-dimensional coupled climate/chemistry model. The coupling is desirable because there may be significant feedbacks between chemistry and climate, since ozone is a strong greenhouse gas. Since no model of this type exists at present, initial investigations should use either a 2-dimensional coupled climate chemistry model, or uncoupled 3-dimensional models.

An important issue regarding the effectiveness of stratospheric scatterers (either aerosols or balloons) in stabilizing climate is the distribution of scatterers within the atmosphere. Model simulations will be needed to determine where, when, and how many scatterers need to be introduced in order to maintain a spatial distribution of scatterers which has a suitable effect on radiative forcing and climate. Since both increased greenhouse gases and any approach that reduces absorption of solar radiation will affect atmospheric circulation patterns, these simulations should ideally be performed within an atmospheric general circulation model which is simulating effects of increased gases in combination with deliberately

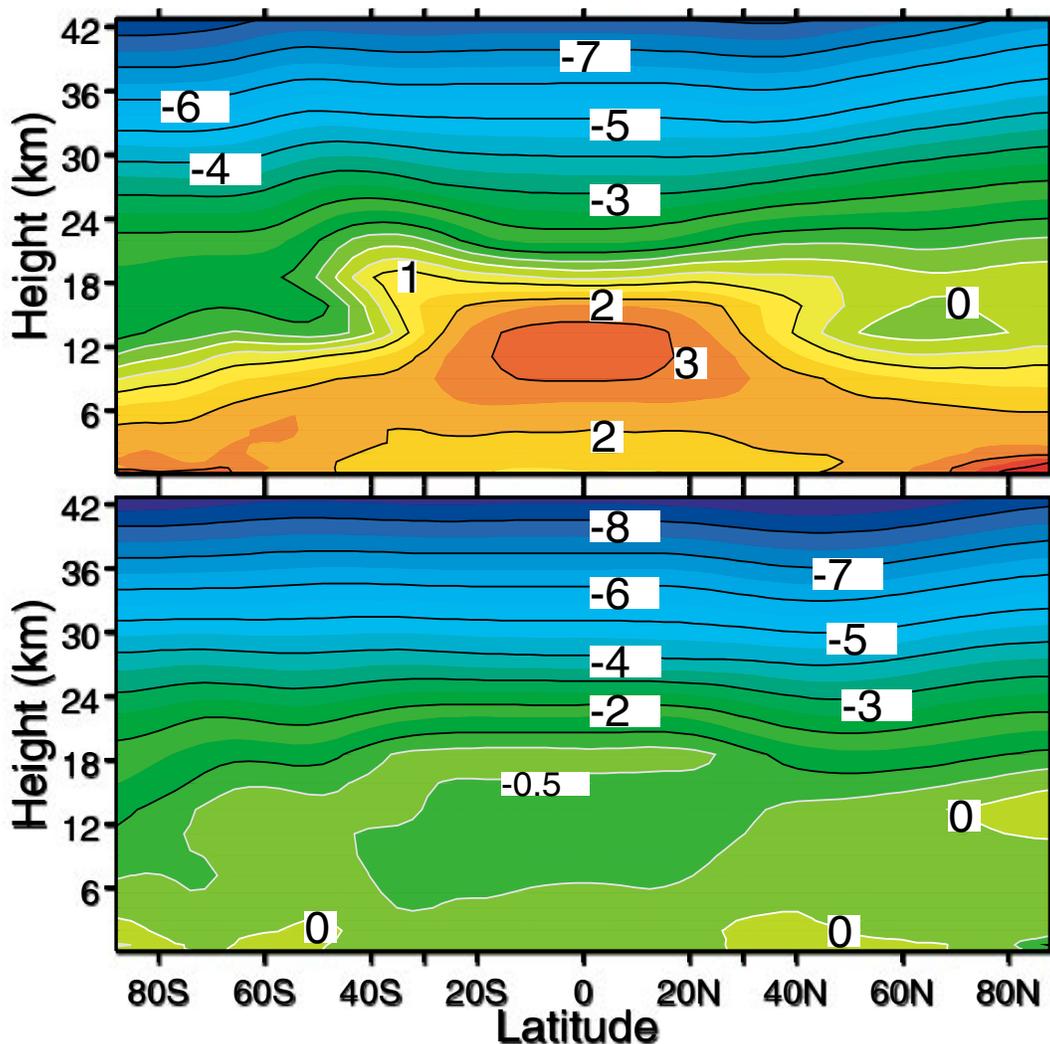


Figure 6: Climate model simulations of zonally-averaged atmospheric temperature changes. The top panel shows temperature changes due to doubling atmospheric CO₂; the troposphere warms while the stratosphere cools. The bottom panel shows temperature changes due to a doubling of CO₂ in combination with a reduction in solar luminosity of 1.8%. Here, the tropospheric warming due to doubling of CO₂ is largely eliminated, but the stratospheric cooling is enhanced. This additional cooling will tend to accelerate ozone loss. From Govindasamy and Caldeira (2000).

introduced atmospheric scatterers. Interestingly, initial studies of these types show that stratospheric tracers quickly acquire and thereafter maintain a quite uniform density, even when injected from point sources.

4.3c Arctic Climate and Ocean Thermohaline Circulation

One of the most serious potential consequences of global warming is a suggested slowdown or collapse of the ocean's thermohaline circulation (THC). This is predicted in global climate models (e.g. Manabe and Stouffer, 1993) to result from increased freshwater fluxes at high latitudes, which reduce the density of surface ocean waters. Climate models can be used to investigate approaches to preventing thermohaline collapse, and to restarting the thermohaline circulation if it were to collapse. For example,

reducing the solar flux regionally (near deep-water forming regions) might cool the surface ocean enough to preserve the THC.

To investigate preventing or reversing a THC collapse, a “stand-alone” ocean circulation model is probably not adequate, because significant changes in ocean circulation will affect atmospheric properties, which in turn influence ocean circulation through surface forcing. These feedbacks are represented only in coupled ocean/atmosphere models. Because of the great computational expense of this type of model, and because simulations of ocean THC will typically need to span one or more centuries, these simulations will be very demanding computationally. For this reason, a model like that of Weaver et al. (2001), which uses a full-fidelity ocean circulation model and a simplified representation of the atmosphere, might be an appropriate tool for initial investigations of this issue.

4.3d Abatement of Hurricanes

A predicted consequence of global warming is a tendency to produce more intense hurricanes (Knutson, and Tuleya, 1999), with the potential to cause significantly more societal impact than today’s storms. A number of approaches have been proposed to reduce this threat. These include putting a thin film on the ocean surface (to reduce latent heat fluxes – the main energy source for hurricanes) and locally reducing solar fluxes (again to reduce latent heat fluxes). The efficacy of these approaches cannot be evaluated using today’s climate models, since these models do not have fine enough spatial resolution to produce hurricanes. Thus, hurricane modeling in the present context would require some novel approach. One such approach would be to “nest” a specialized hurricane model within a high-resolution global climate model. If the resolution were high enough, the global climate model should allow the hurricane model to produce hurricanes. A more straightforward approach would be to use an ultra-high resolution global climate model. Short global climate simulations at 30 or 40 km should be possible now; even finer resolutions will be attainable with future advances in computer power. A more efficient approach would be to use “adaptive mesh refinement” (AMR) within a global climate model. Here the model’s computational mesh is finer in one area of interest (the site of the hurricane); other regions use coarser resolution, thus saving significant computer time. The fine-resolution region moves automatically according to specified criteria (e.g. high wind speeds) and could be made to follow a storm. While the development of an AMR climate model would be a significant undertaking, such a model would have wide usefulness in other DOE climate-modeling programs (e.g. SciDAC).

4.3e Perpetual El Nino

A possible consequence of global warming is changes in modes of natural climate variability. In particular, some model simulations suggest that increasing greenhouse gases may push the climate system towards a permanent El Nino mode (Knutson and Manabe, 1995; Mitchell et al., 1995; Meehl and Washington, 1996; Timmermann et al., 1999; Boer et al., 2000). This would have major consequences for regional climate. If this is indeed a consequence of global warming, it could possibly be prevented or reversed, for example by reducing absorbed solar fluxes globally or regionally. These possibilities should be investigated using global climate models. However, present climate models typically do not represent El Nino realistically, due in part to inadequate spatial resolution (Meehl et al., 2001). Thus a prerequisite to studying this issue is to obtain a realistic representation of El Nino in a global climate model. Higher resolution is probably the first step towards that goal.

4.3f Regional Impacts

Global warming will have strong geographical variability, and may, at least initially, be beneficial in some regions. For this reason, not all regions will benefit equally from activities undertaken to modify or ameliorate the effects of rapid or severe climate change; and some may not benefit at all. It is therefore important to understand the regional-scale impacts of schemes that are being considered. The spatial resolutions (~300 km) typically used in global climate models do not generally produce meaningful

DJF Precipitation

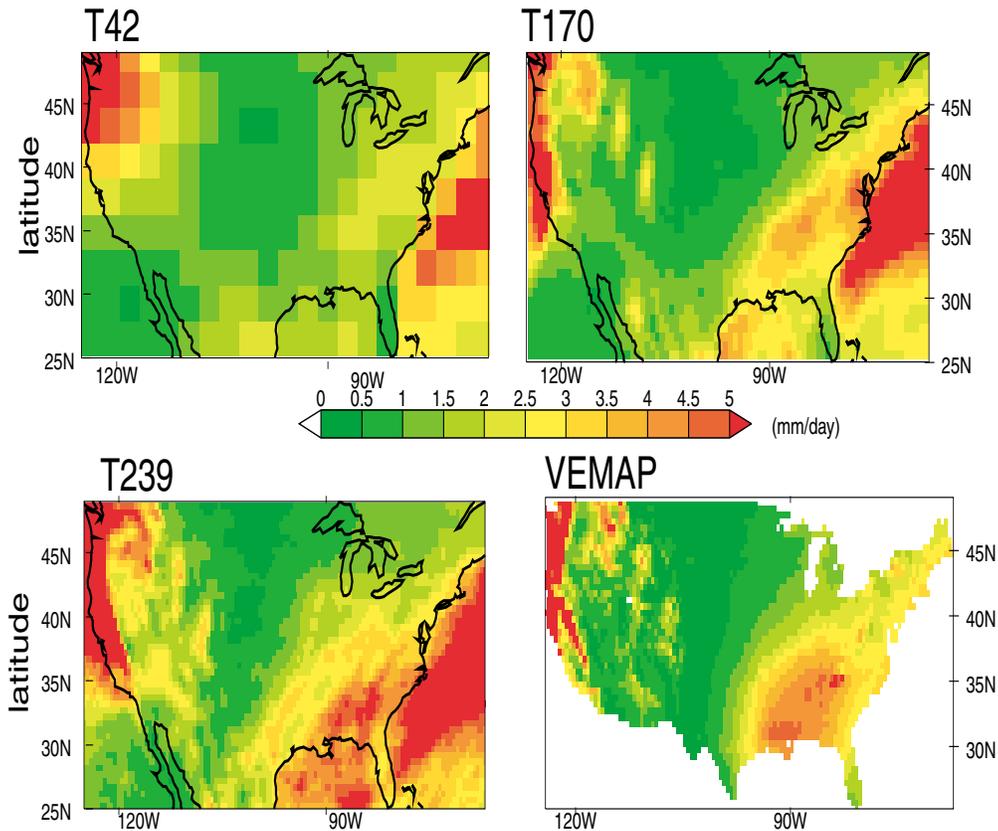


Figure 7: Wintertime precipitation over the US, in the VEMAP (Vegetation/Ecosystem Modeling and Analysis Project) observational data set (lower right) and as simulated using the CCM3 climate model at three different horizontal resolutions. As the model resolution becomes finer, the regional-scale results (e.g. in the Southeastern US) agree better with observations.

results on regional scales; higher resolutions will be needed to assess regional impacts. Recent work has demonstrated the ability to perform global climate simulations at resolutions as high as 50 km, and has shown that this resolution produces much-improved regional-scale results (Figure 7).

5.0 Synergism With Other Ongoing Programs

A substantial basis of understanding for considering the potential effectiveness and associated consequences of potential counter-balancing modification of the climate is provided by the extensive US and international research program on inadvertent global change, which includes research, for example, on climate change, ozone depletion, and occurrence of El Nino events. The international network of surface stations and the extensive set of observing satellites that have been developed by NASA and NOAA provide a wide array of measurements documenting how much and how fast the global environment is changing, providing the basis for a system that could contribute to identifying the onset of rapid or severe change. For example, satellites and ocean buoys combine to warn of the shift in Pacific Ocean temperatures that initiate El Nino events, providing the basis for a prediction system that is starting to show skill out to over a year in advance.

The Atmospheric Radiation Measurement program of DOE makes detailed surface and aircraft observations of solar and infrared (IR) radiation fluxes and related atmospheric variables at several sites around the world. The research program is focused on determining how these fluxes are affected by varying concentrations of gases, aerosols, and clouds. NASA satellites also provide related information on a global scale. Such measurements provide just the types of information needed to test and demonstrate the effectiveness of various options for modulating the amount of sunlight with engineered scatterers, aerosols, and other approaches. The atmospheric chemistry programs of NASA, NOAA, and DOE provide just the needed set of observations, laboratory studies and modeling of atmospheric chemistry needed to initiate study of the potential influences on ozone chemistry of materials injected into the atmosphere.

The USGCRP modeling programs support a focused development and application program that is leading to significant improvements in models. Coordinated efforts by DOE, NOAA, NASA and NSF provide ready opportunities for modifying and using leading models for study of developing and evaluating strategies for modification of solar radiation fluxes and then calculating how the system responds and how these changes interact with ongoing climate change.

A number of other research programs that are underway will also provide the basis for evaluating potential options for ameliorating the prospective consequences of climate variability and change. For example, models developed by NOAA to forecast the intensity and track of hurricanes have been used in initial studies to determine how warming will intensify this type of storm; in addition, these models can be used to evaluate how such intense storms might be moderated. Such cooperative international research programs as the Global Energy and Water Experiment (GEWEX) will provide the data and analysis capabilities needed to evaluate the significance of any changes that might be induced in the hydrologic cycle.

What is clear is that with relatively slight augmentation, as proposed in this White Paper, there is a strong, broad basis for preliminary exploration of the viability of various options. At the same time, to the extent that demonstrations of potential options need to be carried out, there is some infrastructure that can be drawn upon, but much is already committed to ongoing research programs (e.g., about atmospheric chemistry, land cover, etc.) that are vital to enhancing the fundamental research base for global change studies. As such, demonstration projects, which may have to be relatively significant in scope given the nature of the problem, will likely need to be mainly funded by this research activity.

The program addressed in this White Paper leverages ongoing work in the following major U.S. government and International Programs:

- DOE Atmospheric Radiation Measurement Program, ARM
- DOE Atmospheric Chemistry Program, ACP
- DOE Climate Change Prediction Program CCPP
- NOAA, NASA, NSF (NCAR), Climate modeling projects
- Global Energy and Water Experiment (GEWEX)
- NOAA, NASA Satellite Measurements
- Others

6.0 Program Plan, and Schedule:

The attached table gives a description of key activities and the funding requirements for a five-year research and technology program.

| Activity | Funding Requirements, \$M | | | | | Total |
|--|---------------------------|----------|-----------|-----------|-----------|-----------|
| | Year 1 | 2 | 3 | 4 | 5 | |
| 1. Scoping studies, preliminary concept delineation, program coordination | 1 | 1 | 1 | 1 | 1 | 5 |
| 2. Develop and demonstrate engineering feasibility of three alternative technical approaches | 2 | 2 | 3 | 5 | 5 | 17 |
| 3. Develop, design, test instrumentation and monitoring system to detect inception of sudden or severe climate change (to be conducted jointly with NASA and NOAA) | 1 | 1 | 3 | 3 | 3 | 11 |
| 4. Develop validated geophysical and economic models to predict effectiveness of technical approaches and their ancillary impacts | 2 | 2 | 2 | 3 | 3 | 12 |
| 5. Conduct benchmark, pilot scale and field tests to validate effectiveness of technical approaches, validate models, and evaluate environmental impacts | 2 | 2 | 5 | 5 | 5 | 19 |
| TOTAL | 8 | 8 | 14 | 17 | 17 | 64 |

7.0 References

- Boer, G.J., G. Flato, and D. Ramsden, (2000). A transient climate change simulation with greenhouse gas and aerosol forcing: projected climate for the 21st century, *Climate Dynamics*, 16, 427-450.
- Budyko M., (1982). *The Earth's Climate: Past and Future*, Academic Press, New York, USA
- Cuffey, K. E. and S. J. Marshall, (2000). Substantial contribution to sea level rise during the last interglacial from the Greenland ice sheet, *Nature*, 404, 591-594.
- Del Genio A.D. and A.B. Wolf, (2000). The Temperature Dependence of the Liquid Water Path of Low Clouds in the Southern Great Plains, *J. of Climate*, 13, 3465-3486
- Duffy P.B., M.E. Wickett, and K. Caldeira, (2001). Effect of horizontal grid resolution on the near-equilibrium solution of a global ocean/sea ice model, *J. Geophys. Res.*, in press.
- Early J.T. (1989). Space-Based Solar Shield To Offset Greenhouse Effect, *J. Brit. Interplan. Soc.* 42, 567-569.
- Fahey D.W. and S.R. Kauoa et al., (1993). In Situ Measurements Constraining the Role of Sulfate Aerosols in Mid-latitude Ozone Depletion, *Nature*, 363, pp 509-514
- Flannery, B. P., H. Kheshgi, G. Marland and M. C. MacCracken, (1997). *Geoengineering Climate. Engineering Response to Global Climate Change: Planning a Research and Development Agenda*, R. G. Watts, Ed., Lewis Publishers, 379-427.
- Govindasamy B., and K. Caldeira, (2000). Geoengineering Earth's Radiation Balance to Mitigate CO₂-induced Climatic Change, *Geophysical Research Letters*, 27, No. 14, 2141-2144
- IPCC (2001). *Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change* [Houghton, J. T., Y Ding, D. J. Griggs, M. Noguer, P. van der Linden, X. Dai and K. Maskell (eds.)]. Cambridge University Press, 289-348.
- Johnson, R. G. (1997). Climate control requires a dam at the Strait of Gibraltar, *EOS*, 78, 277-287.
- Keith D. W. (2000). Geoengineering the climate: History and Prospect, *Annu. Rev. Energy Environ.* 2000. 25:245-284.
- Keith D. W. and H. Dowlatabadi, (1992). A Serious Look at Geoengineering, *EOS*, 73, 289, 292-293
- Knutson, T.R. and S. Manabe, (1995). Time-mean response over the tropical Pacific to increased CO₂ in a coupled ocean-atmosphere model. *J. Climate*, 8, 2181-2199
- Knutson, T. R. and R.E. Tuleya, (1999). Increased hurricane intensities with CO₂-induced warming as simulated using the GFDL hurricane prediction system, *Climate Dynamics* 15, 503-519.
- Landsea, C. W., and R. A. Pielke, Jr. (1998). Normalized hurricane damages in the United States: *Weather and Forecasting* 1925-95..
- Manabe, S., and R.J. Stouffer, (1993). Century scale effects of Increased atmospheric CO₂ on the ocean-atmosphere system, *Nature*, 364, 215-218
- McCormick M. P., L.W. Thomason and C. R. Trepte, (1995). Atmospheric effects of the Mt Pinatubo Eruption. *Nature* 373, 399-404.
- MacCracken M. C. (1991). *Geoengineering the Climate. Preprint for Workshop on the Engineering Response to Global Climate Change*, LLNL Report Number UCRL-JC-108014.
- Meehl, G.A., P.R. Gent, J.M. Arblaster, B.L. Otto-Blaisner et al., (2001). Factors that effect the amplitude of El nino in global coupled climate models, *Climate Dynamics*, 17, 515-526
- Meehl, G.A., and W.M. Washington, (1996). El Nino-like climate change in a model with increased atmospheric CO₂ concentrations, *Nature*, 382, 56-60

- Mitchell, J.F.B., T.C. Johns, J.M. Gregory and S.F.B. Tett, (1995). Climate response to increasing levels of greenhouse gases and sulfate aerosols, *Nature*, 376, 501-504
- NAS (1992). Policy Implications of Greenhouse Warming: Mitigation, Adaptation, and the Science Base. Panel on Policy Implications of Greenhouse Warming, National Academy of Sciences, National Academy of Engineering, Institute of Medicine. See Chapter 28, Geoengineering, and Appendix Q, Geoengineering Options.
- Nakicenovic N. (2000). IPCC Special Report on Emission Scenarios (SRES)
- Penner S., Schneider A., and E. Kennedy, (1984). Active measures for reducing the global climatic impacts of escalating CO₂ concentrations, *Acta Astronautica* 11(6), 345-348
- Philander, G.S. (1998). Is the Temperature Rising? The Uncertain Science of Global Warming, Princeton University Press, 81-82.
- Ramanathan, V. (1988). The greenhouse theory of climate change: A test by an inadvertent experiment. *Science* 243, 293-299.
- Schwartz S. E. and A. Slingo, (1996). Enhanced shortwave cloud radiative forcing due to anthropogenic aerosols. In *Clouds, Chemistry and Climate--Proceedings of NATO Advanced Research Workshop*.
- Schwartz, S. E. (1996). The Whitehouse Effect--Shortwave radiative forcing of climate by anthropogenic aerosols: An overview. *J. Aerosol. Sci.* 27, 359-382
- Teller E., K. Caldeira, G. Canavan et al., (1999). Long Range Weather Prediction and Prevention of Climate Catastrophes: A Status Report, *LLNL Report No. UCRL-JC-135414*
- Teller E. L. Wood and R. Hyde, (1997). Global warming and ice ages: I. Prospects for physics-based modulation of global change. 22nd International Symposium on Planetary Emergencies, Erice, Sicily, Italy, August 20-23, 1997. *LLNL Report UCRL-JC-128715*.
- Weaver, A.J., M. Eby, E. C. Wiebe, C. M. Bitz, P. B. Duffy, et al., (2001). The UVic Earth System Climate Model: Model description, Climatology and Application to Past, Present and Future Climates, Paper Submitted to *Atmosphere-Ocean*

Related References:

- Higgins, P.A.T., M.D. Masterandrea, S.H. Schneider, (2001). Dynamics of climate and ecosystem coupling: abrupt changes and multiple equilibria. *Philosophical Transactions of the Royal Society of London series B-Biological Sciences*. 357 (in press).
- Hoffert M. et al. (2001). Advanced Technology Paths to Global Climate Stability: Energy for a Greenhouse Planet, Paper Submitted to *Science*
- Keith D. W. (2000). Insight Feature: Geoengineering. *Nature* 409, 420
- Khan E.U., R.L. Kane, A.A. Patrinos, R.S. Kripowicz and M.A.Krebs, (1998). U.S. and Global Carbon Reductions: The Role of Advanced Fossil and Non-Fossil Technologies, Sequestration and Research, Proceedings of the World Energy Congress, Houston, 5, 619-630.
- Mastrandrea M.D. and S.H. Schneider, (2001). Integrated Assessment of Abrupt Climatic Changes, *Climate Policy*, 53, 1-17
- Michaelson J., (1998). Geoengineering: A Climate Change Manhattan Project, *Stanford Environmental Law Journal*
- Ramanathan V., P.J. Crutzen et al., (2001). Aerosols, Climate and Hydrological Cycle, Paper Submitted to *Science*
- Timmermann, A., J. Oherhuber A. Bacher, M. Esch, M. Latif, and E. Roeckner, (1999). Increased El Nino frequency in a climate model forced by future greenhouse warming, *Nature*, 398, 694-696
- United Nations (1978). Convention on the Prohibition of Military or any Other Hostile Use of Environmental Modification Techniques, 1108 U.N.T.S. 151, entered into force Oct. 5, 1978. Available from <http://www1.umn.edu/humanrts/peace/docs/conenvironmodification.html>

Appendix A

A.1 Explore Means to Moderate the Rate of Climate Change in the Arctic

For the last few decades, some regions in the Arctic have been warming at a rate of as much as 1 °C per decade (IPCC, 2001). This high latitude warming is a significant component of overall global warming, and is widely recognized that any further reduction of the areas of highly reflective snow and ice cover will cause an amplification of global warming. The high rate of warming in the Arctic has started to melt permafrost and sea ice, disrupting human systems such as roads, buildings and other infrastructure, and natural ecosystems such as forests and marine life. Continued changes are expected to be larger, more rapid, and much more disruptive. Further warming is likely to increase the rate of melting of mountain glaciers and the rate of deterioration of the Greenland ice sheet, thereby accelerating the rate of rise of sea level. Warming of permafrost and coastal sediments also has the potential to contribute to methane emissions to the atmosphere. Methane is a potent greenhouse gas. In addition, if Arctic warming slows the rate of bottom water formation this too will lead to a significant increase in the rate of sea level rise, which will affect coastal regions around the world.

Thus, *exploring approaches for slowing the rate of climate change in the Arctic* would have important benefits for people and the environment of the region as well as for migrating species and countries around the world. Examples of the types of approaches that might be used to restrain Arctic warming are techniques such as increasing the reflectivity of Arctic stratus clouds, using stratospheric scatterers to reduce incoming solar radiation, altering Arctic ocean salinity by controlling of river or ocean flow, and increasing wintertime heat loss. These candidate approaches must be evaluated carefully for unintended consequences before they are used.

A.2 Explore Means to Divert Severe Hurricanes and Typhoons from Direct Hits on Major Population Centers

Each year several dozen hurricanes and typhoons develop over the warm subtropical oceans areas of the world. Many of these strike highly populated coastal areas each year, and every few years there are very severe storms that are catastrophic over extended regions (e.g., Hurricane Mitch in Honduras, Hurricane Andrew in southern Florida, etc.). The frequency, intensity, and locations of such severe storms seem to vary based on a set of naturally varying conditions ranging from the aridity of the Sahel to the Pacific Ocean which may be experiencing El Niño or La Niña conditions. Although analysis of observations and model simulations do not yet provide a basis for knowing how the frequency and location of these storms may change in response to continued global warming, studies done with the United States national hurricane model indicate that the wind speed and rainfall rate of hurricanes and typhoons that do occur are likely to increase significantly (Knutson and Tuleya, 1999). Other studies suggest that there are long-term variations in the locations that are likely to be struck, for example, by Atlantic hurricanes, with paths during the middle of the past century having been more likely to impact the northeastern US compared to those during the latter part of the past century, which were more likely to have impacted the southeastern and south-central United States.

Major cities around the world, such as Miami, Hong Kong, Tokyo, and others are located along the coastal areas that are currently exposed to major hurricanes and their storm surges, with the potential for very significant damage; many additional cities may face increased exposure as warming continues. For example, if a category 4 hurricanes were to strike New York (as has apparently happened in earlier times), a storm surge in New York harbor of over 20 feet could inundate many parts of Manhattan and other boroughs, flood the subway and other transportation systems, and swamp nationally and internationally important airports, destroy buildings, and discernibly effect the economy.

Finding ways to either reduce the intensity of such severe storms or to divert them away from major cities has the potential to save many lives and significantly reduce damage. Attempting to modify hurricanes using cloud-seeding techniques was pursued several decades ago, but the study was limited in

scope. Much more accurate hurricane models now available will allow conceptual testing of a wider range of ideas about how to attempt to modify hurricanes. For example, a study is underway of possible films for coating the ocean to reduce the uptake of heat and water that power major hurricanes. Other possible approaches may include cooling of ocean waters by bringing colder waters to the surface, seeding clouds to alter the distribution of heating driving the storm, or even modifying other atmospheric systems in ways that might cause them to divert the track of a major hurricane. While the great power of hurricanes can be mitigated but cannot be completely abated significant savings would result if ways can be found to make sure the largest of the storms do not strike the largest concentrations of people and infrastructure.

A.3 Explore Means to Break Sustained Droughts in Key Agricultural Regions

As the world has become more urbanized and interconnected by trade, the importance to the world's food supply from key agricultural regions has grown significantly. For example, only a very few regions (i.e., the North American Great Plains, China, Australia) provide most of the grains delivered by world markets to feed those in many countries around the world. Should the crop fail in any of these regions because of drought or other reasons (as occurred in the Soviet Union in the mid-1970s), international grain prices would significantly rise. It should be noted that the aggregate world reserves of about two months' consumption is shorter than the typical growing season. Should drought or other climatic variation cause failures in more than one of the major regions or for several seasons in a row, the world's food supply could become constricted and, unless foodstuff substitution were successful, large populations around the world could suffer malnutrition and national economies could be disrupted by price distortions. Even with new seed strains and the green revolution, world food stocks remain quite limited, and there is significant vulnerability to sustained or widespread drought.

The climate record provides many examples of the potential for drought. Imagine the consequences if the Dust Bowl conditions of the 1930s returned, or recall what happened to the countries of Southeast Asia during the major El Niño of 1997-98. Climatic records from the Great Plains and California, for example, indicate that much more persistent drought conditions have occurred as a result of the climate apparently locking in to certain patterns for very long intervals of time. Not only can such variations occur naturally, but also model simulations indicate that the swings of the El Niño/La Niña cycle could become more severe, perhaps making such conditions more likely in the future. In addition, observations indicate that the monsoons that bring rainfall to China, India, the Sahel, Australia, and the southwestern US, and other regions can experience long-term variations that can sharply reduce essential rainfall, causing widespread crop failure.

Exploring ways to possibly disrupt the climatic conditions that lead to persistent droughts would provide a means for helping to ensure that sufficient food will be available for the world's population. Possible approaches for a research program to evaluate such prospects include, for example, modifying the extent and reflectivity of marine stratus clouds that are a vital component of the El Niño/La Niña cycle, exploring the ways in which changes in land cover and in regional aerosol loading affect atmospheric circulation, and determining if materials injected into the stratosphere (much like a volcanic eruption) might cause changes in atmospheric circulation that could help to reestablish the normal variability of the climate on which many nations depend.

Appendix B

B.1 Technical Approaches for Modifying Energy Fluxes within the Earth System

Typical time-averaged fluxes of solar energy within the Earth system are of order a few hundred watts per square meter, with about half of incoming solar radiation absorbed at the surface. The historic record and model simulations indicate that natural variations in these fluxes during the past several thousand years is only about 1%, so only a few watts per square meter can have significant influences on the climate.

Fluxes of energy in the form of heat (i.e., infrared radiation) and latent heat (i.e., as water vapor) are also typically of the same magnitude as the solar fluxes, with infrared actually being somewhat higher and latent heat being somewhat lower. Given these magnitudes, changes of these fluxes of order 1% can have important influences. In particular regions, fluxes of sensible heat (i.e., energy resulting from convective transfer) can even be sufficiently large so that modification can cause changes in fluxes by a few watts per square meter.

This section highlights a few of the possible ways in which non-solar fluxes of energy can be modified to an extent that might be able to ameliorate an important potential adverse consequence of climate variability and change.

B.1a. Ocean Slicks for Moderating Hurricanes and Extreme Events and for Limiting Water Vapor Feedback

Tropical cyclones rank among the very most deadly and costly natural catastrophes affecting mankind today. In 1970, a single storm killed more than 300,000 people in Bangladesh, while more than 10,000 perished in Hurricane Mitch a few years ago. While the death toll in such storms has been reduced substantially in developed countries, thanks to successful warning and evacuation strategies, the economic toll is enormous. Hurricane Andrew in 1992 caused more than \$27 billion in damages, and it has been estimated (Landsea and Pielke, 1998) that a repeat of the 1926 Miami hurricane would cause in excess of \$75 billion 1996 dollars, compromising the entire U.S. insurance industry. Recent model simulations (Knutson and Tuleya, 1999) indicate that global warming may increase the intensity of future hurricanes, making very damaging storms more likely unless we adopt mitigation measures.

Virtually all efforts directed at reducing the risk of tropical cyclones have focused on warnings and evacuation for preventing loss of life and on improved construction for reducing damages. While warnings and evacuation have proven highly effective in reducing loss of life in developed countries, developing nations lack the cultural background and material infrastructure (e.g., communications and transportation) necessary for effective warning and evacuation, so that the potential for loss of life is actually increasing, owing to growing populations in affected areas. Recent history demonstrates that future storms could individually kill hundreds of thousands of people. And while better building codes and construction techniques have improved the ability of structures to withstand marginal hurricane-force winds in the developed world, it is still too costly to build residences capable of withstanding winds in excess of about 120 MPH or strong storm surges.

The large human and material cost of tropical cyclones leads to consideration of approaches for reducing the intensity of these storms or redirecting them away from highly populated and developed regions. Several approaches merit consideration:

- **Surface monolayers:** It has been known for some time that the tropical cyclone possesses an “Achilles Heel”: the molecular interface between the ocean and atmosphere through which water must pass in the process of evaporation. The transfer of enthalpy (i.e., heat and latent heat) from ocean to atmosphere when seawater evaporates is the energy source for tropical cyclones, and it is well-known that any reduction in the rate of evaporation that does not also reduce the “drag

coefficient” affecting the flow of air over the sea surface will reduce the maximum wind speeds of the storms. (Indeed, the rapid reduction of intensity when storms reach landfall is a direct and obvious result of the reduction of evaporation from the surface.) Moreover, the evaporation need only be reduced over a remarkably small region under the storm’s eyewall; i.e., over a roughly circular patch of about 150 km diameter. This offers some hope that practical techniques could be developed to reduce the enthalpy transfer from ocean to atmosphere needed to sustain tropical cyclones. Application to the sea surface of molecular monolayers is known to reduce evaporation in benign wind speed conditions. A great advantage of such a layer is that only about 2 kg of substance are required to cover each square kilometer of the sea surface; this could easily be deployed using two tanker aircraft. A monolayer of simple molecules such as the long-chain alcohols will inevitably be disrupted by strong winds and a turbulent water surface. Two possible ways of overcoming this problem are: (i) incorporation of a polymeric surfactant into the monolayer; and (ii) increasing the spreading rate of the monolayer material. Because the physics of air-sea transfer at extraordinary wind speeds is poorly understood, and because there are no direct measurements of such transfer in high wind conditions, “high-risk, high-payoff” research is needed to advance understanding of air-sea transfer at very high wind speeds and to improved techniques for reducing rates of evaporation.

- ***Cooling of ocean waters:*** An alternative approach to limiting heat transfer to the atmosphere is to cool regions of the ocean just upwind of major developed areas. This could have the effect of reducing the amount of energy available to drive the hurricane. Hurricane intensity and path are known to be affected by ocean temperatures. One approach for cooling ocean surface waters would be to bring deeper and cooler ocean waters to the surface. Interestingly, this is just what is proposed in the process of Ocean Thermal Energy Conversion (OTEC), which is an energy technology designed for use in regions of very warm surface waters like those on which hurricanes feed. Thus, it seems worth considering whether a way to protect major developed areas from direct hits by intense hurricanes might be to locate OTEC facilities upwind of these areas, providing energy as a co-benefit.
- ***Seeding of hurricane clouds:*** With the development of more detailed models, careful analysis can be made of the potential for diverting hurricanes or moderating their intensity through cloud seeding at various times in their lifetimes. What seeding of clouds can do is to cause an early or directed release of energy that might have the effect of disrupting storm development. In that major hurricanes depend on not being sheared apart by the winds, it is not inconceivable that hurricane structure could be modified through cloud seeding. Such ideas have been considered in the past, but, lacking adequate modeling capabilities to test the concept, were abandoned as being impractical, and possibly dangerous, to simply test on real hurricanes.
- ***Atmospheric blocking of hurricanes:*** The paths of hurricanes are determined not only by oceanic and land surface conditions, but also by the prevailing circulation in the atmosphere. Improved weather forecast models are now allowing much more accurate forecasts of hurricane track and interactions with surrounding weather systems than have been possible in the past. With such information, the possibility emerges of carrying out a reverse calculation, determining where it might be possible to, for example, amplify a nascent atmospheric disturbance through the injection of energy. This might be accomplished by, for example, cloud seeding, modification of cloud albedo, or even large solar reflectors, with a relatively small amount of initiating energy being amplified by the various forms of potential energy already present in the atmosphere. The notion would be that such an injection of energy would promote the development of a front or other atmospheric circulation so as to divert a major hurricane away from a major developed area.

B.1b. Warming the Polar Stratosphere to Ameliorate Severe Ozone Loss

Dramatic decreases in concentrations of stratospheric ozone occur annually over Antarctica in the Southern Hemisphere late winter and spring -- the so-called "ozone hole". These events result from

reactions of inorganic chlorine compounds, which are not reactive in the gas phase, on the surfaces of stratospheric aerosol particles; the chlorine compounds, present at mixing ratios in excess of 3 ppb, derive from stratospheric reactions of chlorofluorocarbons CFC-11 and CFC-12, among other sources. The particles are naturally present at low temperatures in the winter austral lower stratosphere, where stratospheric circulation results in seasonal isolation from mixing of warmer, ozone-rich air from lower latitudes. The ozone destruction exhibits an onset threshold at inorganic chlorine mixing ratios greater than 2 ppb Cl. The ozone destruction also exhibits non-linear temperature dependence as a consequence of the onset of substantial ice aerosol condensation at a threshold temperature of about 189 K. Because the northern hemisphere polar stratosphere is naturally warmer and less isolated in the winter than its southern counterpart, a reduction in temperature below the heterogeneous process thresholds has not occurred, although several studies have indicated that the Northern Hemisphere stratosphere is poised for similar dramatic ozone reductions in the Arctic spring, should there be a reduction in temperature.

One consequence of increasing concentrations of greenhouse gases is a cooling of the stratosphere resulting from more of the terrestrial infrared radiation being trapped in the troposphere, and thus the potential exists for changing the Arctic regime to one of high springtime ozone loss. Increased stratospheric water vapor concentration arising from the oxidation of methane, the concentration of which is also increasing with time, would further enhance the likelihood of the onset of this phenomenon. Any substantial depletion of stratospheric ozone at high latitudes in the Northern Hemisphere would directly affect high latitude populations and the high latitude biosphere through enhanced ultraviolet radiation at the surface. The high latitude ozone depletion would contribute to global scale mid-latitude diminution of the ozone layer, with significant implications for human health and welfare. Despite reductions in emissions of CFCs arising out of the Montreal Protocols and subsequent international agreements, the stratosphere is committed to mixing ratios of chlorine above 3 ppb for at least the next several decades, giving rise to the possibility of the onset of severe ozone depletion in the Northern Hemisphere early spring as concentrations of greenhouse gases continue to increase.

The possible occurrence of Northern Hemisphere ozone hole raises the question of whether this phenomenon can be averted by active intervention to warm the polar winter stratosphere above the threshold for supporting the undesirable heterogeneous chemistry. A warming of perhaps a few degrees K would be sufficient. Two of many possible approaches are: (1) injecting microwave energy to create higher electron densities and warming through accelerating charged particles, and (2) enhancing the frequency of sudden stratospheric warmings (SSWs), natural events that warm the polar stratospheric and promote mixing during the winter. For warming by microwaves, the antennae should be located where the lowest temperatures and polar stratospheric clouds tend to occur by orographic forcing. The issue of scale of the intervention certainly arises here. SSWs occur as a result of large-scale wave activity over the globe. Finding a method to change their occurrence frequency is a major challenge. A third idea, warming through absorption of short- or long-wave radiation is problematic, since the polar cap is dark during the winter, and of infrared radiation absorbers actually participate as emitters to space and are responsible for the low temperatures that occur. Research required on the deposition of microwaves would relate to scaling issues and observation of the locations of the active heterogeneous surfaces and how they develop in time over the winter and spring. Research required for enhancing SSWs would address understanding forcing and propagation processes in the current atmosphere and generation of ideas for promoting or intervening in these processes.

B.1c. Altering the Polar Energy Balance to Sustain/Restore Arctic Sea Ice

Observations indicate that Arctic sea ice has thinned substantially since the 1960s and its area is also beginning to retreat. Because of an albedo feedback, these changes have contributed to warming of as much as about 1°C per decade for the last few decades across much of the surrounding continental areas, particularly in Siberia and Alaska. These climatic changes are in turn starting to cause significant effects on permafrost, northern ecosystems, and migrating species as well as impacting Native traditions and their subsistence economies.

Examination of the energy balance of the Arctic suggests several ways in which the polar energy balance could be modified to limit warming in the region. Possibilities meriting consideration include:

- **Limiting solar energy input:** The three approaches described in Section 3.2 all merit consideration for limiting the heating caused by solar radiation. Because of its high latitude position, use of scatterers or cloud albedo enhancers would only need to be used during the summer season when, as it turns out, the long daylight hours mean that the Arctic receives more solar energy per day than do equatorial latitudes.
- **Promoting wintertime energy loss:** The sea ice that is present has the effect of insulating the heat absorbed during the polar summer from the very cold temperatures of the Arctic night. Measurements indicate that surface heat loss is of order 100 times as much from the ocean leads (i.e., cracks of open water) than through the sea ice. Thus, the mechanical creation of cracks, for example by the use of ice-breakers, could be undertaken as a means of promoting the cooling of ocean waters. This in turn leads to thickening of the sea ice and would help it persist through the coming warm season, especially in that the high albedo of the thicker sea ice would help to raise the surface albedo and reflect additional solar energy.
- **Modifying Arctic Ocean stratification:** At low temperatures, the density of water is strongly affected by its salinity. As ice freezes, the salt is forced out and the cold, dense water sinks. Later, when the sea ice melts, it releases less dense fresh water that tends to remain at the ocean surface until mixed by atmospheric winds. In addition, ocean stratification is affected by the river runoff from the surrounding continents, with the fresh water also tending to be near the surface. As winter comes, this fresher water tends to freeze more easily, thus creating an insulating blanket over the solar energy absorbed by the ocean waters. Altering this stratification, either by promoting mixing or perhaps by diversion of river water (something considered several decades ago by Soviet planners to provide a source of water to replenish water lost to irrigation in the Caspian and Aral sea basins), could be undertaken to again promote loss of energy and thickening of the sea ice.

B.1d. Altering Ocean Currents to Sustain the Thermohaline Circulation

The North Atlantic component of the global ocean thermohaline overturning circulation is responsible for a substantial fraction of the poleward transport of energy in the Northern Hemisphere. The thermohaline circulation (THC) is driven by the sinking of dense surface waters in a few rather localized areas in the North Atlantic and Southern Oceans. The density of seawater depends on temperature and salinity, hence the term thermohaline. (This is in contrast to wind-driven circulations). The thermohaline circulation has major effects on regional climate through a substantial latitudinal transport of heat. One well-known result of this heat flow is the relative warmth of western European winters compared to what would be experienced otherwise. Another important effect is that, by supplying cold water to the deep ocean, the THC limits the warming of the deep ocean and thereby reduces the rate of rise of global sea level due to thermal expansion. In addition, the THC brings nutrients to the ocean surface, so its maintenance is important to biological activity in the ocean.

Comprehensive ocean-atmosphere circulation models show that global warming may eventually slow or stop the THC in the North Atlantic through a combination of warming and increased freshwater input from rainfall. Both effects act to decrease surface water density and thus hinder the tendency for downwelling. A total collapse of the THC would have major consequences for ocean ecosystems, for regional climate, and would dramatically accelerate the rate of sea level rise. All else being equal, the potential for THC collapse increases with increasing global warming, both in magnitude and time rate of change. Although a THC collapse is generally considered unlikely for current projections of global warming, the phenomenon is not well understood and the consequences would be large. If it occurred it could be permanent on a human times scale, since there is reason to believe a collapsed THC might represent an alternate stable climate state.

It should be noted that a dramatically altered North Atlantic circulation is not just a product emerging from a model. Information gathered from ocean cores indicates that freshwater inputs to the Atlantic from collapsing ice sheets at the end of glacial periods caused episodes of very rapid THC slowdown and collapse.

Candidate approaches for addressing this threat include:

- ***Ocean Barriers and Dams:*** Barriers at key straits would alter the salinity balance of the North Atlantic and could thus either enhance or suppress the tendency of high latitude waters to sink. Possible locations for barriers include Bering, Florida and Indonesia.
- ***Diverting Rivers:*** Many major rivers empty into the Arctic and Atlantic, contributing to a freshening of ocean waters. Diverting these river flows (e.g., diverting Russian rivers to the Caspian and Aral sea basins, as was considered several decades ago), or storing runoff from one season to another, may be a means for limiting the freshening of waters of the North Atlantic and thereby encouraging the THC.
- ***Space-Based Shading:*** Surface water temperatures in the relatively small areas where downwelling occurs could be manipulated by energy management from orbital mirrors or shades. This would be more feasible than whole-planet space-based approaches since only the areas where thermohaline downwelling occurs would be targeted.
- ***Inhibiting Subtropical Ocean Evaporation:*** Freshwater inputs to the high latitude North Atlantic region derive in part from evaporation from subtropical ocean areas. Approaches that would reduce evaporation from these ocean areas (e.g., thin films) would act to increase high latitude water density and promote stronger downwelling.
- ***Inhibiting Precipitation Over the North Atlantic:*** Modifying cloud characteristics to suppress rainfall over the North Atlantic would increase surface water salinity and enhance the potential for downwelling
- ***Increasing Ocean Reflectivity:*** “Pre-cooling” the Gulf Stream by adding myriad reflective floaters (of any size) at subtropical latitudes would increase water density and the potential for sinking by the time the water reached high latitudes.
- ***Limiting Glacial Melting:*** The freshwater releases from melting of the Greenland ice sheet and from large mountain glaciers contribute freshwater to the North Atlantic basin and contribute to limiting the THC. Finding ways to preserve these ice sheets may assist in sustaining the THC.

Any approach that would act to reduce overall global warming would help reduce this threat as well.

Although all climate models project some slowing of the North Atlantic thermohaline circulation by the end of the 21st century, narrowing down the range of global climate sensitivity, improving the simulation of precipitation and improving the resolution and sub-grid scale processes in ocean circulation models are all modeling areas that need attention in order to evaluate how the THC may be sustained (see section 4). Observationally, our ability to monitor the magnitude of the North Atlantic overturning is very poor.

B.1e. Insulating Greenland and Antarctica to Preserve Polar Ice Caps and Limit Sea Level Rise

Greenland and the West Antarctic Ice Sheets each store the equivalent of about 5 – 7 meters of sea level; that is, their combined loss would raise sea level by of order 10 – 15 meters (about 30 – 45 feet!). IPCC (2001) suggests that global warming of several degrees would cause the melting of much of these ice

masses over a period of about 1000 years, implying that once the process started, sea level rise from these ice sheets alone would be of order 1 m/century (3 feet/century). Such a rate of rise would seriously impact coastal communities, at first during storm-induced surges and later simply by steady-state inundation.

At present, NASA satellite surveys and ground observations indicate that some parts of the Greenland ice sheet are starting to deteriorate (Krabill et al., 2000). Most of the major ice streams for West Antarctica look to be relatively stable, although many of the glaciers on the Antarctic Peninsula to the north have been undergoing rapid deterioration. That such destruction is an important risk to consider is evident in elevated seashores evident in geological formations from the last interglacial just over 115,000 years ago when sea level was apparently several meters higher (e.g., Cuffey and Marshall, 2000). What seems clear is that once deterioration starts during warming conditions, significant loss is likely.

Given the dramatic global consequences possible if either of these ice sheets begins to deteriorate, finding ways to preserve them or otherwise slow their potential contributions to sea level rise would be of great benefit to coastal communities. Several types of still rather speculative approaches would seem to merit investigation to determine possible feasibility:

- ***Reducing the Heating of Ice Sheets:*** Depending on the causes of the deterioration, some locations may benefit from reducing the amount of incoming solar radiation through broad-scale injection of scatterers into the stratosphere, brightening of clouds in the region, or use of surface reflectors. Reducing the amount of soot aerosol falling on the ice sheets would also be very beneficial (and reduction of soot emissions would also limit over all global warming). Because these ice sheets are so thick, however, little of what is done at the surface affects their interior thermodynamics for very long times (although this does need to be viewed as a long-term issue).
- ***Slowing the Flow of Ice Sheets:*** The amount of ice present is a balance between what is deposited as snow on top and what is lost out the sides as flows (e.g., into the Antarctic ice shelves or the icebergs present in the North Atlantic). Slowing ice outflows, or at least ensuring that acceleration does not occur, may be possible by adding physical restrictions to the flow path, freezing the underlying base of the ice sheet, or injecting some sort of hardening material into the ice sheet that increases its rigidity in certain regions. Such efforts may only be needed in very limited areas of the various ice streams.
- ***Enhancing Deposition of Snow onto the Ice Sheets:*** At present, wintertime conditions over Greenland and Antarctica are so cold that snowfall is limited. Finding ways of warming wintertime conditions even modestly (so still remaining below freezing) or of promoting more or warmer storms to cross over these regions would tend to enhance snowfall and counter effects of loss of ice. This will happen naturally at least to some extent, and IPCC (2001) indicates that substantial additional snowfall is likely onto the East Antarctic Ice Sheet, which is much more resistant to the effects of global warming because it is grounded above sea level. In addition, if energy could somehow be derived from regional temperature gradients, pumping of water up onto the East Antarctic ice sheet as part of a snowmaking operation might be feasible.

Appendix C

Response Options To Limit (RSCC) Rapid or Severe Climate Change Assessment of Research Needs Workshop Agenda

October 9, 2001

PART 1

| | | |
|-----------------------------|---|---|
| 11:00 a.m. (EDT) | Welcome and Introductions | Ehsan Khan, DOE Wanda Ferrell, DOE |
| 11:15 | President's NCCTI | Ari Patrinos, DOE |
| 11:25 | Role of the Office of Planning and Analysis | Bill Valdez, DOE |
| 11:35 | Making a Case for an Contingency Quick Response Strategy | Ehsan Khan, DOE Marty Hoffert, NYU |
| 12:20 | Break | |

PART 2

| | | |
|--------------|--|--------------------------------|
| 12:30 | RSCC--Causes, History, Triggering Mechanisms and Consequences | Mike MacCracken, USGCRP |
| 12:45 | Thermohaline Circulation | Paul Higgins, Stanford |

PART 3

| | | |
|-------------|---|--------------------------------|
| 1:00 | Approaches for Limiting RSCC | Steve Schwartz, BNL |
| 1:15 | Engineered Stratospheric Scatterers | Lowell Wood, LLNL |
| 1:45 | Aerosols for Limiting RSCC | V. Ramanathan, UCSD |
| 2:10 | Aerosols (continued) | Steve Schwartz, BNL |
| 2:30 | Approaches for Limiting Severe or Rapid Consequences and Impacts | Mike MacCracken, USGCRP |
| 2:50 | Discussions | All |

PART 4

| | | |
|-------------|--|--|
| 3:35 | Satellite Measurements To Study Inception of RSCC | Don Anderson, NASA/HQ |
| 4:00 | R&D Needs- Models | Phil Duffy, LLNL |
| 4:20 | R&D Needs – (Cont.) | Doug Rotman, LLNL Alan Sanstad, LBNL Mike Mastrandrea, Stanford |
| 4:45 | Discussions | All |

Adjourn at 5:45 p.m.

Workshop Attendees:

Germantown Maryland

1. Barbara Carlson, NASA/GISS
2. John Ruether, DOE/NETL
3. Beth Moore, DOE/EMSP
4. Jim Disbrow, DOE/EIA
5. David Morehouse, DOE/EIA
6. Moonis Ally, ORNL
7. Don Anderson, NASA/HQ
8. Ari Patrinos, DOE/SC
9. Jack Kaye, NASA/HQ
10. Warren Washington, NCAR
11. Steve Schwartz, BNL
12. Martin Hoffert, NYU
13. Mike MacCracken, USGCRP
14. Bill Fulkerson, JIEE
15. Jeff Gaffney, ANL
16. Normen Miller, LBNL
17. Alan Sanstad, LBNL
18. David Keith, CMU
19. Norm Kreisman, DOE/SC
20. Bill Valdez, DOE/SC
21. Ehsan Khan, DOE/SC
22. Wanda Ferrell, DOE/SC

Sandia/Livermore

1. John Vitko Jr., SNL
2. Dwain Spencer, SIMTECHE
3. Peter Connell, LLNL
4. Michael Mastrandrea, Stanford
5. Paul Higgins, Stanford
6. Lowell Wood, LLNL
7. Ken Caldeira, LLNL
8. Starley Thompson, LLNL
9. Phillip Duffy, LLNL
10. Doug Rotman, LLNL

Scripps

1. V. Ramanathan, Scripps/UCSD

20 reasons why geoengineering may be a bad idea

Carbon dioxide emissions are rising so fast that some scientists are seriously considering putting Earth on life support as a last resort. But is this cure worse than the disease?

BY ALAN ROBOCK

THE STATED OBJECTIVE OF THE 1992 U.N. Framework Convention on Climate Change is to stabilize greenhouse gas concentrations in the atmosphere “at a level that would prevent dangerous anthropogenic interference with the climate system.” Though the framework convention did not define “dangerous,” that level is now generally considered to be about 450 parts per million (ppm) of carbon dioxide in the atmosphere; the current concentration is about 385 ppm, up from 280 ppm before the Industrial Revolution.

In light of society’s failure to act concertedly to deal with global warming in spite of the framework convention agreement, two prominent atmospheric scientists recently suggested that humans consider geoengineering—in this case, deliberate modification of the climate to achieve specific effects such as cooling—to address global warming. Nobel laureate Paul Crutzen, who is well regarded for his work on ozone damage and nuclear winter, spearheaded a special August 2006 issue of *Climatic Change* with a controversial editorial about injecting sulfate

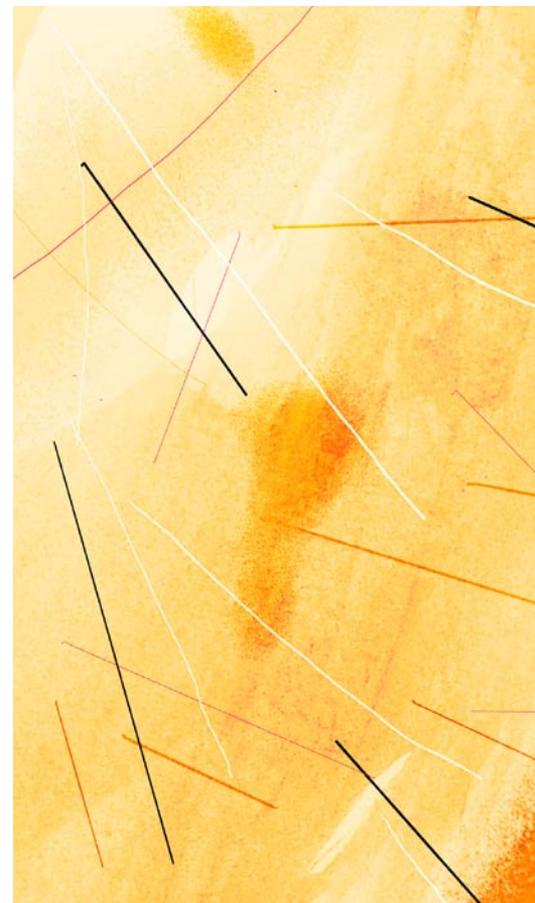
aerosols into the stratosphere as a means to block sunlight and cool Earth. Another respected climate scientist, Tom Wigley, followed up with a feasibility study in *Science* that advocated the same approach in combination with emissions reduction.¹

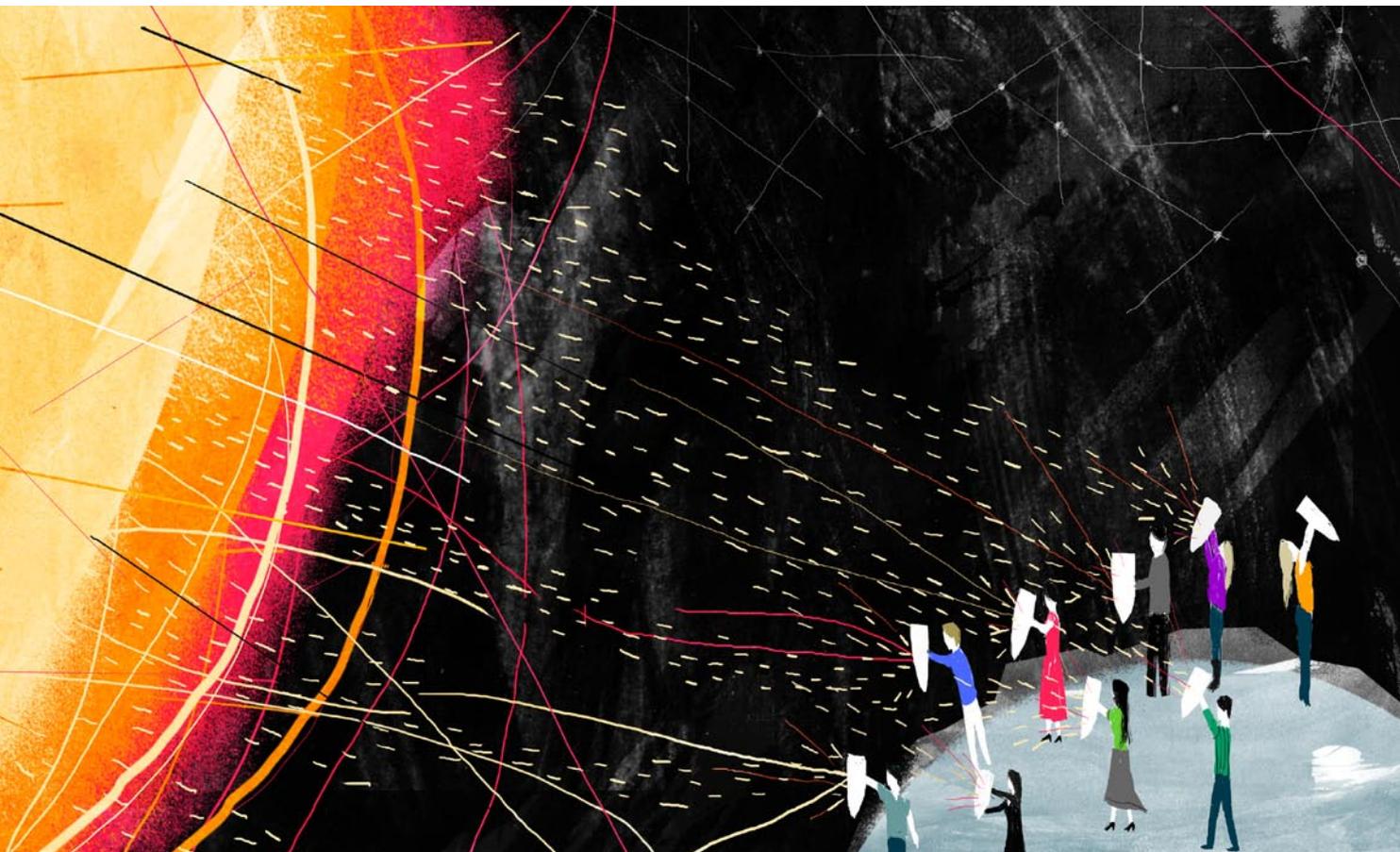
The idea of geoengineering traces its genesis to military strategy during the early years of the Cold War, when scientists in the United States and the Soviet Union devoted considerable funds and research efforts to controlling the weather. Some early geoengineering theories involved damming the Strait of Gibraltar and the Bering Strait as a way to *warm* the Arctic, making Siberia more habitable.² Since scientists became aware of rising concentrations of atmospheric carbon dioxide, however, some have proposed artificially altering climate and weather patterns to reverse or mask the effects of global warming.

Some geoengineering schemes aim to remove carbon dioxide from the atmosphere, through natural or mechanical means. Ocean fertilization, where iron dust is dumped into the open ocean to

trigger algal blooms; genetic modification of crops to increase biotic carbon uptake; carbon capture and storage techniques such as those proposed to outfit coal plants; and planting forests are such examples. Other schemes involve blocking or reflecting incoming solar radiation, for example by spraying seawater hundreds of meters into the air to seed the formation of stratocumulus clouds over the subtropical ocean.³

Two strategies to reduce incoming solar radiation—stratospheric aerosol injection as proposed by Crutzen and space-based sun shields (i.e., mirrors or shades placed in orbit between the sun and Earth)—are among the most widely discussed geoengineering schemes in scientific circles. While these schemes (if they could be built) would cool Earth, they might also have adverse consequences. Several papers in the August 2006 *Climatic Change* discussed some of these issues, but here I present a fairly comprehensive list of reasons why geoengineering might be a bad idea, first written down during a two-day NASA-





sponsored conference on Managing Solar Radiation (a rather audacious title) in November 2006.⁴ These concerns address unknowns in climate system response; effects on human quality of life; and the political, ethical, and moral issues raised.

1. Effects on regional climate. Geoengineering proponents often suggest that volcanic eruptions are an innocuous natural analog for stratospheric injection of sulfate aerosols. The 1991 eruption of Mount Pinatubo on the Philippine island of Luzon, which injected 20 megatons of sulfur dioxide gas into the stratosphere, produced a sulfate aerosol cloud that is said to have caused global cooling for a couple of years without adverse effects. However, researchers at the National Center for Atmospheric Research showed in 2007 that the Pinatubo eruption caused large hydrological responses, including reduced precipitation, soil moisture, and river flow in many regions.⁵ Simulations of the climate response to volcanic eruptions have also

shown large impacts on regional climate, but whether these are good analogs for the geoengineering response requires further investigation.

Scientists have also seen volcanic eruptions in the tropics produce changes in atmospheric circulation, causing winter warming over continents in the Northern Hemisphere, as well as eruptions at high latitudes weaken the Asian and African monsoons, causing reduced precipitation.⁶ In fact, the eight-month-long eruption of the Laki fissure in Iceland in 1783–1784 contributed to famine in Africa, India, and Japan.

If scientists and engineers were able to inject smaller amounts of stratospheric aerosols than result from volcanic eruptions, how would they affect summer wind and precipitation patterns? Could attempts to geoengineer isolated regions (say, the Arctic) be confined there? Scientists need to investigate these scenarios. At the fall 2007 American Geophysical Union meeting, researchers presented preliminary findings from several different climate models that simulated

geoengineering schemes and found that they reduced precipitation over wide regions, condemning hundreds of millions of people to drought.

2. Continued ocean acidification. If humans adopted geoengineering as a solution to global warming, with no restriction on continued carbon emissions, the ocean would continue to become more acidic, because about half of all excess carbon dioxide in the atmosphere is removed by ocean uptake. The ocean is already 30 percent more acidic than it was before the Industrial Revolution, and continued acidification threatens the entire oceanic biological chain, from coral reefs right up to humans.⁷

3. Ozone depletion. Aerosol particles in the stratosphere serve as surfaces for chemical reactions that destroy ozone in the same way that water and nitric acid aerosols in polar stratospheric clouds produce the seasonal Antarctic ozone hole.⁸ For the next four decades or so, when the concentration of anthropogenic ozone-depleting substances will still be large enough in the stratosphere

CAPITALIZING ON CARBON

Without market incentives, geoengineering schemes to reflect solar heat are still largely confined to creative thought and artists' renderings. But a few ambitious entrepreneurs have begun to experiment with privatizing climate mitigation through carbon sequestration. Here are a few companies in the market to offset your carbon footprint:

California-based technology startups Planktos and Climos are perhaps the most prominent groups offering to sell carbon offsets in exchange for performing ocean iron fertilization, which induces blooms of carbon-eating phytoplankton. Funding for Planktos dried up in early 2008 as scientists grew increasingly skeptical about the technique, but Climos has managed to press on, securing \$3.5 million in funding from Braemar Energy Ventures as of February.

Also in the research and development phase is Sydney, Australia-based Ocean Nourishment Corporation, which similarly aims to induce oceanic photosynthesis, only it fertilizes with nitrogen-rich urea instead of iron. Atmocean, based in Santa Fe, New Mexico, takes a slightly different tack: It's developed a 200-meter deep, wave-powered pump that brings colder, more biota-rich water up to the surface where lifeforms such as tiny, tube-like salps sequester carbon as they feed on algae.

Related in mission if not in name, stationary carbon-capture technologies, which generally aren't considered geoengineering, are nonetheless equally inventive: Skyonic, a Texas-based startup, captures carbon dioxide at power plants (a relatively well-proven technology) and mixes it with sodium hydroxide to render high-grade baking soda. A pilot version of the system is operating at the Brown Stream Electric Station in Fairfield, Texas. To the west in Tucson, Arizona, Global Research Technologies, the only company in the world dedicated to carbon capture from ambient air, recently demonstrated a working "air extraction" prototype—a kind of carbon dioxide vacuum that stands upright and is about the size of a phone booth. Meanwhile, GreenFuel Technologies Corporation, in collaboration with Arizona Public Service Company, is recycling carbon dioxide emissions from power plants by using it to grow biofuel stock in the form of—what else?—algae.

KIRSTEN JERCH

to produce this effect, additional aerosols from geoengineering would destroy even more ozone and increase damaging ultraviolet flux to Earth's surface.

4. Effects on plants. Sunlight scatters as it passes through stratospheric aerosols, reducing direct solar radiation and increasing diffuse radiation, with important biological consequences. Some studies, including one that measured this effect in trees following the Mount Pinatubo eruption, suggest that diffuse radiation allows plant canopies to photosynthesize more efficiently, thus increasing their capacity as a carbon sink.⁹ At the same time, inserting aerosols or reflective disks into the atmosphere would reduce the total sunlight to reach Earth's surface. Scientists need to assess the impacts on crops and natural vegetation of reductions in total, diffuse, and direct solar radiation.

5. More acid deposition. If sulfate is injected regularly into the stratosphere, no matter where on Earth, acid deposition will increase as the material passes through the troposphere—the atmospheric layer closest to Earth's surface. In 1977, Russian climatologist Mikhail Budyko calculated that the additional acidity caused by sulfate injections would be negligibly greater than levels that resulted from air pollution.¹⁰ But the relevant quantity is the *total* amount of acid that reaches the ground, including both wet (acid rain, snow, and fog) and dry deposition (acidic gases and particles). Any additional acid deposition would harm the ecosystem, and it will be important to understand the consequences of exceeding different biological thresholds. Furthermore, more acidic particles in the troposphere would affect public health. The effect may not be large compared to the

impact of pollution in urban areas, but in pristine areas it could be significant.

6. Effects of cirrus clouds. As aerosol particles injected into the stratosphere fall to Earth, they may seed cirrus cloud formations in the troposphere.¹¹ Cirrus clouds affect Earth's radiative balance of incoming and outgoing heat, although the amplitude and even direction of the effects are not well understood. While evidence exists that some volcanic aerosols form cirrus clouds, the global effect has not been quantified.¹²

7. Whitening of the sky (but nice sunsets). Atmospheric aerosols close to the size of the wavelength of light produce a white, cloudy appearance to the sky. They also contribute to colorful sunsets, similar to those that occur after volcanic eruptions. The red and yellow sky in *The Scream* by Edvard Munch was inspired by the brilliant sunsets he witnessed over Oslo in 1883, following the eruption of Krakatau in Indonesia.¹³ Both the disappearance of blue skies and the appearance of red sunsets could have strong psychological impacts on humanity.

8. Less sun for solar power. Scientists estimate that as little as a 1.8 percent reduction in incoming solar radiation would compensate for a doubling of atmospheric carbon dioxide. Even this small reduction would significantly affect the radiation available for solar power systems—one of the prime alternate methods of generating clean energy—as the response of different solar power systems to total available sunlight is not linear. This is especially true for some of the most efficiently designed systems that reflect or focus direct solar radiation on one location for direct heating.¹⁴ Following the Mount Pinatubo eruption and the 1982 eruption of El Chichón in Mexico, scientists observed a direct solar radiation decrease of 25–35 percent.¹⁵

9. Environmental impacts of implementation. Any system that could inject aerosols into the stratosphere, i.e., commercial jetliners with sulfur mixed into their fuel, 16-inch naval rifles firing 1-ton shells of dust vertically into the air, or hoses suspended from stratospheric balloons, would cause enormous environmental damage. The same could be said for systems that would deploy sun

shields. University of Arizona astronomer Roger P. Angel has proposed putting a fleet of 2-foot-wide reflective disks in a stable orbit between Earth and the sun that would bend sunlight away from Earth.¹⁶ But to get the needed *trillions* of disks into space, engineers would need 20 electromagnetic launchers to fire missiles with stacks of 800,000 disks every five minutes for twenty years. What would be the atmospheric effects of the resulting sound and gravity waves? Who would want to live nearby?

10. Rapid warming if deployment stops. A technological, societal, or political crisis could halt a project of stratospheric aerosol injection in mid-deployment. Such an abrupt shift would result in rapid climate warming, which would produce much more stress on society and ecosystems than gradual global warming.¹⁷

11. There's no going back. We don't know how quickly scientists and engineers could shut down a geoengineering system—or stem its effects—in the event of excessive climate cooling from large volcanic eruptions or other causes. Once we put aerosols into the atmosphere, we cannot remove them.

12. Human error. Complex mechanical systems never work perfectly. Humans can make mistakes in the design, manufacturing, and operation of such systems. (Think of Chernobyl, the *Exxon Valdez*, airplane crashes, and friendly fire on the battlefield.) Should we stake the future of Earth on a much more complicated arrangement than these, built by the lowest bidder?

13. Undermining emissions mitigation. If humans perceive an easy technological fix to global warming that allows for “business as usual,” gathering the national (particularly in the United States and China) and international will to change consumption patterns and energy infrastructure will be even more difficult.¹⁸ This is the oldest and most persistent argument against geoengineering.

14. Cost. Advocates casually claim that it would not be too expensive to implement geoengineering solutions, but there have been no definitive cost studies, and estimates of large-scale government projects are almost always too low.

(Boston's “Big Dig” to reroute an interstate highway under the coastal city, one of humankind's greatest engineering feats, is only one example that was years overdue and billions over budget.) Angel estimates that his scheme to launch reflective disks into orbit would cost “a few trillion dollars.” British economist Nicholas Stern's calculation of the cost of climate change as a percentage of global GDP (roughly \$9 trillion) is in the same ballpark; Angel's estimate is also orders of magnitude greater than current global investment in renewable energy technology. Wouldn't it be a safer and wiser investment for society to instead put that money in solar power, wind power, energy efficiency, and carbon sequestration?

15. Commercial control of technology. Who would end up controlling geoengineering systems? Governments? Private companies holding patents on proprietary technology? And whose benefit would they have at heart? These systems could pose issues analogous to those raised by pharmaceutical companies and energy conglomerates whose products ostensibly serve the public, but who often value shareholder profits over the public good.

16. Military use of the technology. The United States has a long history of trying to modify weather for military purposes, including inducing rain during the Vietnam War to swamp North Vietnamese supply lines and disrupt antiwar protests by Buddhist monks.¹⁹ Eighty-five countries, including the United States, have signed the U.N. Convention on the Prohibition of Military or Any Other Hostile Use of Environmental Modification Techniques (ENMOD), but could techniques developed to control global climate forever be limited to peaceful uses?

17. Conflicts with current treaties. The terms of ENMOD explicitly prohibit “military or any other hostile use of environmental modification techniques having widespread, long-lasting or severe effects as the means of destruction, damage, or injury to any other State Party.” Any geoengineering scheme that adversely affects regional climate, for example, producing warming or drought, would therefore violate ENMOD.

18. Control of the thermostat. Even if scientists could predict the behavior

and environmental effects of a given geoengineering project, and political leaders could muster the public support and funding to implement it, how would the world agree on the optimal climate? What if Russia wants it a couple of degrees warmer, and India a couple of degrees cooler? Should global climate be reset to preindustrial temperature or kept constant at today's reading? Would it be possible to tailor the climate of each region of the planet independently without affecting the others? If we proceed with geoengineering, will we provoke future climate wars?

19. Questions of moral authority. Ongoing global warming is the result of inadvertent climate modification. Humans emit carbon dioxide and other greenhouse gases to heat and cool their homes; to grow, transport, and cook their food; to run their factories; and to travel—not intentionally, but as a by-product of fossil fuel combustion. But now that humans are aware of their effect on climate, do they have a moral right to continue emitting greenhouse gases? Similarly, since scientists know that stratospheric aerosol injection, for example, might impact the ecosphere, do humans have a right to plow ahead regardless? There's no global agency to require an environmental impact statement for geoengineering. So, how should humans judge how much climate control they may try?

20. Unexpected consequences. Scientists cannot possibly account for all of the complex climate interactions or predict all of the impacts of geoengineering. Climate models are improving, but scientists are discovering that climate is changing more rapidly than they predicted, for example, the surprising and unprecedented extent to which Arctic sea ice melted during the summer of 2007. Scientists may never have enough confidence that their theories will predict how well geoengineering systems can work. With so much at stake, there is reason to worry about what we don't know.

THE REASONS WHY GEOENGINEERING may be a bad idea are manifold, though a moderate investment in *theoretical*

AN ETHICAL ASSESSMENT OF GEOENGINEERING

While there are many questions about the feasibility, cost, and effectiveness of geoengineering plans, my colleague Alan Robock has been the most systematic and persistent of a number of scientists in raising ethical quandaries about the enterprise. But just how serious are these ethical quandaries?

Most science poses risks of unintended consequences, and lots of science raises issues of commercial and military control. At issue here is whether there is any reason to believe *ex ante* that these are special or unusually large risks. Merely asserting them does not ground an objection *per se*.

Not all of Robock's concerns involve ethics, but of those that do, some involve issues of procedural justice (such as who decides) while others involve matters of distributive justice (such as uneven benefit and harm). To simplify things, let's assume that injecting aerosols into the stratosphere successfully cooled Earth without any untoward effects and with evenly distributed benefits. One might still object that there are issues of procedural justice involved—who decides and who controls. But such concerns don't get much traction when everyone benefits.

Let's pull back from this idealization to imagine an outcome that involves untoward consequences and an uneven distribution of benefits. We deal with consequences by balancing them against the benefits of our interventions. The issue is whether or not we can obtain reliable estimates of both risks and benefits without full-scale implementation of the planned intervention. We already know from modeling that the impact of any such intervention will be uneven, but again, without knowing what the distribution of benefit and harm would be, it's hard to estimate how much this matters. Let's differentiate two circumstances under which going ahead with the intervention might be judged: One is where everyone benefits, while the other is a circumstance in which something less is the case. A conservative conclusion would be to say that beyond modeling and controlled, low-level tests (if the modeling justifies it), we shouldn't sanction any large-scale interventions unless they are in everyone's interest. A slightly eased condition, proposed by the philosopher Dale Jamieson, would be that at least nobody is worse off. That may not be as farfetched a condition as one might think, since, in the end, we are considering this intervention as a means to balance a risk we all face—global warming.

But suppose there are isolated livelihoods that only suffer negative effects of geoengineering. Then numbers begin to matter. In the case that a geoengineering scheme were to harm the few, we should have the foresight to be able to compensate, even if doing so requires something as drastic as relocating populations. I don't mean to oversimplify a complicated issue, but objection to any negative consequences whatsoever isn't a strong enough argument to end discussion.

More trenchant is the worry that the mere possibility of geoengineering would undermine other efforts to decrease our carbon output. Such moral hazard is a familiar worry, and we don't let it stop us in other areas: Antilock braking systems and airbags may cause some to drive more recklessly, but few would let that argument outweigh the overwhelming benefits of such safety features.

As Robock correctly asserts, the crux of addressing global warming may be a political—not a scientific—problem, but it doesn't follow that we may not need geoengineering to solve it. If it is a political problem, it is a *global* political problem, and getting global agreement to curb greenhouse gases is easier said than done.

With geoengineering, in principle, one nation or agent could act, but a challenge arises if the intervention is certain to have uneven impacts among nations. At this early stage, there is no cost associated with improving our ability to quantify and describe what those inequalities would look like. Once we have those answers in hand, then we can engage in serious ethical consideration over whether or not to act.

MARTIN BUNZL

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geoengineering research might help scientists to determine whether or not it is a bad idea. Still, it's a slippery slope: I wouldn't advocate actual small-scale stratospheric experiments unless comprehensive climate modeling results could first show that we could avoid at least all of the potential consequences we *know* about. Due to the inherent natural variability of the climate system, this task is not trivial. After that there are still the unknowns, such as the long-term effects of short-term experiments—stratospheric aerosols have an atmospheric lifetime of a couple years.

Solving global warming is not a difficult technical problem. As Stephen Pacala and Robert Socolow detail with their popular wedge model, a combination of several specific actions can stabilize the world's greenhouse gas emissions—although I disagree with their proposal to use nuclear power as one of their “wedges.”²⁰ Instead, the crux of addressing global warming is political. The U.S. government gives multibillion-dollar subsidies to the coal, oil, gas, and nuclear industries, and gives little support to alternative energy sources like solar and wind power that could contribute to a solution. Similarly, the federal government is squashing attempts by states to mandate emissions reductions. If global warming is a political problem more than it is a technical problem, it follows that we don't need geoengineering to solve it.

The U.N. Framework Convention on Climate Change defines “dangerous anthropogenic interference” as *inadvertent* climate effects. However, states must also carefully consider geoengineering in their pledge to prevent dangerous anthropogenic interference with the climate system. ■

FOR NOTES, PLEASE SEE P. 59.

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a geoengineering research agenda.**

NOTES

20 reasons why geoengineering may be a bad idea

CONTINUED FROM P. 18

1. Paul Crutzen, "Albedo Enhancement by Stratospheric Sulfur Injections: A Contribution to Solve a Policy Dilemma?" *Climatic Change*, vol. 77, pp. 211–19 (2006); Tom M. L. Wigley, "A Combined Mitigation/Geoengineering Approach to Climate Stabilization," *Science*, vol. 314, pp. 452–54 (2006).

2. See the chapter on climate modification schemes in Spencer R. Weart, *The Discovery of Global Warming* (2007), available at <http://www.aip.org/history/climate/RainMake.htm>; a long history of geoengineering proposals in James R. Fleming, "Fixing the Weather and Climate: Military and Civilian Schemes for Cloud Seeding and Climate Engineering," in Lisa Rosner, ed., *The Technological Fix* (New York: Routledge, 2004), pp. 175–200; and James R. Fleming, "The Pathological History of Weather and Climate Modification," *Historical Studies in the Physical Sciences*, vol. 37, pp. 3–25 (2006). See also N. Rusin and L. Flit, *Man Versus Climate* (Moscow: Peace Publishers, 1960); Mikhail I. Budyko, *Climatic Changes* (Washington, D.C.: American Geophysical Union, 1977); Ralph J. Cicerone et al., "Global Environmental Engineering," *Nature*, vol. 356, p. 472 (1992); Edward Teller et al., *Global Warming and Ice Ages: I. Prospects for Physics-Based Modulation of Global Change* (Lawrence Livermore National Laboratory Publication UCRL-JC-128715, 1997); David W. Keith, "Geoengineering the Climate: History and Prospect," *Annual Review of Energy and the Environment*, vol. 25, pp. 245–84 (2000).

3. John Latham first raised this idea in two articles that appeared in *Nature*, vol. 347, no. 6291: "Control of Global Warming," pp. 330–40, and "Effect on Global Warming of Wind-Dependent Aerosol Generation at the Ocean Surface," pp. 372–73 (1990). Keith Bower offers a numerical evaluation in "Computational Assessment of a Proposed Technique for Global Warming Mitigation Via Albedo-Enhancement of Marine Strato-cumulous Clouds," *Atmospheric Research*, vol. 82, pp. 328–36 (2006).

4. See Lee Lane, Ken Caldeira, Robert Chatfield, and Stephanie Langhoff, eds., "Workshop Report on Managing Solar Radiation," NASA/CP-2007-214558 (2007).

5. Kevin E. Trenberth and Aiguo Dai, "Effects of Mount Pinatubo Volcanic Eruption on the

Hydrological Cycle as an Analog of Geoengineering," *Geophysical Research Letters*, vol. 34, no. 16, (2007).

6. For more on warming over continents of the Northern Hemisphere, see Alan Robock, "Volcanic Eruptions and Climate," *Reviews of Geophysics*, vol. 38, pp. 191–219 (2000); Georgiy Stenchikov et al., "Arctic Oscillation Response to Volcanic Eruptions in the IPCC AR4 Climate Models," *Journal of Geophysical Research*, vol. 111, (2006). For more on the effects of Asian and African monsoons, see Luke Oman et al., "Climatic Response to High-Latitude Volcanic Eruptions," *Journal of Geophysical Research*, vol. 110, (2005); Luke Oman et al., "High-Latitude Eruptions Cast Shadow Over the African Monsoon and the Flow of the Nile," *Geophysical Research Letters*, vol. 33, (2006).

7. Royal Society, *Ocean Acidification Due to Increasing Atmospheric Carbon Dioxide*, June 30, 2005, available at royalsociety.org/displaypagedoc.asp?id=13539

8. Susan Solomon et al., "The Role of Aerosol Variations in Anthropogenic Ozone Depletion at Northern Midlatitudes," *Journal of Geophysical Research*, vol. 101, (1996); Susan Solomon, "Stratospheric Ozone Depletion: A Review of Concepts and History," *Reviews of Geophysics*, vol. 37, (1999).

9. L. Gu et al., "Responses of Net Ecosystem Exchanges of Carbon Dioxide to Changes in Cloudiness: Results from Two North American Deciduous Forests," *Journal of Geophysical Research*, vol. 104, no. 31, pp. 421–31, 434 (1999); L. Gu et al., "Advantages of Diffuse Radiation for Terrestrial Ecosystem Productivity," *Journal of Geophysical Research*, vol. 107, (2002); L. Gu et al., "Response of a Deciduous Forest to the Mount Pinatubo Eruption: Enhanced Photosynthesis," *Science*, vol. 299, pp. 2,035–38 (2003).

10. Budyko, *Climatic Changes*.

11. Richard P. Turco et al., "A Study of Mesospheric Rocket Contrails and Clouds Produced by Liquid-Fueled Rockets," *Space Solar Power Review*, vol. 3, pp. 223–34 (1982); V. A. Mohnen, "Stratospheric Ion and Aerosol Chemistry and Possible Links With Cirrus Cloud Microphysics—A Critical Assessment," *Journal of Atmospheric Science*, vol. 47, pp. 1,933–48 (1990).

12. K. Sassen et al., "The 5–6 December 1991 FIRE IFO II Jet Stream Cirrus Case Study: Possible Influences of Volcanic Aerosols," *Journal of Atmospheric Science*, vol. 52, pp. 97–123 (1993).

13. D. W. Olsen et al., "When the Sky Ran Red: The Story Behind *The Scream*," *Sky & Telescope*, February 2004, pp. 29–35.

14. For the estimate for reducing incoming

solar radiation, see Balan Govindasamy and Ken Caldeira, "Geoengineering Earth's Radiation Balance to Mitigate CO₂-Induced Climate Change," *Geophysical Research Letters*, vol. 27, pp. 2,141–44 (2000). For the response of solar power systems, see Michael C. MacCracken, "Geoengineering: Worthy of Cautious Evaluation?" *Climatic Change*, vol. 77, pp. 235–43 (2006).

15. Robock, "Volcanic Eruptions and Climate," pp. 191–219.

16. Roger P. Angel, "Feasibility of Cooling the Earth with a Cloud of Small Spacecraft Near the Inner Lagrange Point (L₁)," *Proceedings of the National Academy of Sciences*, vol. 103, pp. 17,184–89 (2006).

17. See Figure 1 in Wigley, "A Combined Mitigation/Geoengineering Approach to Climate Stabilization," pp. 452–54, and Figure 3 in H. Damon Matthews and Ken Caldeira, "Transient Climate-Carbon Simulations of Planetary Geoengineering," *Proceedings of the National Academy of Sciences*, vol. 104, pp. 9,949–54 (2007).

18. See for example Stephen H. Schneider, "Earth Systems: Engineering and Management," *Nature*, vol. 409, pp. 417–19, 421 (2001), and Ralph J. Cicerone, "Geoengineering: Encouraging Research and Overseeing Implementation," *Climatic Change*, vol. 77, pp. 221–26 (2006).

19. James R. Fleming writes eloquently about the militaristic history of climate modification schemes in "The Climate Engineers," *Wilson Quarterly*, Spring 2007, pp. 46–60. See also Fleming, "Fixing the Weather and Climate," and Fleming, "The Pathological History of Weather and Climate Modification."

20. Stephen W. Pacala and Robert Socolow, "Stabilization Wedges: Solving the Climate Problem for the Next 50 Years with Current Technologies," *Science*, vol. 305, pp. 968–72 (2004); Alan Robock, "Nuclear Power's Costs and Perils" (Letter to the Editor), *Physics Today*, vol. 60, no. 1, p. 14 (2007).

Climate change and security

CONTINUED FROM P. 24

1. Climate Change 2007: Summary for Policy Makers. Contribution of Working Group II to the Fourth Assessment Report of the

ATMOSPHERIC SCIENCE

Whither Geoengineering?

Alan Robock

According to the Intergovernmental Panel on Climate Change (IPCC) (1), global warming will soon have severe consequences for our planet. The IPCC also estimates (2) that mitigation would only cost ~0.1% of the global gross national product per year for the next 30 years, a price far smaller than the damage that would occur. As a potential route to mitigation, the old idea of “geoengineering” has gotten much attention in the last 2 years (3, 4). On page 1201 of this issue, Tilmes *et al.* (5) quantify the effects of one geoengineering approach—the introduction of additional aerosols into Earth’s stratosphere, akin to a volcanic eruption—on high-latitude stratospheric ozone concentrations.

Geoengineering involves trying to reduce the amount of sunlight reaching Earth’s surface to compensate for the additional long-wave infrared radiation from greenhouse gases, thereby reducing or reversing global warming (6). Even if it works, there are problems with this approach (7). If perceived to be a possible remedy for global warming, it would reduce societal pressure to reduce greenhouse gas emissions. It could reduce overall precipitation, particularly Asian and African summer monsoon rainfall, threatening the food supply of billions. It would allow continued ocean acidification, because some of the carbon dioxide humans put into the atmosphere continues to accumulate in the ocean. Weather modification could be used as a weapon (8), thus violating the 1977 U.N. Convention on the Prohibition of Military or Any Other Hostile Use of Environmental Modification Techniques. There would be rapid warming if geoengineering stopped suddenly. If geoengineering worked, whose hand would be on the thermostat? How could the world agree on an optimal climate?

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A polar stratospheric cloud over McMurdo, Antarctica, on 24 August 2004. These clouds cause ozone depletion every spring because of anthropogenic chlorine in the stratosphere. The ozone hole is expected to disappear by the middle of this century, but with geoengineering, the Antarctic ozone hole would continue to form for another 30 to 70 years.

Nevertheless, for some schemes, the benefits may outweigh the problems, especially if used on a temporary basis. To date, only some schemes have been investigated in detail. Furthermore, proponents of geoengineering, especially the fossil fuel industry, will continue to push for its use.

Sunshades in orbit around Earth (9) or cloud seeding to brighten them (10) have been proposed, but most geoengineering ideas focus on emulating explosive volcanic eruptions by injecting SO₂ or H₂S into the stratosphere, producing a sulfuric acid cloud to scatter solar radiation back to space and cool the planet. Deciding whether this is a good idea or not requires detailed analysis of the costs, benefits, and harm to the planet that such a strategy would entail, and comparison to the same metrics for mitigation and sequestration. Given the need for rapid mitigation, these ideas need rapid and thorough investigation.

It has been suggested (3, 4) that the cooling of the global climate for a couple years after large volcanic eruptions—like the 1991 Mount Pinatubo eruption—serves as an innocuous model for what humans could do by creating a permanent stratospheric aerosol layer. However, volcanic eruptions actually serve as a warning about geoengineering:

Costs, benefits, and harms associated with geoengineering must be assessed before it is used to mitigate climate change.

They produce drought (11), hazy skies, much less direct solar radiation for use as solar power, and ozone depletion (12).

We now have an ozone hole over Antarctica every spring because the polar stratospheric clouds that form there (see the figure) serve as surfaces for heterogeneous chemistry that releases chlorine, which then catalytically destroys ozone. Polar stratospheric clouds only form when the temperature falls below ~195 K, but additional sulfate aerosols provided by geoengineering or volcanic eruptions alter these temperature restrictions and provide more surface area for the chemistry, allowing more chlorine to

be activated and more ozone to be destroyed.

Advocates of geoengineering suggest that this ozone problem would not be important, because the stratospheric concentration of chlorine is slowly decreasing as a result of global environmental agreements (13). However, Tilmes *et al.* show that even with the projected chlorine declines, ozone depletion (and increased ultraviolet flux) would be prolonged for decades by geoengineering of the stratospheric sulfate layer. In their model, the effects would occur every spring in the Southern Hemisphere and in most springs in the warmer Northern Hemisphere. The presence of sulfate aerosols would raise the temperature needed for chlorine activation over 200 K, expanding both vertically and horizontally the regions of polar ozone depletion.

A U.S. Department of Energy white paper (14) in October 2001 recommended a \$13 million/year national geoengineering research effort, but the paper was never released. According to the paper, “any effort to deliberately moderate or ameliorate threats that may arise or become more likely as a result of climate change should be undertaken only in extraordinary circumstances.... In view of the risk of significant consequences to society and the environment from either inaction or

poorly understood actions, research should be initiated now to examine possible options to moderate adverse climate threats; to ensure that these options are effective, affordable, reversible and sustainable.”

It is not too late to make up for lost time, but further delay must be avoided. A research program, more generously funded than that proposed in 2001, supported by the U.S. federal government with international cooperation, will allow us to compare the efficacy, costs, and consequences of the various options of responding to global warming—mitigation, sequestration, geo-engineering, or doing nothing—so that an informed public can agree on the best courses of action.

ASTRONOMY

A Blast from the Past

Andrew C. Fabian

Have you ever wanted to view an event that happened many years ago? Most of the light from that event is still traveling through space and can, in principle, be reflected back to us to reconstruct the event. This is, of course, completely impractical for events that occur on a human scale, but when a star explodes as a supernova, so much light is emitted that it may be possible to see a delayed reflection from surrounding dust clouds. On page 1195 of this issue, Krause *et al.* (1) report their observations of a light echo for the outburst of Cassiopeia A (Cas A), which is the most recent nearby supernova known to have occurred in our Galaxy.

The remnant of Cas A was first discovered in 1947 and identified optically in 1950. From its observed expansion, it can be deduced that the explosion itself would have occurred around 1680, as viewed from Earth. A recent x-ray image of the remnant is shown in the figure.

More recently, infrared images made with the Spitzer Space Telescope revealed moving light echoes around Cas A 4 years ago (2). These echoes were monitored last year with the Calar Alto optical telescope in Spain, and a spectrum of a particularly bright patch was taken by the Subaru telescope in Hawaii. The echo spectrum clearly shows light from the supernova. When a star of 10 to 20 solar

masses explodes, an energy equivalent to about 1% of the mass of the Sun is turned into kinetic energy of the stellar envelope, which then expands into space at velocities of 10,000 km/s or more. The spectrum shows emission and absorption lines Doppler-broadened by such large velocities. The presence of hydrogen lines in the spectrum places it in the category of a type II supernova, which results from collapse of the core of a massive star when it runs out of fuel, as was long suspected from the properties of the still-expanding remnant. The spectrum is remarkably similar to that of supernova 1993J

1. IPCC, *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, S. Solomon *et al.*, Eds. (Cambridge Univ. Press, Cambridge, UK, and New York, NY, 2007).
2. IPCC, *Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, B. Metz, O. R. Davidson, P. R. Bosch, R. Dave, L. A. Meyer, Eds. (Cambridge Univ. Press, Cambridge, UK, 2007).
3. P. J. Crutzen, *Climatic Change* **77**, 211 (2006).
4. T. M. L. Wigley, *Science* **314**, 452 (2006).
5. S. Tilmes, R. Müller, R. Salawitch, *Science* **320**, 1201 (2008).
6. I use “geoengineering” to refer to schemes designed to reduce solar radiation input to the climate system; I exclude the broader meaning that includes sequestration of atmospheric carbon dioxide, for example, by iron fertilization of the oceans [an idea that has been shown to be premature (15)], afforestation, and reforestation.
7. A. Robock, *Bull. Atomic Scientists* **64**(2), 14 (2008).
8. J. R. Fleming, *Wilson Q.* **2007**, 46 (spring 2007).
9. R. Angel, *Proc. Nat. Acad. Sci. U.S.A.* **103**, 17184 (2006).
10. K. Bower, T. Choullarton, J. Latham, J. Sahraei, S. Salter, *Atm. Res.* **82**, 328 (2006).
11. K. Trenberth, A. Dai, *Geophys. Res. Lett.* **34**, L15702, 10.1029/2007GL030524 (2007).
12. S. Solomon, *Rev. Geophys.* **37**, 275 (1999).
13. L. Lane, K. Caldeira, R. Chatfield, S. Langhoff, Eds., *Workshop Report on Managing Solar Radiation*, NASA/CP-2007-214558 (NASA, Ames Research Center, Moffett Field, CA, 2007).
14. E. Khan *et al.*, *Response Options to Limit Rapid or Severe Climate Change* (Department of Energy, Washington, DC, 2001).
15. K. O. Buesseler *et al.*, *Science* **319**, 162 (2008).
16. I thank R. Salawitch, S. Tilmes, G. Stenchikov, and A. Marquardt for valuable suggestions. Supported by NSF grant ATM-0730452.

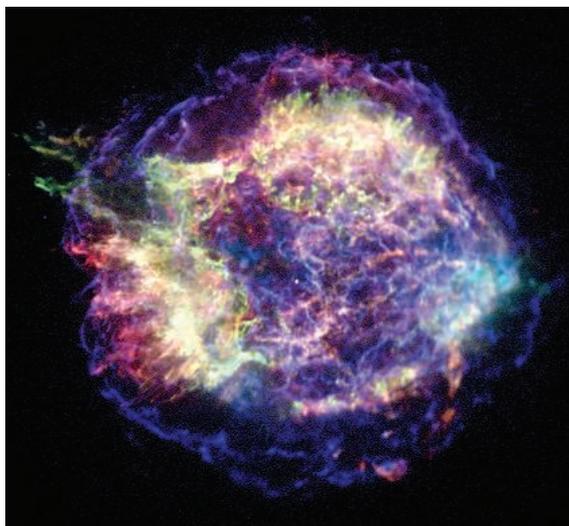
10.1126/science.1159280

Echoes of light, reflections from nearby gas and dust clouds, can be used to reconstruct past astronomical events.

(SN 1993J), a type IIb supernova seen (in 1993) in the nearby galaxy M81.

Light echoes also have recently been seen from SN 1993J (3), and from other supernovae in our satellite galaxy, the Large Magellanic Cloud (4), including the famous SN 1987A (5), which is the only supernova to have been seen with the naked eye since the invention of the telescope more than 400 years ago. Van den Bergh (6) in 1966 had tried to look for an echo around Cas A. However, we now know that it was much too faint to be seen with the photographic plates available at that time.

The light echo spectrum from Cas A is notable primarily because Cas A is a type IIb supernova and its remnant has been so well studied due to its proximity and youth. We can assume (7) that Cas A was a red giant before it exploded, and that it probably had a binary companion at some stage. The progenitor of SN 1993J was predicted to have been a member of a binary, and a massive star consistent with a companion remains at the site (8). There is no such stellar companion remaining at the position of Cas A, so it possibly spiraled into the progenitor some time before the explosion. A faint non-variable pointlike x-ray source has been found (9) close to the center of the remnant and is probably a neutron star.



Supernova remnant. An image of the Cas A remnant taken by the Chandra X-ray Observatory (CXO).

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Regional climate responses to geoengineering with tropical and Arctic SO₂ injections

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[1] Anthropogenic stratospheric aerosol production, so as to reduce solar insolation and cool Earth, has been suggested as an emergency response to geoengineer the planet in response to global warming. While volcanic eruptions have been suggested as innocuous examples of stratospheric aerosols cooling the planet, the volcano analog actually argues against geoengineering because of ozone depletion and regional hydrologic and temperature responses. To further investigate the climate response, here we simulate the climate response to both tropical and Arctic stratospheric injection of sulfate aerosol precursors using a comprehensive atmosphere-ocean general circulation model, the National Aeronautics and Space Administration Goddard Institute for Space Studies ModelE. We inject SO₂ and the model converts it to sulfate aerosols, transports the aerosols and removes them through dry and wet deposition, and calculates the climate response to the radiative forcing from the aerosols. We conduct simulations of future climate with the Intergovernmental Panel on Climate Change A1B business-as-usual scenario both with and without geoengineering and compare the results. We find that if there were a way to continuously inject SO₂ into the lower stratosphere, it would produce global cooling. Tropical SO₂ injection would produce sustained cooling over most of the world, with more cooling over continents. Arctic SO₂ injection would not just cool the Arctic. Both tropical and Arctic SO₂ injection would disrupt the Asian and African summer monsoons, reducing precipitation to the food supply for billions of people. These regional climate anomalies are but one of many reasons that argue against the implementation of this kind of geoengineering.

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1. Introduction

[2] 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.” “Dangerous anthropogenic interference” was not defined, but is now generally considered to be at a CO₂ level of about 450 ppm, and we are currently at about 385 ppm.

[3] In light of the failure of society to take any concerted actions to deal with global warming in spite of the 1992 UNFCCC agreement, two prominent atmospheric scientists published papers recently suggesting that society consider geoengineering solutions to global warming [Crutzen, 2006;

Wigley, 2006]. While this suggestion is not new [Rusin and Flit, 1960; Environmental Pollution Panel, 1965; Budyko, 1977; Cicerone et al., 1992; Panel on Policy Implications of Greenhouse Warming, 1992; Leemans et al., 1996; Dickinson, 1996; Schneider, 1996, 2001; Flannery et al., 1997; Teller et al., 1997, 1999, 2002; Keith, 2000, 2001; Boyd et al., 2000; Khan et al., 2001; Bower et al., 2006] (and a long history of geoengineering proposals as detailed by Fleming [2004, 2006, 2007]), it generated much interest in the press and in the scientific community, including five commentaries published with the Crutzen [2006] article: MacCracken [2006], Bengtsson [2006], Cicerone [2006], Kiehl [2006], and Lawrence [2006].

[4] There have been many types of suggested geoengineering, including those based on changing the CO₂ concentration in the atmosphere (ocean fertilization, carbon capture and sequestration, and genetic modification of ecosystem productivity), damming the ocean (e.g., Gibraltar or Bering Straits), modification of the ocean surface albedo or evaporation, or albedo enhancement of marine stratocumulus clouds (see references above). Another approach, evaluated in this paper, is reducing the incoming solar radiation with artificial stratospheric aerosols or space-based sun shields, that is, injecting sulfate or soot aerosols or their

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precursors into the stratosphere or by placing mirrors or shades in orbit between the Sun and Earth to reduce the amount of insolation [Angel, 2006]. In the case of “solar radiation management” [Lane *et al.*, 2007], the idea is that reduced insolation will compensate for the additional radiative forcing from greenhouse gases. As Teller *et al.* [1997, p. 5] point out, “The Earth’s surface is not considered for reasons of land use and local microclimate impacts, while the ocean surface poses stability/durability/navigation compatibility concerns, and tropospheric residence times are not usefully long for the types of scattering systems which we consider.”

[5] This paper evaluates the suggestions for using sulfate aerosols in the stratosphere to reduce insolation. These ideas have been evaluated with simple general circulation model (GCM) experiments by Govindasamy and Caldeira [2000], in which geoengineering was simulated as a reduction of the solar constant. However, the details of the solar forcing from the specific effects of stratospheric aerosols were not evaluated in any detail. Govindasamy and Caldeira [2000] used a slab ocean and only evaluated equilibrium experiments that reduced the solar constant at the same time as doubling CO₂. They found that a reduction of 1.8% in solar irradiance would balance the global warming produced by a CO₂ doubling. Govindasamy *et al.* [2002] evaluated the effects of the same experiment on land surface vegetation and the carbon cycle with the same GCM coupled to a terrestrial biosphere model, but again did not evaluate the effects of aerosols. Govindasamy *et al.* [2003] continued the analysis for a quadrupling of CO₂, but again with equilibrium experiments and a slab ocean.

[6] Teller *et al.* [1997] discussed various geoengineering proposals, and Teller *et al.* [1999, 2002] did not propose new geoengineering beyond Teller *et al.* [1997], but described the results of the Govindasamy and Caldeira [2000] and Govindasamy *et al.* [2002] GCM experiments. Wigley [2006], with an energy balance model, and Matthews and Caldeira [2007], with an intermediate complexity atmosphere-ocean GCM coupled to a carbon cycle model, used solar constant reduction to mimic geoengineering. The only experiment done so far explicitly looking at stratospheric aerosol injection was by Rasch *et al.* [2008] with an atmospheric GCM coupled to a slab ocean, who used tropical injection of stratospheric aerosols prescribed at two size distributions. Most of the previous experiments looked at the equilibrium climate response; the only time-dependent studies were by Wigley [2006] with an energy balance model and Matthews and Caldeira [2007] with a simplified GCM. The results presented here are the first with a comprehensive atmosphere-ocean GCM, the first to include interactive injection, transport, and removal of stratospheric aerosol for Arctic injection, and the first comprehensive GCM experiment to look at the time-dependent climate system response.

2. Volcanic Eruptions as an Analog for Geoengineering

[7] Geoengineering suggestions [e.g., Crutzen, 2006; Wigley, 2006] have claimed that volcanic eruptions provide a good analog for stratospheric aerosol injection, and that the example of the 1991 Mt. Pinatubo eruption was a rather

innocuous event, which should give us confidence that geoengineering is safe. However, tropical eruptions produce changes in atmospheric circulation, with winter warming over Northern Hemisphere continents [e.g., Graf *et al.*, 1993; Koderer *et al.*, 1996; Robock, 2000; Stenchikov *et al.*, 2002, 2004, 2006], but this winter warming is only for 1 or 2 years after the eruption, when a temperature gradient is maintained in the stratosphere and also depends on the phase of the quasi-biennial oscillation [Stenchikov *et al.*, 2004]. Here we address the question of whether such a circulation anomaly would persist with a continuous aerosol cloud. If so, regional warming from greenhouse gases would be enhanced over some regions by a geoengineering “solution.” Furthermore, high-latitude eruptions weaken the Asian and African monsoons causing precipitation reductions [Oman *et al.*, 2005, 2006a]. In fact, the 1783–1784 Laki eruption produced famine in Africa, India, and Japan. Here we examine how smaller amounts of stratospheric aerosols would affect summer wind and precipitation patterns and investigate whether schemes to geoengineer just the Arctic would be confined there.

[8] Robock and Liu [1994], using model simulations of volcanic eruptions, and Trenberth and Dai [2007], using observations following the 1991 Pinatubo eruption, found large reductions in the strength of the global hydrological cycle including in precipitation, soil moisture, and river flow. Here we also examine the hydrological response to a long-lasting stratospheric aerosol cloud to see whether this response was due to the episodic and unbalanced nature of the aerosol forcing, or is a robust response to geoengineering.

[9] Volcanic eruptions have also been observed to produce large stratospheric ozone depletion following the 1982 El Chichón and 1991 Pinatubo eruptions [Solomon, 1999]. Tilmes *et al.* [2008] showed that in spite of the gradual decline of anthropogenic ozone depleting substances expected over the next several decades, geoengineering with stratospheric aerosols would produce large ozone depletion in the Arctic in winters with a cold polar lower stratosphere, and would delay the disappearance of the Antarctic ozone hole, with effects lasting throughout the 21st Century.

[10] Thus, on first glance, the volcano analog actually seems to argue against geoengineering, as there are negative consequences that accompany the cooling [Robock, 2008a]. Here we evaluate the regional climate changes in detail to see the climatic response to both tropical and Arctic aerosol precursor injection.

3. Experimental Design

[11] A number of different aerosol types have been proposed for geoengineering. Budyko [1977] describes detailed plans for adjusting the sulfur content of jet fuel so that airplanes traveling in the lower stratosphere would inject the correct amount (as determined from climate model calculations) of SO₂ into the stratosphere to form sulfate aerosols. Turco [1995] proposed a scheme involving the conversion and release of fossil fuel sulfur as carbonyl sulfide (OCS), which enhances the stratospheric sulfate layer, discussing the processes and potential pitfalls. Leemans *et al.* [1996] discussed many options, and pointed

out that sulfate aerosols in the stratosphere might deplete ozone, and that pure soot aerosols, while not chemically reactive with ozone, would affect ozone chemistry and reduce ozone because of the ensuing temperature rise in the stratosphere. This was verified in GCM calculations by Mills *et al.* [2008] recently. Teller *et al.* [1997] suggested using dielectric material of an optimum size, electrical conductors (metal particles), or resonant molecules to scatter sunlight. Teller *et al.* [1997, p. 6] claimed that “appropriately fine-scale particulate loadings of the middle stratosphere will persist for five-year intervals” which seems like an overestimate to us, on the basis of past work with volcanic sulfate aerosols, which have a 1-year *e*-folding lifetime [e.g., Stenchikov *et al.*, 1998; Gao *et al.*, 2007]. Budyko [1977] assumed an average lifetime of stratospheric aerosols of 2 years, which is a more reasonable estimate.

[12] Teller *et al.* [1997, p. 15] claimed that “Consistent with the slow latitudinal mixing-time of the stratosphere well above the tropopause, different amounts of scattering material might be deployed (e.g., at middle stratospheric altitudes, ~25 km) at different latitudes, so as to vary the magnitude of insolation modulation for relatively narrow latitudinal bands around the Earth, e.g., to reduce heating of the tropics by preferential loading of the mid-stratospheric tropical reservoir with insolation scatterer,” but on the basis of observations of the dispersion of stratospheric volcanic aerosols, this claim does not describe the way the stratosphere behaves. In fact, proposals to inject artificial aerosols into the tropical stratosphere, so that atmospheric winds would disperse them globally, earlier in the same paper are more consistent with stratospheric dynamics. As Budyko [1977, p. 241] says, “The choice of the region where the reagent is scattered is of limited importance since data on the dispersion of product of volcanic eruptions demonstrate that reagent from any point outside the tropical zone rapidly spreads over the entire hemisphere.” But he also continues, “Circulation in the lower stratosphere can be of importance in selecting optimal regions and periods of time for ejecting the reagent to ensure its most effective use.”

[13] Previous geoengineering simulations have introduced sulfate aerosol precursors into the tropical stratosphere [Rasch *et al.*, 2008] or simulated aerosol injection by reducing solar insolation either uniformly globally [Govindasamy and Caldeira, 2000; Govindasamy *et al.*, 2002, 2003; Matthews and Caldeira, 2007] or in the Arctic [Lane *et al.*, 2007]. Therefore, we decided to conduct experiments for both tropical and Arctic SO₂ injections, and to calculate the time-dependent climate response.

[14] We use the National Aeronautics and Space Administration Goddard Institute for Space Studies ModelE atmosphere-ocean GCM. We used the stratospheric version with 4° latitude by 5° longitude horizontal resolution and 23 vertical levels up to 80 km [Schmidt *et al.*, 2006]. It is fully coupled to a 4° latitude by 5° longitude dynamic ocean with 13 vertical levels [Russell *et al.*, 1995]. It is important to use a full dynamic ocean in these simulations to obtain the most realistic climate response, including how long it takes for the temperature and precipitation to recover if the injecting of SO₂ should stop. This climate model has been tested extensively in global warming experiments [Hansen *et al.*, 2005; Schmidt *et al.*, 2006] and to examine the effects of volcanic eruptions on climate [Oman *et al.*, 2005, 2006a,

2006b] and nuclear winter [Robock *et al.*, 2007a, 2007b]. The climate model (with a mixed layer ocean) does an excellent job of modeling the climatic response to the 1783 Laki [Oman *et al.*, 2006a] and the 1912 Katmai [Oman *et al.*, 2005] volcanic eruptions. We have also used this model to simulate the transport and removal of sulfate aerosols from tropical and high-latitude volcanic eruptions [Oman *et al.*, 2006b], and have shown that it does a good job of simulating the lifetime and distribution of the volcanic aerosols. In the stratosphere, the aerosols from a tropical eruption have an *e*-folding residence time of 12 months in the model, in excellent agreement with observations, although the model transports aerosols poleward a little too fast.

[15] The aerosol module [Koch *et al.*, 2006] accounts for SO₂ conversion to sulfate aerosols, and transport and removal of the aerosols. The radiative forcing from the aerosols is fully interactive with the atmospheric circulation. We define the dry aerosol effective radius as 0.25 μm, compared to 0.35 μm for our Pinatubo simulations. This creates hydrated sulfate aerosols with an effective radius of approximately 0.30–0.35 μm for our geoengineering runs and 0.47–0.52 μm for our Pinatubo simulations. It is difficult to say the size to which the aerosols will grow without a microphysical model that has coagulation, but by injecting SO₂ continuously (as compared to one eruption per year), coagulation would be reduced, since concentrations would be lower and the aerosol particles will be more globally distributed. The smaller size aerosols have a slightly longer lifetime so this would reduce the rate of injection needed to maintain a specific loading, as described in detail by Rasch *et al.* [2008]. By using a smaller aerosol size (about 30% less than Pinatubo), there is about half the heating of the lower tropical stratosphere (0.2–0.5°C for our 5 Tg/a case) as compared to the equivalent loading using a Pinatubo size aerosol. But as Tilmes *et al.* [2008] point out, smaller aerosol particles would cause much more ozone depletion for the same mass of aerosol, because they would have a larger total surface area for chemical reactions. For our tropical experiments, we injected SO₂ at a slightly lower altitude than Pinatubo. The altitude and size distribution of the aerosols affect the amount of warming of the tropopause cold point and the amount of additional water vapor let into the stratosphere, which produces global warming to counteract the geoengineering. Our model includes this feedback, but we have not yet examined the sensitivity of the results to the details for stratospheric injection height and size distribution.

[16] It is possible to conduct experiments gradually increasing geoengineering to just match global warming and keep global average surface air temperature constant [Wigley, 2006], but this presupposes that the current climate (whenever geoengineering would start) would be the optimal one. As we were interested in the response of the climate system to a “permanent” stratospheric aerosol cloud, we conducted experiments by injection of SO₂ at a constant rate for 20 years, and then continuing our experiments for another 20 years to examine the response to an instantaneous shutoff of geoengineering. We conducted the following GCM simulations: (1) an 80-year control run with greenhouse concentrations and tropospheric aerosols at 1999 levels; (2) a 40-year run, which we will refer to as the

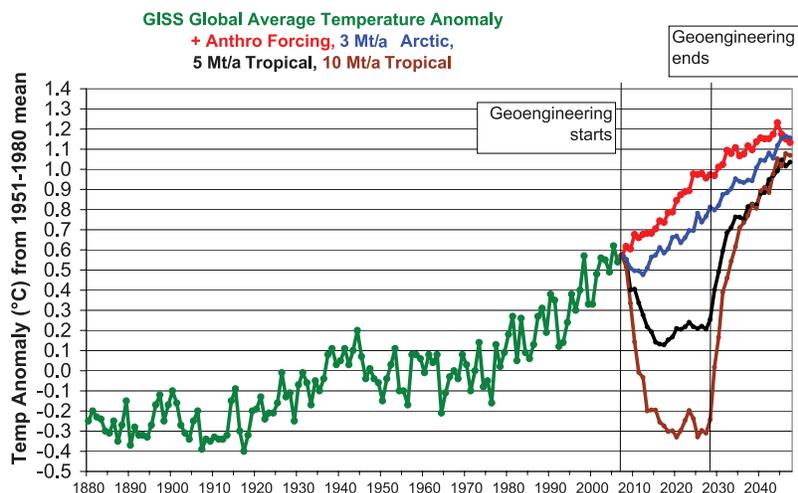


Figure 1. Global average surface air temperature change from the A1B anthropogenic forcing run (red), Arctic 3 Mt/a SO₂ (blue), tropical SO₂ 5 Mt/a (black), and tropical 10 Mt/a SO₂ (brown) cases in the context of the climate change of the past 125 years. Observations (green) are from the National Aeronautics and Space Administration Goddard Institute for Space Studies analysis [Hansen *et al.*, 1996] (updated at <http://data.giss.nasa.gov/gistemp/2007/>).

A1B run, forced by greenhouse gases (CO₂, CH₄, N₂O, and O₃) and tropospheric aerosols (sulfate, biogenic, and soot), using the IPCC A1B business-as-usual global warming scenario, in which we conducted a three-member ensemble with different initial conditions for each ensemble member to address the issue of random climate variability; (3) 40-year A1B anthropogenic forcing plus Arctic lower stratospheric injection of 3 Mt SO₂/a, also a three-member ensemble (Arctic 3 Mt/a run); (4) 40-year A1B anthropogenic forcing plus tropical lower stratospheric injection of 5 Mt SO₂/a, also a three-member ensemble (tropical 5 Mt/a run); and (5) 40-year A1B anthropogenic forcing plus tropical lower stratospheric injection of 10 Mt SO₂/a, in which we conducted only one run (tropical 10 Mt/a run).

[17] We only conducted one tropical 10 Mt/a run because it is an extreme case and the variability between ensemble members is small. We focus most of the analysis on the Arctic 3 Mt/a and tropical 5 Mt/a runs. For the tropical experiments, we put SO₂ into a box one grid cell wide and three model layers thick over the equator at longitude 120°E in the lower stratosphere (16–23 km) at every time step at a rate equal to 5 Mt/a or 10 Mt/a for 20 years, and then continue to run for another 20 years to see how fast the system warms afterward. As the 1991 Mt. Pinatubo eruption put about 20 Mt of SO₂ into the stratosphere [Bluth *et al.*, 1992], 5 Mt/a is the equivalent of a Pinatubo every 4 years and 10 Mt/a is a Pinatubo every 2 years, but we inject the SO₂ continuously at those rates in the experiments here. For the Arctic experiment, we used a lower injection rate, as the idea is to limit the climate response to the Arctic and produce a shorter lifetime for the aerosols. We injected SO₂ continuously at a rate equal to 3 Mt/a into a box one grid cell wide and three model layers thick at latitude 68°N and longitude 120°E in the lower stratosphere (10–15 km). (The longitude of the injection is arbitrary and does not affect the results, as the atmosphere quickly smooths out the aerosol distribution.)

[18] We should also point out that we know of no practical mechanism for actually injecting SO₂ into the stratosphere, on a continuous or even episodic basis, at the rates in our experiments. Suggestions of a geoengineering air force, sulfur injection from commercial air flights, artillery, and hoses suspended from dirigibles are all problematic, but discussion of the details is beyond the scope of this paper. Nevertheless, because there have been serious suggestions to attempt to develop such technology, we study here the climate response to hypothetical SO₂ injections.

4. Results

[19] Figure 1 shows the annual average surface air temperature for the ensemble mean of each of our runs compared to the observed climate change since 1880. While the A1B simulation produces continued global warming at a rate very similar to that observed for the past 30 years, each of the geoengineering runs reduces the global warming, with more reduction for more SO₂ injected. However, the Arctic SO₂ has a proportionately smaller impact on cooling the climate for two reasons. The lifetime of the aerosols is shorter, as they are removed mainly in the Arctic, because of the prevailing stratospheric circulation, while the tropical aerosols are transported poleward before much removal. In addition, because the Arctic aerosols are at high latitudes, they cover a relatively small area and the intensity of solar radiation is less there. While the midsummer insolation is the same at high latitudes as at lower latitudes, averaged over the year, there is less radiation to scatter. The global average reduction in downward shortwave radiation at the surface for the Arctic 3 Mt/a is only about 0.2 W m⁻², while for the tropical 5 Mt/a run it is 1.8 W m⁻² (Figure 2). The effects of the tropical 10 Mt/a case are approximately double those of the tropical 5 Mt/a case, so we concentrate on the latter for detailed analysis of a tropical scenario. Infrared effects of the aerosols (on enhanced downward

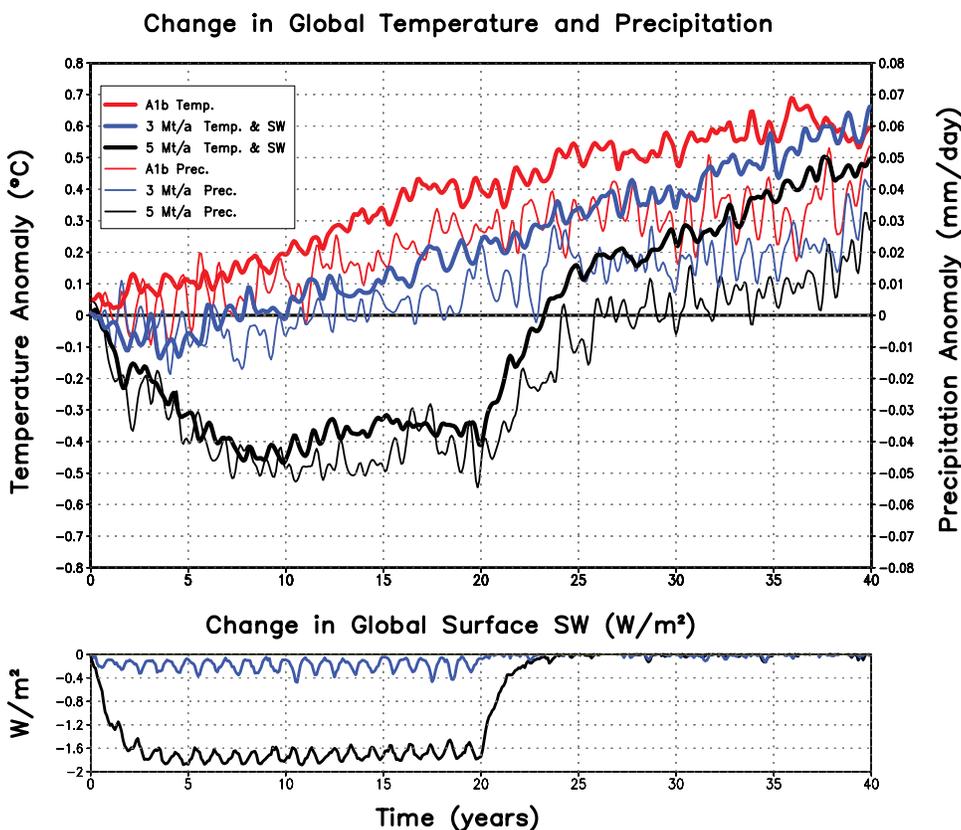


Figure 2. Global monthly average changes (compared to the control run) in temperature (thick lines) and precipitation (thin lines) for A1B (red), Arctic 3 Mt/a (blue), and tropical 5 Mt/a (black) runs and change in downward solar radiation at the surface (as compared to the A1B runs) for the Arctic 3 Mt/a (blue) and tropical 5 Mt/a (black) runs.

radiation) are 2 orders of magnitude less than shortwave effects.

[20] Figure 2 also shows the global average temperature and precipitation anomalies for the A1B, Arctic 3 Mt/a, and tropical 5 Mt/a runs. The global average precipitation is reduced along with the temperature in the geoengineering runs, as expected. However, compared to the radiative forcing from greenhouse gases, the radiative forcing from reduction of solar radiation has a disproportionately large impact on precipitation as compared to temperature, because the radiative forcing from shortwave radiation has no compensating impact on the vertical temperature structure of the atmosphere [Yang *et al.*, 2003]. This can be seen, for example, by comparing years 15–20 for the A1B and tropical 5 Mt/a runs. While the temperature changes are about the same ($+0.4^{\circ}\text{C}$ for the warming and -0.4°C for the cooling), the precipitation reduction for the tropical 5 Mt/a run is almost twice the precipitation increase for the A1B run. In fact, for a 1 W m^{-2} change in radiative forcing in the shortwave, we get a 1.7% change in precipitation, but for the same change in the longwave, we get 1.0%.

[21] We now examine the seasonal and regional distributions of radiative forcing and climate change. We examine a 10-year average of the anomaly patterns for the second half of the 20-year period during which we applied the geoengineering forcing, by which time any initial effects from

the initiation of geoengineering are minimal (Figure 1). Figure 3 shows the change in downward surface shortwave flux from the tropical 5 Mt/a and Arctic 3 Mt/a runs as compared to the A1B run. The Arctic aerosol precursors were emitted at 68°N , and the aerosols spread both northward and southward. Although the main radiative forcing is in the Arctic, the effect is significant as far south as 30°N . Thus suggestions of geoengineering only the Arctic, as simulated in preliminary experiments by reducing the incoming solar radiation in Arctic caps with fixed southern borders [Lane *et al.*, 2007], are not supported by these results. The radiative forcing from the tropical 5 Mt injection is rather uniform, as the aerosols spread poleward before being removed. The pattern is quite similar to what would be achieved from a uniform reduction of insolation. The *e*-folding lifetime of the stratospheric aerosols for the Arctic 3 Mt/a case is 3 months, while for the tropical 5 Mt/a case it is 12 months, comparable to that for volcanic eruptions. There is a clear seasonal cycle in the *e*-folding lifetime of the stratospheric aerosols in the Arctic case ranging from 2 to 4 months. The maximum lifetime occurs during boreal summer with a minimum during boreal winter with the formation of the polar vortex and higher rates of tropopause folding.

[22] The surface air temperature and precipitation changes for the A1B runs as compared to the mean of the control run

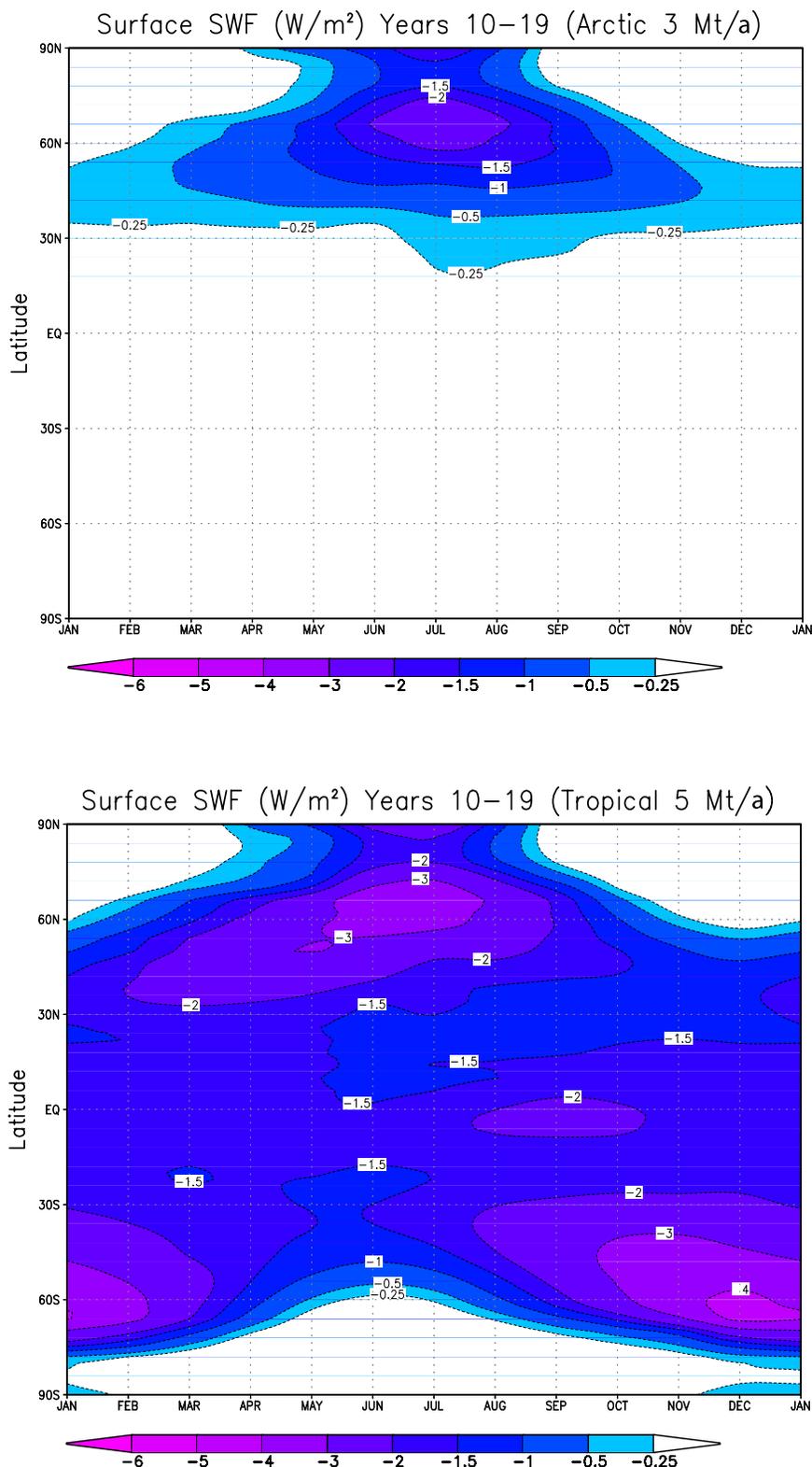


Figure 3. Change in downward surface shortwave flux from the Arctic 3 Mt/a and tropical 5 Mt/a runs as compared to the A1B run, as a function of latitude and month, averaged for the second 10 years of the 20-year period during which the geoengineering was applied.

are shown in Figure 4. As is typical of such results, the warming is enhanced in the polar regions, particularly in the winter. There is less warming in the northeast Atlantic Ocean and around Antarctica because of ocean circulation feed-

backs. Annual average changes in precipitation are very small in spite of the warming, as expected [Yang *et al.*, 2003]. There are no significant precipitation changes over land in Northern Hemisphere summer or winter either.

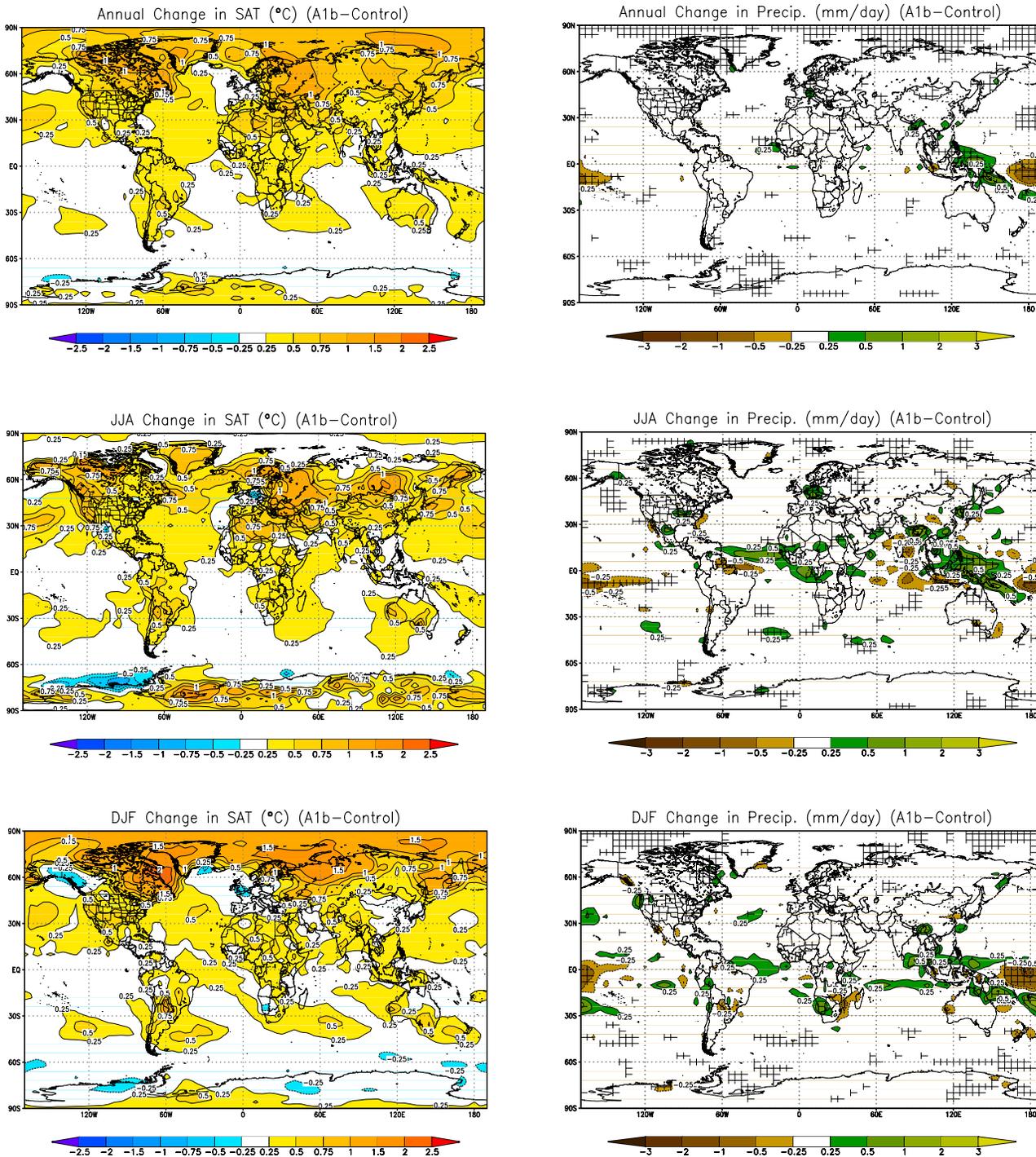


Figure 4. (left) Surface air temperature change and (right) precipitation change for A1B run compared to the control run, averaged for the second 10 years of the 20-year geoengineering period, for (top) annual average, (middle) Northern Hemisphere summer, and (bottom) Northern Hemisphere winter. Hatch marks on precipitation plots indicate changes significant at the 5% level.

[23] While the Arctic 3 Mt/a scenario produces only a little less global average warming than the A1B run (Figures 2 and 3), there are still large regional changes (Figure 5). The Northern Hemisphere warms less than in the A1B run (Figure 5, right), but there is even more warming over northern Africa and India in the Northern Hemisphere

summer. This is produced by a weakening of the African and Asian summer monsoon circulation, an effect found previously from high-latitude volcanic eruptions, both in model results and in observations [Oman *et al.*, 2005, 2006a] and in nuclear winter simulations [Robock *et al.*, 2007a, 2007b]. The warming is produced by a reduction in cloudiness. And

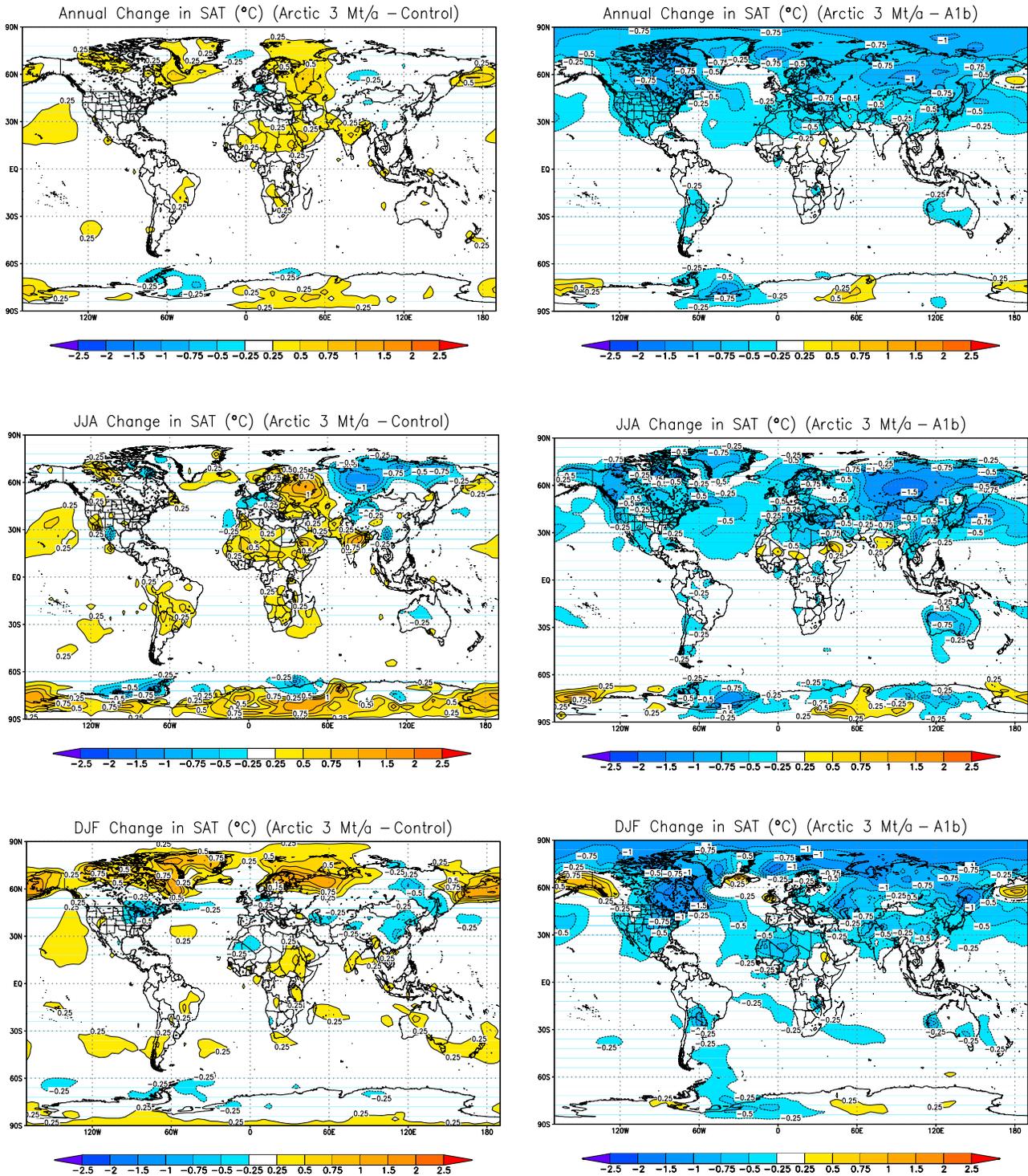


Figure 5. For the Arctic 3 Mt/a runs, (top) annual average, (middle) Northern Hemisphere summer, and (bottom) Northern Hemisphere winter surface air temperature differences (left) from the control climate and (right) from the A1B runs, averaged for the second 10 years of the 20-year geoengineering period.

even though the annual average temperature does not change much anywhere, there is still a small warming over eastern Europe (Figure 5, top left), particularly in the Northern Hemisphere summer (Figure 5, middle left). The winter warming in the Bering Sea (Figure 5, bottom left), is from a strengthened Aleutian Low advecting warmer maritime air

to the north, although it is difficult to gauge its significance. The temperature field is close to significant at the 5% level, but the sea level pressure change, 1.0–1.5 mbar lower than the control over this time period, is not significant.

[24] Figure 6 shows the temperature changes for the tropical 5 Mt/a case. As compared to the A1B case

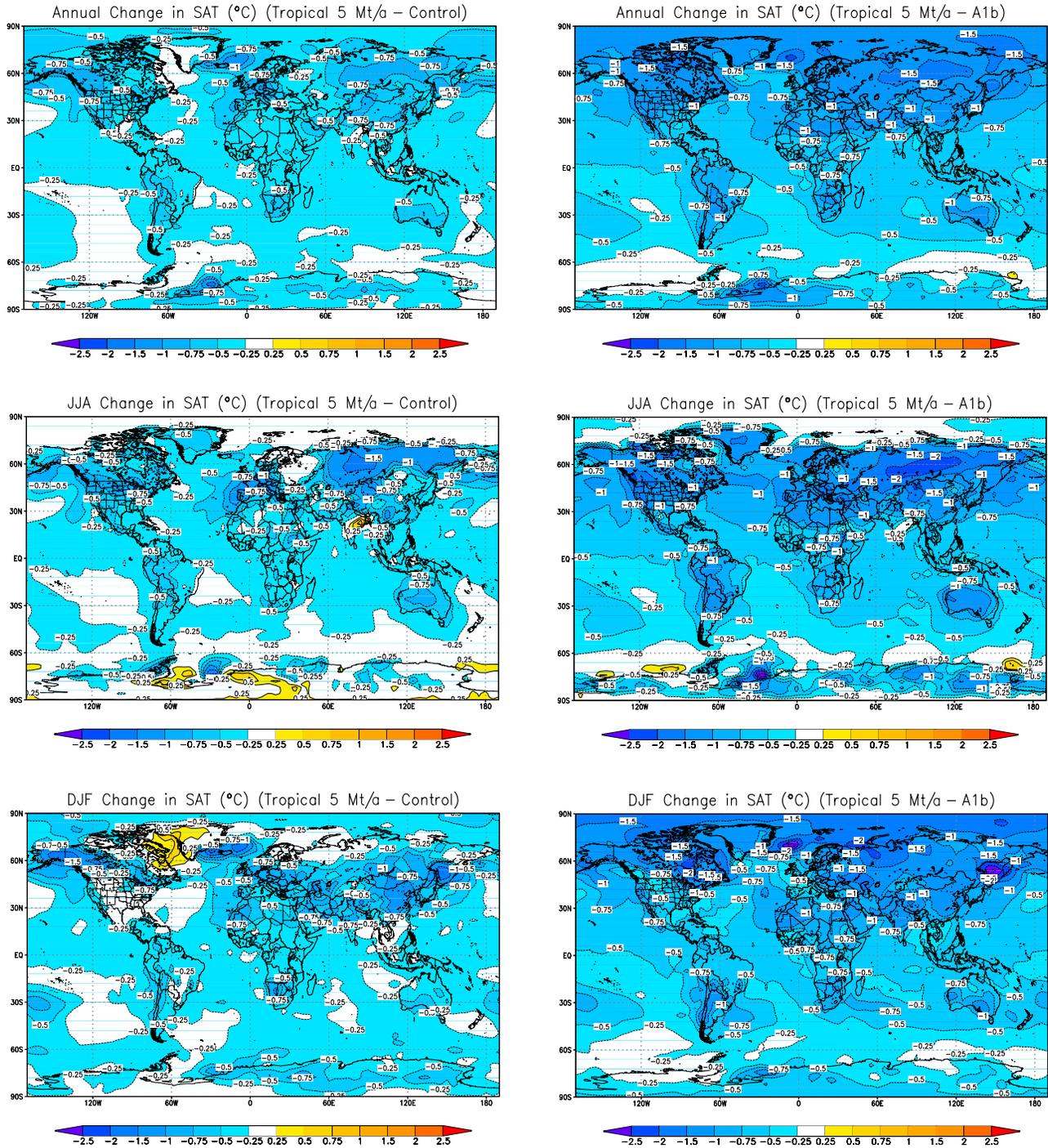


Figure 6. For the tropical 5 Mt/a runs, (top) annual average, (middle) Northern Hemisphere summer, and (bottom) Northern Hemisphere winter surface air temperature differences (left) from the control climate and (right) from the A1B runs, averaged for the second 10 years of the 20-year geoengineering period.

(Figure 6, right), there is global cooling, particularly over the continents, as expected. Even in absolute terms as compared to the control case (Figure 6, left), there is cooling. But even in this case, there is a region of warming over India in the summer, for the same reasons as discussed above. In the tropical 5 Mt/a case there is more cooling over the Asian continent than in the Arctic 3 Mt/a case (Figure 5),

but because the aerosol cloud also covers the tropics it also cools the ocean. Therefore, the effect on the temperature gradient is not as large and there is not as large an impact on the summer monsoon.

[25] The Northern Hemisphere winter pattern for the tropical 5 Mt/a case (Figure 6, bottom) shows little evidence of winter warming, which is found in the first, and some-

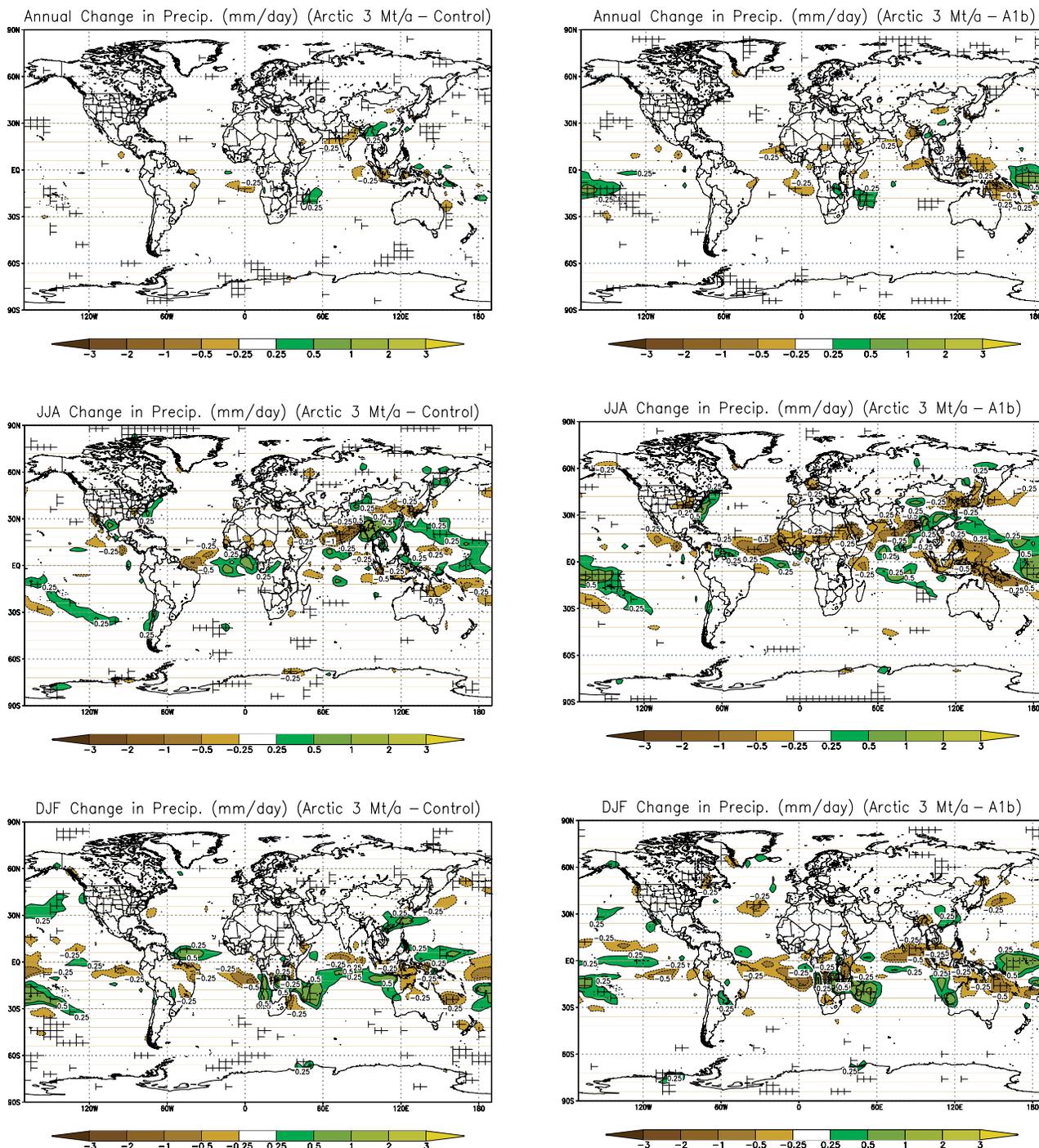


Figure 7. For the Arctic 3 Mt/a runs, (top) annual average, (middle) Northern Hemisphere summer, and (bottom) Northern Hemisphere winter precipitation differences (left) from the control climate and (right) from the A1B runs, averaged for the second 10 years of the 20-year geoengineering period. Hatch marks indicate changes significant at the 5% level.

times second, winter after tropical volcanic eruptions, as discussed above. The winter warming pattern, the positive mode of the Arctic Oscillation [Thompson and Wallace, 1998], is produced by a temperature gradient in the lower stratosphere caused by heating of the tropical region by absorption of both terrestrial longwave and solar near-infrared radiation by the volcanic aerosol cloud. However,

in the case of geoengineering here, the aerosol cloud is well distributed in latitude (Figure 3), so there is not a large temperature gradient to produce a stronger polar vortex.

[26] Figure 7 shows patterns of precipitation change for the Arctic 3 Mt/a case. While most of the world shows little annual average change, there is still a significant reduction of precipitation in India (Figure 7, top left). In addition,

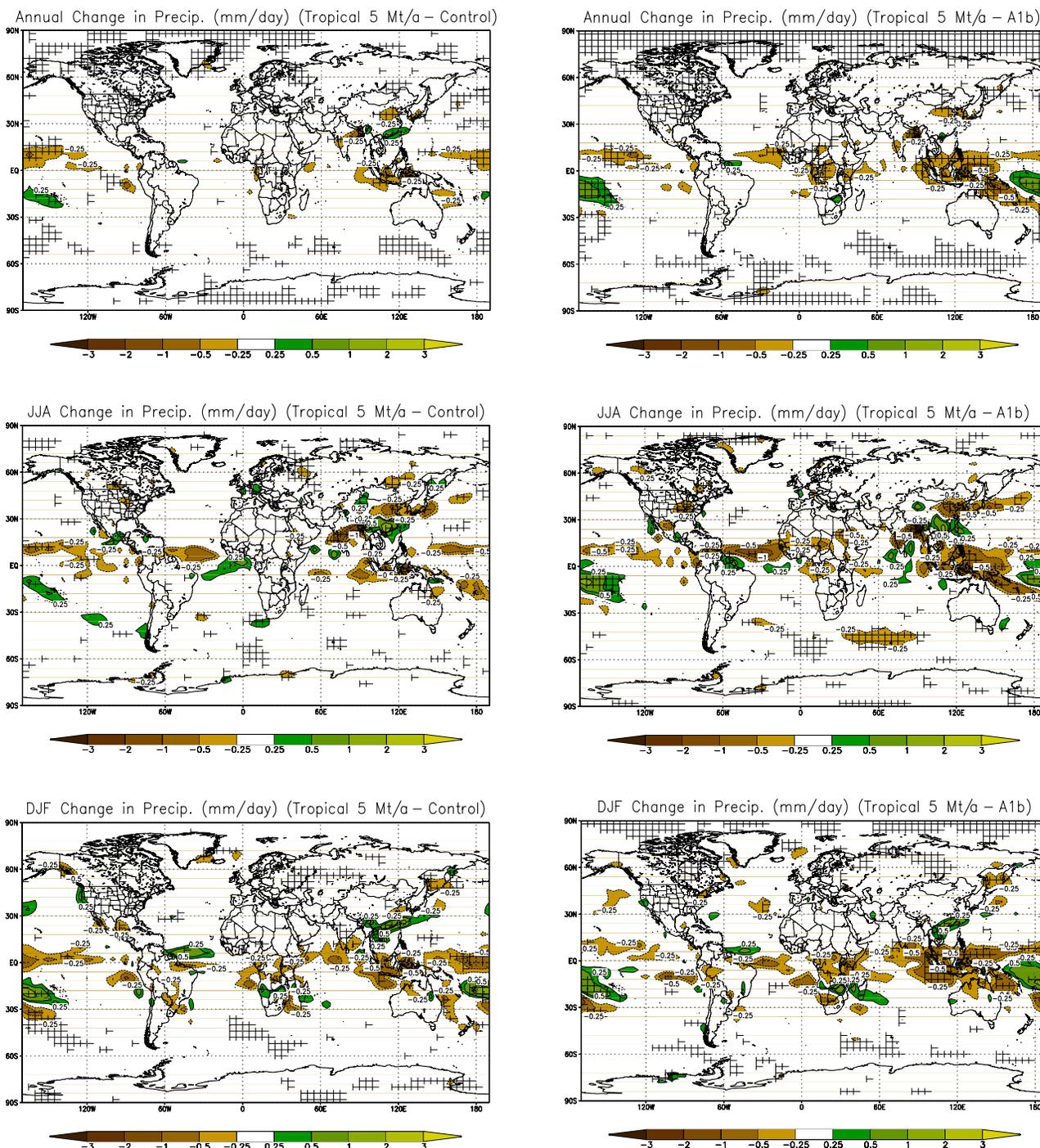


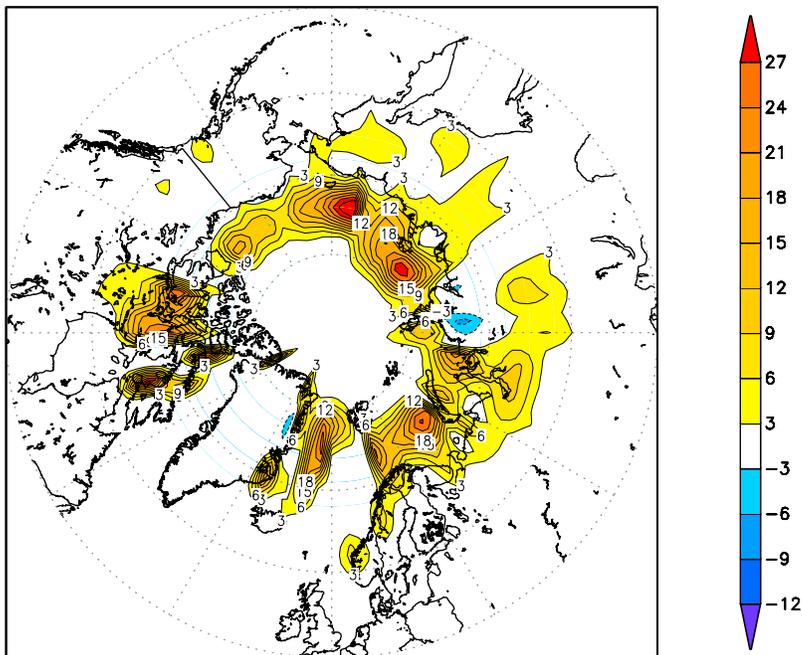
Figure 8. For the tropical 5 Mt/a runs, (top) annual average, (middle) Northern Hemisphere summer, and (bottom) Northern Hemisphere winter precipitation differences (left) from the control climate and (right) from the A1B runs, averaged for the second 10 years of the 20-year geoengineering period. Hatch marks indicate changes significant at the 5% level.

there is a large reduction over India and northern China in the Northern Hemisphere summer, associated with the reduction of the summer monsoon, as discussed above, which is significant over India. As compared to the A1B case, there is also a significant reduction over the Sahel and over northern China and Japan (Figure 7, middle right). The precipitation patterns for the tropical 5 Mt/a case are similar

(Figure 8). The annual average patterns are similar to those of *Rasch et al.* [2008], but they did not examine the seasonal patterns.

[27] Because of the observed rapid decrease in summer Arctic sea ice [*Kerr*, 2007], even larger than climate model predictions [*Vinnikov et al.*, 1999; *Intergovernmental Panel on Climate Change*, 2007; *Stroeve et al.*, 2007], one of the

Sept. Change in Snow & Ice (%) Years 10–19 (Arctic 3 Mt/a)



Sept. Change in Snow & Ice (%) Years 10–19 (Trop. 5 Mt/a)

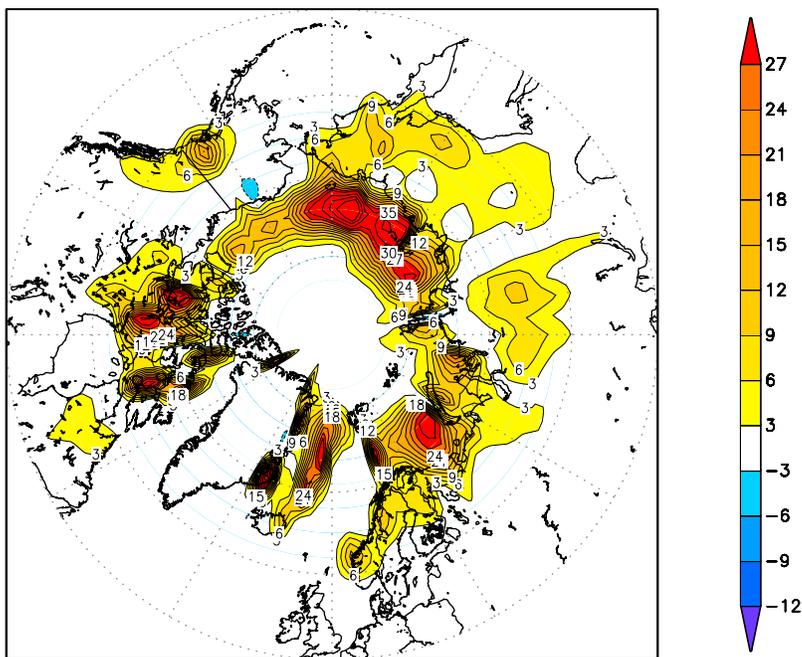


Figure 9. Change of September Arctic snow and sea ice coverage, as compared to the A1B run, for the Arctic 3 Mt/a and tropical 5 Mt/a runs, averaged for the second 10 years of the 20-year geoengineering period. Units are % of total coverage, not of the A1B values.

goals of proposed geoengineering is to prevent the disappearance of Arctic sea ice in the summer and the resultant large consequences for the entire ecosystem, including endangered or precarious indigenous species, such as polar

bears and walrus. Figure 9 shows that both the Arctic 3 Mt/a and tropical 5 Mt/a cases produce much more sea ice in September, the time of minimum sea ice extent. This is shown in the time series of September Arctic sea ice in

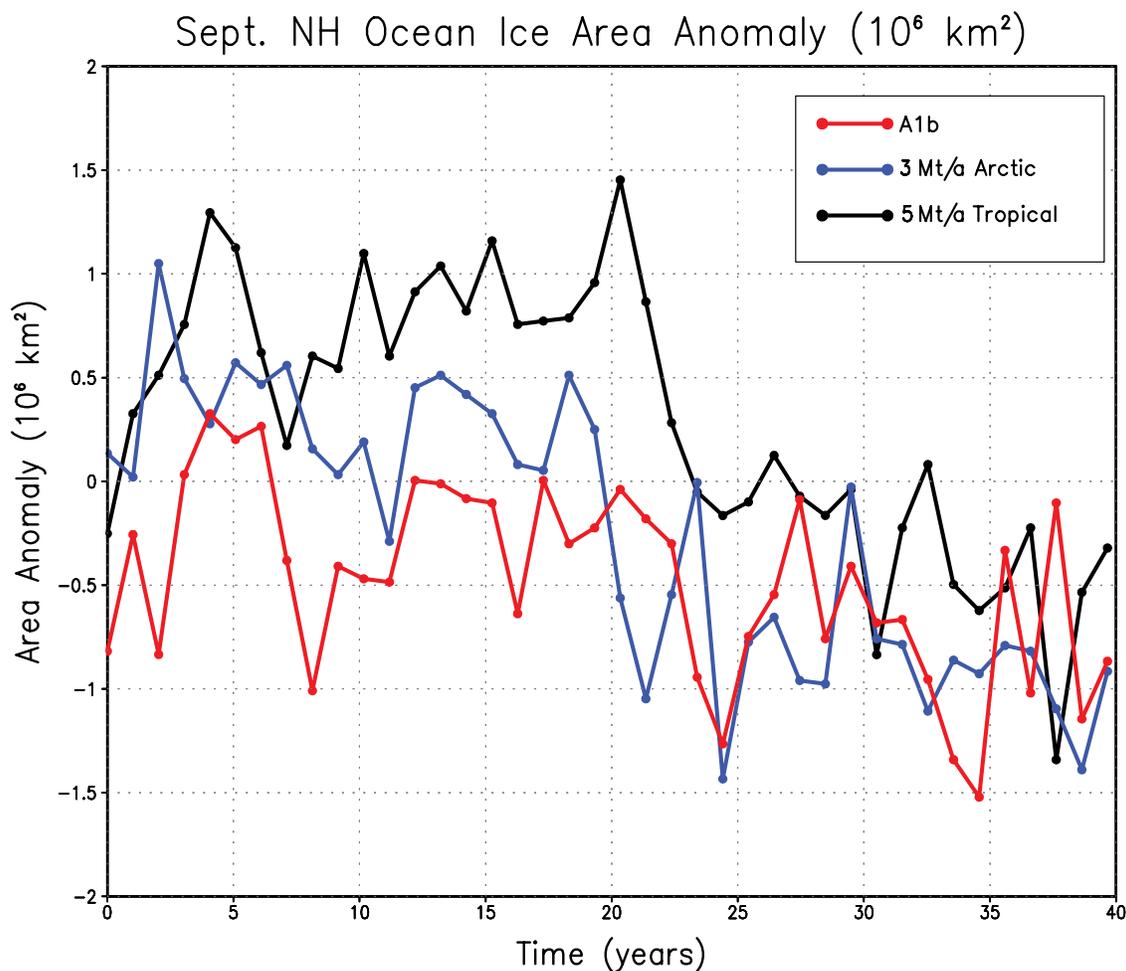


Figure 10. Time series of September Arctic sea ice area for the different experiments.

Figure 10, which also shows rapid ice melting as soon as geoengineering stops.

5. Discussion and Conclusions

[28] It is clear from our results that if enough aerosols could be put into the stratosphere, they would cool the planet and even reverse global warming (Figure 1). This brings up the question of what the optimal global climate should be, if we could control it. And who would decide? Should it be the current climate? The preindustrial climate? Figure 1 shows that if enough SO_2 could be continuously injected into the stratosphere, the global thermostat could be adjusted at any setting, but that if stopped at some time, say by lack of technical capability, political will, or discovery of unforeseen negative consequences, there would be even more rapid global warming than has occurred in the past century or than is projected with business as usual, as previously shown by Wigley [2006] and Matthews and Caldeira [2007]. Adaptation to such a rapid climate change would be difficult.

[29] Tropical injection schemes could cool the global average climate. There would be more cooling over continental areas, as expected. But the consequences for the African and Asian summer monsoons could be serious,

threatening the food and water supplies to billions of people.

[30] The safety and efficacy of the recent suggestion of injection of sulfate aerosols into the Arctic stratosphere to prevent sea ice and Greenland from melting while avoiding adverse effects on the biosphere at lower latitudes [Lane *et al.*, 2007] are not supported by our results. While Arctic temperature could be controlled, and sea ice melting could be reversed, there would still be large consequences for the summer monsoons, since the aerosols would not be confined to the polar region.

[31] Mitigation (reducing emissions of greenhouse gases) will reduce global warming, but is only now being seriously addressed by the planet. Whether we should use geoengineering as a temporary measure to avoid the most serious consequences of global warming requires a detailed evaluation of the benefits, costs, and dangers of different options. MacCracken [2006], Bengtsson [2006], Cicerone [2006], Kiehl [2006], and Lawrence [2006] all express concern about geoengineering. Robock [2008b] lists 20 reasons that argue against the implementation of this kind of geoengineering. The work here helps to document some benefits of geoengineering (global cooling and preservation of Arctic sea ice), but also the possible side effects on regional climate, item 1 on that list.

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References

- Angel, R. (2006), Feasibility of cooling the Earth with a cloud of small spacecraft near the inner Lagrange point (L1), *Proc. Natl. Acad. Sci. U.S.A.*, *103*, 17,184–17,189, doi:10.1073/pnas.0608163103.
- Bengtsson, L. (2006), Geo-engineering to confine climate change: Is it at all feasible?, *Clim. Change*, *77*, 229–234, doi:10.1007/s10584-006-9133-3.
- Bluth, G. J. S., S. D. Doiron, S. C. Schnetzler, A. J. Krueger, and L. S. Walter (1992), Global tracking of the SO₂ clouds from the June, 1991 Mount Pinatubo eruptions, *Geophys. Res. Lett.*, *19*, 151–154, doi:10.1029/91GL02792.
- Bower, K., T. Choullarton, J. Latham, J. Sahraei, and S. Salter (2006), Computational assessment of a proposed technique for global warming mitigation via albedo-enhancement of marine stratocumulus clouds, *Atmos. Res.*, *82*, 328–336, doi:10.1016/j.atmosres.2005.11.013.
- Boyd, P. W., et al. (2000), A mesoscale phytoplankton bloom in the polar Southern Ocean stimulated by iron fertilization, *Nature*, *407*, 695–702, doi:10.1038/35037500.
- Budyko, M. I. (1977), *Climatic Changes*, 261 pp., AGU, Washington, D. C.
- Cicerone, R. (2006), Geoengineering: Encouraging research and overseeing implementation, *Clim. Change*, *77*, 221–226, doi:10.1007/s10584-006-9102-x.
- Cicerone, R. J., S. Elliott, and R. P. Turco (1992), Global environmental engineering, *Nature*, *356*(472), doi:10.1038/356472a0.
- Crutzen, P. (2006), Albedo enhancement by stratospheric sulfur injections: A contribution to resolve a policy dilemma?, *Clim. Change*, *77*, 211–219, doi:10.1007/s10584-006-9101-y.
- Dickinson, R. E. (1996), Climate engineering: A review of aerosol approaches to changing the global energy balance, *Clim. Change*, *33*, 279–290, doi:10.1007/BF00142576.
- Environmental Pollution Panel (1965), *Restoring the Quality of Our Environment*, 292 pp., The White House, Washington, D. C.
- Flannery, B. P., H. Keshgi, G. Marland, and M. C. MacCracken (1997), Geoengineering climate, in *Engineering Response to Global Climate Change*, edited by R. G. Watts, chap. 8, pp. 379–427, Lewis, New York.
- Fleming, J. R. (2004), Fixing the weather and climate: Military and civilian schemes for cloud seeding and climate engineering, in *The Technological Fix: How People Use Technology to Create and Solve Problems*, edited by L. Rosner, pp. 175–200, Routledge, New York.
- Fleming, J. R. (2006), The pathological history of weather and climate modification: Three cycles of promise and hype, *Hist. Stud. Phys. Biol. Sci.*, *37*, 3–25, doi:10.1525/hsp.2006.37.1.3.
- Fleming, J. R. (2007), The climate engineers, *Wilson Q.*, *46*–60, Spring.
- Gao, C., L. Oman, A. Robock, and G. L. Stenchikov (2007), Atmospheric volcanic loading derived from bipolar ice cores accounting for the spatial distribution of volcanic deposition, *J. Geophys. Res.*, *112*, D09109, doi:10.1029/2006JD007461.
- Govindasamy, B., and K. Caldeira (2000), Geoengineering Earth's radiation balance to mitigate CO₂-induced climate change, *Geophys. Res. Lett.*, *27*, 2141–2144, doi:10.1029/1999GL006086.
- Govindasamy, B., S. Thompson, P. B. Duffy, K. Caldeira, and C. Delire (2002), Impact of geoengineering schemes on the terrestrial biosphere, *Geophys. Res. Lett.*, *29*(22), 2061, doi:10.1029/2002GL015911.
- Govindasamy, B., K. Caldeira, and P. B. Duffy (2003), Geoengineering Earth's radiation balance to mitigate climate change from a quadrupling of CO₂, *Global Planet. Change*, *37*, 157–168, doi:10.1016/S0921-8181(02)00195-9.
- Graf, H.-F., I. Kirchner, A. Robock, and I. Schult (1993), Pinatubo eruption winter climate effects: Model versus observations, *Clim. Dyn.*, *9*, 81–93.
- Hansen, J., R. Ruedy, M. Sato, and R. Reynolds (1996), Global surface air temperature in 1995: Return to pre-Pinatubo level, *Geophys. Res. Lett.*, *23*, 1665–1668, doi:10.1029/96GL01040.
- Hansen, J., et al. (2005), Efficacy of climate forcings, *J. Geophys. Res.*, *110*, D18104, doi:10.1029/2005JD005776.
- Intergovernmental Panel on Climate Change (2007), Climate Change 2007: The Physical Science Basis, in *Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by S. Solomon et al., Cambridge Univ. Press, Cambridge, U. K.
- Keith, D. W. (2000), Geoengineering the climate: History and prospect, *Annu. Rev. Energy Environ.*, *25*, 245–284, doi:10.1146/annurev.energy.25.1.245.
- Keith, D. (2001), Geoengineering, *Nature*, *409*(420), doi:10.1038/35053208.
- Kerr, R. A. (2007), Is battered Arctic sea ice down for the count?, *Science*, *318*, 33–34, doi:10.1126/science.318.5847.33a.
- Khan, E. et al. (2001), *Response options to limit rapid or severe climate change*, 37 pp., Dep. of Energy, Washington, D. C.
- Kiehl, J. T. (2006), Geoengineering climate change: Treating the symptom over the cause?, *Clim. Change*, *77*, 227–228, doi:10.1007/s10584-006-9132-4.
- Koch, D., G. A. Schmidt, and C. V. Field (2006), Sulfur, sea salt, and radionuclide aerosols in GISS ModelE, *J. Geophys. Res.*, *111*, D06206, doi:10.1029/2004JD005550.
- Kodera, K., M. Chiba, H. Koide, A. Kitoh, and Y. Nikaidou (1996), Inter-annual variability of the winter stratosphere and troposphere in the northern hemisphere, *J. Meteorol. Soc. Jpn.*, *74*, 365–382.
- Lane, L., K. Caldeira, R. Chatfield, and S. Langhoff (Eds.) (2007), Workshop report on managing solar radiation, *NASA/CP-2007-214558*, 31 pp.
- Lawrence, M. G. (2006), The geoengineering dilemma: To speak or not to speak, *Clim. Change*, *77*, 245–248, doi:10.1007/s10584-006-9131-5.
- Leemans, R., S. Agrawal, J. A. Edmunds, M. C. MacCracken, R. Moss, and P. S. Ramakrishnan (1996), Mitigation: Cross-sectoral and other issues, in *Climate Change 1995, Impacts Adaptations and Mitigation of Climate Change: Scientific-Technical Analyses, Contribution of Working Group II to the Second IPCC Assessment*, edited by R. T. Watson, M. C. Zinyowera, and R. H. Moss, chap. 25, pp. 799–819, Cambridge Univ. Press, Cambridge, U. K.
- MacCracken, M. C. (2006), Geoengineering: Worthy of cautious evaluation?, *Clim. Change*, *77*, 235–243, doi:10.1007/s10584-006-9130-6.
- Matthews, H. D., and K. Caldeira (2007), Transient climate-carbon simulations of planetary geoengineering, *Proc. Natl. Acad. Sci. U.S.A.*, *104*, 9949–9954, doi:10.1073/pnas.0700419104.
- Mills, M. J., O. B. Toon, R. P. Turco, D. E. Kinnison, and R. R. Garcia (2008), Massive global ozone loss predicted following regional nuclear conflict, *Proc. Natl. Acad. Sci. U.S.A.*, *105*, 5307–5312.
- Oman, L., A. Robock, G. Stenchikov, G. A. Schmidt, and R. Ruedy (2005), Climatic response to high latitude volcanic eruptions, *J. Geophys. Res.*, *110*, D13103, doi:10.1029/2004JD005487.
- Oman, L., A. Robock, G. L. Stenchikov, and T. Thordarson (2006a), High-latitude eruptions cast shadow over the African monsoon and the flow of the Nile, *Geophys. Res. Lett.*, *33*, L18711, doi:10.1029/2006GL027665.
- Oman, L., A. Robock, G. Stenchikov, T. Thordarson, D. Koch, D. Shindell, and C. Gao (2006b), Modeling the distribution of the volcanic aerosol cloud from the 1783–1784 Laki eruption, *J. Geophys. Res.*, *111*, D12209, doi:10.1029/2005JD006899.
- Panel on Policy Implications of Greenhouse Warming (1992), *Policy Implications of Greenhouse Warming: Mitigation, Adaptation, and the Science Base*, Natl. Acad. Press, Washington, D. C.
- Rasch, P. J., P. J. Crutzen, and D. B. Coleman (2008), Exploring the geoengineering of climate using stratospheric sulfate aerosols: The role of particle size, *Geophys. Res. Lett.*, *35*, L02809, doi:10.1029/2007GL032179.
- Robock, A. (2000), Volcanic eruptions and climate, *Rev. Geophys.*, *38*, 191–219, doi:10.1029/1998RG000054.
- Robock, A. (2008a), Whither geoengineering?, *Science*, *320*, 1166–1167, doi:10.1126/science.1159280.
- Robock, A. (2008b), 20 reasons why geoengineering may be a bad idea, *Bull. At. Sci.*, *64*(2), 14–18, 59, doi:10.2968/064002006.
- Robock, A., and Y. Liu (1994), The volcanic signal in Goddard Institute for Space Studies three-dimensional model simulations, *J. Clim.*, *7*, 44–55, doi:10.1175/1520-0442(1994)007<0044:TVSIG>2.0.CO;2.
- Robock, A., L. Oman, G. L. Stenchikov, O. B. Toon, C. Bardeen, and R. P. Turco (2007a), Climatic consequences of regional nuclear conflicts, *Atmos. Chem. Phys.*, *7*, 2003–2012.
- Robock, A., L. Oman, and G. L. Stenchikov (2007b), Nuclear winter revisited with a modern climate model and current nuclear arsenals: Still catastrophic consequences, *J. Geophys. Res.*, *112*, D13107, doi:10.1029/2006JD008235.
- Rusin, N., and L. Flit (1960), *Man Versus Climate*, 175 pp., Peace, Moscow.
- Russell, G. L., J. R. Miller, and D. Rind (1995), A coupled atmosphere-ocean model for transient climate change, *Atmos. Ocean*, *33*, 683–730.
- Schmidt, G. A., et al. (2006), Present day atmospheric simulations using GISS ModelE: Comparison to in-situ, satellite and reanalysis data, *J. Clim.*, *19*, 153–192, doi:10.1175/JCLI3612.1.
- Schneider, S. H. (1996), Geoengineering: Could-or should-we do it?, *Clim. Change*, *33*, 291–302, doi:10.1007/BF00142577.
- Schneider, S. H. (2001), Earth systems: Engineering and management, *Nature*, *409*, 417–419, 421, doi:10.1038/35053203.
- Solomon, S. (1999), Stratospheric ozone depletion: A review of concepts and history, *Rev. Geophys.*, *37*, 275–316, doi:10.1029/1999RG000008.
- Stenchikov, G. L., I. Kirchner, A. Robock, H.-F. Graf, J. C. Antuña, R. G. Grainger, A. Lambert, and L. Thomason (1998), Radiative forcing from

- the 1991 Mount Pinatubo volcanic eruption, *J. Geophys. Res.*, *103*, 13,837–13,857, doi:10.1029/98JD00693.
- Stenchikov, G., A. Robock, V. Ramaswamy, M. D. Schwarzkopf, K. Hamilton, and S. Ramachandran (2002), Arctic Oscillation response to the 1991 Mount Pinatubo eruption: Effects of volcanic aerosols and ozone depletion, *J. Geophys. Res.*, *107*(D24), 4803, doi:10.1029/2002JD002090.
- Stenchikov, G., K. Hamilton, A. Robock, V. Ramaswamy, and M. D. Schwarzkopf (2004), Arctic Oscillation response to the 1991 Pinatubo eruption in the SKYHI GCM with a realistic Quasi-Biennial Oscillation, *J. Geophys. Res.*, *109*, D03112, doi:10.1029/2003JD003699.
- Stenchikov, G., K. Hamilton, R. J. Stouffer, A. Robock, V. Ramaswamy, B. Santer, and H.-F. Graf (2006), Arctic Oscillation response to volcanic eruptions in the IPCC AR4 climate models, *J. Geophys. Res.*, *111*, D07107, doi:10.1029/2005JD006286.
- Stroeve, J., M. M. Holland, W. Meier, T. Scambos, and M. Serreze (2007), Arctic sea ice decline: Faster than forecast, *Geophys. Res. Lett.*, *34*, L09501, doi:10.1029/2007GL029703.
- Teller, E., L. Wood, and R. Hyde (1997), Global warming and ice ages: I. Prospects for physics-based modulation of global change, *Publ. UCRL-JC-128715*, 18 pp., Lawrence Livermore Natl. Lab., Livermore, Calif.
- Teller, E. et al. (1999), Long-range weather prediction and prevention of climate catastrophes: A status report, *Publ. UCRL-JC-135414*, 44 pp., Lawrence Livermore Natl. Lab., Livermore, Calif.
- Teller, E., R. Hyde, and L. Wood (2002), Active climate stabilization: Practical physics-based approaches to prevention of climate change, *Publ. UCRL-JC-148012*, 8 pp., Lawrence Livermore Natl. Lab., Livermore, Calif.
- Thompson, D. W. J., and J. M. Wallace (1998), The Arctic Oscillation signature in the wintertime geopotential height and temperature fields, *Geophys. Res. Lett.*, *25*, 1297–1300, doi:10.1029/98GL00950.
- Tilmes, S., R. Müller, and R. Salawitch (2008), The sensitivity of polar ozone depletion to proposed geoengineering schemes, *Science*, *320*, 1201–1204, doi:10.1126/science.1153966.
- Trenberth, K. E., and A. Dai (2007), Effects of Mount Pinatubo volcanic eruption on the hydrological cycle as an analog of geoengineering, *Geophys. Res. Lett.*, *34*, L15702, doi:10.1029/2007GL030524.
- Turco, R. P. (1995), Global environmental engineering: Prospects and pitfalls, in *Human Population and the Environmental Crisis*, edited by B. Zuckerman and D. Jefferson, chap. 7, pp. 93–113, Jones and Bartlett, Sudbury, Mass.
- Vinnikov, K. Y., A. Robock, R. J. Stouffer, J. E. Walsh, C. L. Parkinson, D. J. Cavalieri, J. F. B. Mitchell, D. Garrett, and V. F. Zakharov (1999), Global warming and Northern Hemisphere sea ice extent, *Science*, *286*, 1934–1937, doi:10.1126/science.286.5446.1934.
- Wigley, T. M. L. (2006), A combined mitigation/geoengineering approach to climate stabilization, *Science*, *314*, 452–454, doi:10.1126/science.1131728.
- Yang, F., A. Kumar, M. E. Schlesinger, and W. Wang (2003), Intensity of hydrological cycles in warmer climates, *J. Clim.*, *16*, 2419–2423, doi:10.1175/2779.1.

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REVIEW

An overview of geoengineering of climate using stratospheric sulphate aerosols

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We provide an overview of geoengineering by stratospheric sulphate aerosols. The state of understanding about this topic as of early 2008 is reviewed, summarizing the past 30 years of work in the area, highlighting some very recent studies using climate models, and discussing methods used to deliver sulphur species to the stratosphere. The studies reviewed here suggest that sulphate aerosols can counteract the globally averaged temperature increase associated with increasing greenhouse gases, and reduce changes to some other components of the Earth system. There are likely to be remaining regional climate changes after geoengineering, with some regions experiencing significant changes in temperature or precipitation. The aerosols also serve as surfaces for heterogeneous chemistry resulting in increased ozone depletion. The delivery of sulphur species to the stratosphere in a way that will produce particles of the right size is shown to be a complex and potentially very difficult task. Two simple delivery scenarios are explored, but similar exercises will be needed for other suggested delivery mechanisms. While the introduction of the geoengineering source of sulphate aerosol will perturb the sulphur cycle of the stratosphere significantly, it is a small perturbation to the total (stratosphere and troposphere) sulphur cycle. The geoengineering source would thus be a small contributor to the total global source of ‘acid rain’ that could be compensated for through improved pollution control of anthropogenic tropospheric sources. Some areas of research remain unexplored. Although ozone may be depleted, with a consequent increase to solar ultraviolet-B (UVB) energy reaching the surface and a potential impact on health and biological populations, the aerosols will also scatter and attenuate this part of the energy spectrum, and this may compensate the UVB enhancement associated with ozone depletion. The aerosol will also change the ratio of diffuse to direct energy reaching

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the surface, and this may influence ecosystems. The impact of geoengineering on these components of the Earth system has not yet been studied. Representations for the formation, evolution and removal of aerosol and distribution of particle size are still very crude, and more work will be needed to gain confidence in our understanding of the deliberate production of this class of aerosols and their role in the climate system.

Keywords: climate change; geoengineering; sulphate aerosols; global warming

1. Introduction

The concept of ‘geoengineering’ (the deliberate change of the Earth’s climate by mankind; Keith 2000) has been considered at least as far back as the 1830s with J. P. Espy’s suggestion (Fleming 1990) of lighting huge fires that would stimulate convective updrafts and change rain intensity and frequency of occurrence. Geoengineering has been considered for many reasons since then, ranging from making polar latitudes habitable to changing precipitation patterns.

There is increasing concern by scientists and society in general that energy system transformation is proceeding too slowly to avoid the risk of dangerous climate change from humankind’s release of radiatively important atmospheric constituents (particularly CO₂). The assessment by the Intergovernmental Panel on Climate Change (IPCC 2007a) shows that unambiguous indicators of human-induced climate change are increasingly evident, and there has been little societal response to the scientific consensus that reductions must take place soon to avoid large and undesirable impacts.

To reduce carbon dioxide emissions soon enough to avoid large and undesirable impacts requires a near-term revolutionary transformation of energy and transportation systems throughout the world (Hoffert *et al.* 1998). The size of the transformation, the lack of effective societal response and the inertia to changing our energy infrastructure motivate the exploration of other strategies to mitigate some of the planetary warming. For this reason, geoengineering for the purpose of cooling the planet is receiving increasing attention. A broad overview to geoengineering can be found in the reviews of Keith (2000), WRMSR (2007), and the papers in this volume. The geoengineering paradigm is not without its own perils (Robock 2008). Some of the uncertainties and consequences of geoengineering by stratospheric aerosols are discussed in this paper.

This study describes an approach to cooling the planet, which goes back to the mid-1970s, when Budyko (1974) suggested that, if global warming ever became a serious threat, we could counter it with airplane flights in the stratosphere, burning sulphur to make aerosols that would reflect sunlight away. The aerosols would increase the planetary albedo and cool the planet, ameliorating some (but as discussed below, not all) of the effects of increasing CO₂ concentrations. The aerosols are chosen/designed to reside in the stratosphere because it is remote, and they will have a much longer residence time than tropospheric aerosols that are rapidly scavenged. The longer lifetime means that a few aerosols need be delivered per unit time to achieve a given aerosol burden, and that the aerosols will disperse and act to force the climate system over a larger area.

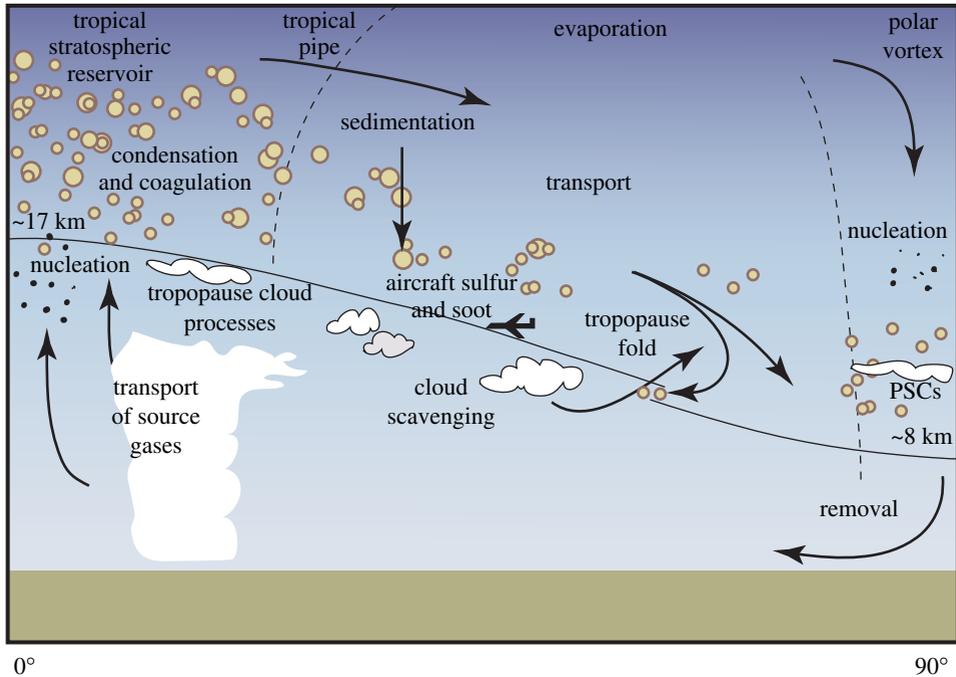


Figure 1. A schematic of the processes that influence the life cycle of stratospheric aerosols (adapted with permission from SPARC 2006).

Sulphate aerosols are always found in the stratosphere. Low background concentrations arise due to transport from the troposphere of natural and anthropogenic sulphur-bearing compounds. Occasionally much higher concentrations arise from volcanic eruptions, resulting in a temporary cooling of the Earth system (Robock 2000), which disappears as the aerosol is flushed from the atmosphere. The volcanic injection of sulphate aerosol thus serves as a natural analogue to the geoengineering aerosol. The analogy is not perfect because the volcanic aerosol is flushed within a few years, and the climate system does not respond in the same way as it would if the particles were continually replenished, as they would be in a geoengineering effort. Perturbations to the system that might become evident with constant forcing disappear as the forcing disappears.

This study reviews the state of understanding about geoengineering by sulphate aerosols as of early 2008. We review the published literature, introduce some new material and summarize some very recent results that are presented in detail in the submitted articles at the time of the writing of this paper. In our summary we also try to identify areas where more research is needed.

Since the paper by Budyko (1974), the ideas generated there have received occasional attention in discussions about geoengineering (e.g. NAS92 1992; Turco 1995; Govindasamy & Caldeira 2000, 2003; Govindasamy *et al.* 2002; Crutzen 2006; Wigley 2006; Matthews & Caldeira 2007).

There are also legal, moral, ethical, financial and international political issues associated with a manipulation of our environment. Commentaries (Bengtsson 2006; Cicerone 2006; Kiehl 2006; Lawrence 2006; MacCracken 2006) to Crutzen

(2006) address some of these issues and remind us that this approach does not treat all the consequences of higher CO₂ concentrations (such as ocean acidification; others are discussed in Robock 2008). Recently, climate modellers have begun efforts to provide more quantitative assessments of the complexities of geoengineering by sulphate aerosols and the consequences to the climate system (Rasch *et al.* 2008; Tilmes *et al.* 2008, submitted; Robock *et al.* 2008).

2. An overview of stratospheric aerosols in the Earth system

(a) General considerations

Sulphate aerosols are an important component of the Earth system in the troposphere and stratosphere. Because sulphate aerosols play a critical role in the chemistry of the lower stratosphere and occasionally, following a volcanic eruption, in the radiative budget of the Earth by reducing the incoming solar energy reaching the Earth surface, they have been studied for many years. A comprehensive discussion of the processes that govern the stratospheric sulphur cycle can be found in the recent assessment of stratosphere aerosols (SPARC 2006). Figure 1, taken from that report, indicates some of the processes that are important in that region.

Sulphate aerosols play additional roles in the troposphere (IPCC (2007a) and references therein). As in the stratosphere they act to reflect incoming solar energy (the ‘aerosol direct effect’), but also act as cloud condensation nuclei, influencing the size of cloud droplets and the persistence or lifetime of clouds (the ‘aerosol indirect effect’) and thus the reflectivity of clouds.

Although our focus is on stratospheric aerosols, one cannot ignore the troposphere, and so we include a brief discussion of some aspects of the tropospheric sulphur cycle also. A very rough budget describing the sources, sinks and transformation pathways¹ during volcanically quiescent times is displayed in figure 2. Sources, sinks and burdens for sulphur species are much larger in the troposphere than in the stratosphere. The sources of the aerosol precursors are natural and anthropogenic sulphur-bearing reduced gases (DMS, dimethyl sulphide; SO₂, sulphur dioxide; H₂S, hydrogen sulphide; OCS, carbonyl sulphide). These precursor gases are gradually oxidized (through both gaseous and aqueous reactions) to end products involving the sulphate anion (SO₄²⁻) in combination with various other cations. In the troposphere where there is sufficient ammonia, most of the aerosols exist in the form of mixtures of ammonium sulphate ((NH₄)₂SO₄) and bisulphate ((NH₄)HSO₄).

The stratospheric sulphur-bearing gases oxidize (primarily via reactions with the OH radical) to SO₂, which is then further oxidized to gaseous H₂SO₄. Stratospheric sulphate aerosols exist in the form of mixtures of condensed sulphuric acid (H₂SO₄), water and, under some circumstances, hydrates with nitric acid (HNO₃).

¹ Sulphur emissions and burdens are frequently expressed in differing units. They are sometimes specified with respect to their molecular weight. Elsewhere they are specified according to the equivalent weight of sulphur. They may be readily converted by multiplying by the ratio of molecular weights of the species of interest. We use only units of S in this paper, and have converted all references in other papers to these units. Also, in the stratosphere, we have assumed that the sulphate binds with water in a ratio of 75/25 H₂SO₄/water to form particles. Hence

$$3 \text{ Tg SO}_4^{2-} = 2 \text{ Tg SO}_2 = 1 \text{ Tg S} \approx 4 \text{ Tg aerosol particles.}$$

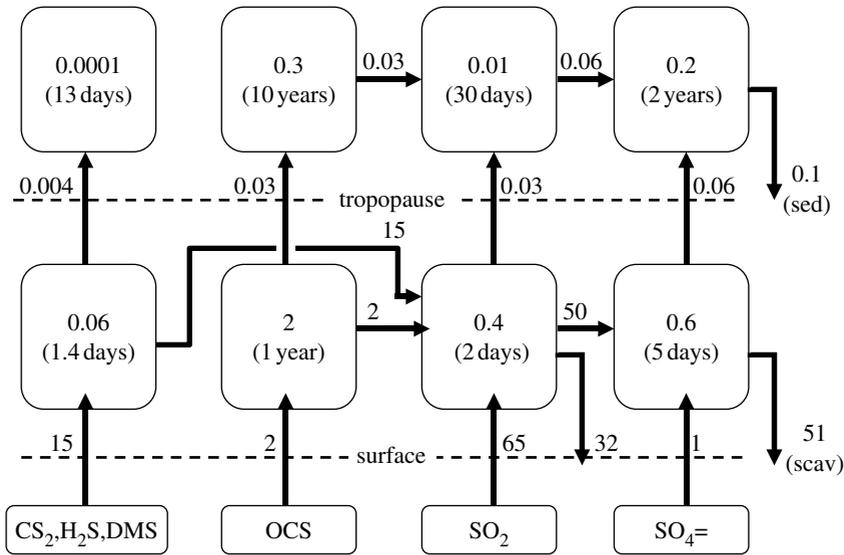


Figure 2. A very rough budget (approx. 1 digit of accuracy) for most of the major atmospheric sulphur species during volcanically quiescent situations, following Rasch *et al.* (2000), SPARC (2006) and Montzka *et al.* (2007). Numbers inside boxes indicate species burden in units of Tg S, and approximate lifetime against the strongest source or sink. Numbers beside arrows indicate net source or sinks (transformation, transport, emissions, and deposition processes) in Tg S yr⁻¹.

Although the OCS source is relatively small compared with other species, owing to its relative stability, it is the dominant sulphur-bearing species in the atmosphere. Oxidation of OCS is a relatively small contributor to the radiatively active sulphate aerosol in the troposphere, but it plays a larger role in the stratosphere where it contributes perhaps half the sulphur during volcanically quiescent conditions. Some sulphur also enters the stratosphere as SO_2 and as sulphate aerosol particles. The reduced sulphur species oxidize there and form sulphuric acid gas. The H_2SO_4 vapour partial pressure in the stratosphere—almost always determined by photochemical reactions—is generally supersaturated, and typically highly supersaturated, over its binary H_2O – H_2SO_4 solution droplets. The particles form and grow through vapour deposition, depending on the ambient temperature and concentrations of H_2O and H_2SO_4 . These aerosol particles are then transported by winds (as are their precursors). Above the lower stratosphere, the particles can evaporate, and in the gaseous form the sulphuric acid can be photolysed to SO_2 , where it can be transported as a gas, and may again oxidize and condense in some other part of the stratosphere. Vapour deposition is the main growth mechanism in the ambient stratosphere, and in volcanic clouds, over time.

Because sources and sinks of aerosols are so much stronger in the troposphere, the lifetime of sulphate aerosol particles in the troposphere is a few days, while that of stratospheric aerosol is a year or so. This explains the relatively smooth spatial distribution of sulphate aerosol and resultant aerosol forcing in the stratosphere, and much smaller spatial scales associated with tropospheric aerosol.

The net source¹ of sulphur to the stratosphere is believed to be of the order of 0.1 Tg S yr⁻¹ during volcanically quiescent conditions. A volcanic eruption completely alters the balance of terms in the stratosphere. For example, the eruption

of Mount Pinatubo is believed to have injected approximately 10 Tg S (in the form of SO₂) over a few days. This injection amount provides a source approximately 100 times that of all other sources over the year. The partial pressure of sulphuric acid gas consequently reaches much higher levels than those during background conditions. After an eruption, new particles are nucleated only in the densest parts of eruption clouds. These rapidly coagulate and disperse to concentration levels that do not aggregate significantly. Particle aggregation is controlled by Brownian coagulation (except perhaps under very high sulphur loadings). Coagulation mainly limits the number of particles, rather than the overall size of the particles, which depends more on the sulphur source strength (although considering the overall sulphur mass balance, the two processes both contribute). The particles' growth is thus influenced by both vapour deposition and proximity to other particles.

The primary loss mechanism for sulphur species from the stratosphere is believed to be the sedimentation of the aerosol particles. Particle sedimentation is governed by Stokes' equation for drag corrected to compensate for the fact that in the stratosphere at higher altitudes the mean free path between air molecules can far exceed the particle size, and particles fall more rapidly than they would otherwise. The aerosol particles settle out (larger particles settle faster), gradually entering the troposphere, where they are lost via wet and dry deposition processes.

Examples of the nonlinear relationships between SO₂ mass injection, particle size and visible optical depth as a function of time assuming idealized dispersion can be found in Pinto *et al.* (1998). These are detailed microphysical simulations, although in a one-dimensional model with specified dispersion. The rate of dilution of injected SO₂ is critical owing to the highly nonlinear response of particle growth and sedimentation rates within expanding plumes; particles have to be only 10 µm or less to fall rapidly, which greatly restricts the total suspended mass, optical depth and infrared effect. The mass limitation indicates that 10 times the mass injection (of say Pinatubo) might result in only a modestly larger visible optical depth after some months.

The life cycle of these particles is thus controlled by a complex interplay between meteorological fields (like wind, humidity and temperature), the local concentrations of the gaseous sulphur species, the concentration of the particles themselves and the size distribution of the particles.

In the volcanically quiescent conditions (often called background conditions), partial pressures of sulphur gases remain relatively low, and the particles are found to be quite small (Bauman *et al.* 2003), with a typical size distribution that can be described with a lognormal distribution with a dry mode radius, standard deviation and effective radius of 0.05/2.03/0.17 µm, respectively. After volcanic eruptions when sulphur species concentrations get much higher, the particles grow much larger (Stenchikov *et al.* 1998). Rasch *et al.* (2008) used numbers for a size distribution 6–12 months after an eruption for the large volcanic-like distribution of 0.376/1.25/0.43 µm following Stenchikov *et al.* (1998) and Collins *et al.* (2004). There is uncertainty in the estimates of these size distributions, and volcanic aerosol standard distribution σ_{LN} was estimated to range from 1.3 to greater than 2 in Steele & Turco (1997).

When the particles are small, they primarily scatter in the solar part of the energy spectrum, and play no role in influencing the infrared (long-wave) part of the energy spectrum. Larger particles seen after an eruption scatter and absorb in the solar wavelengths, but also absorb in the infrared (Stenchikov *et al.* 1998).

Thus small particles tend to scatter solar energy back to space. Large particles scatter less efficiently, and also trap some of the outgoing energy in the infrared. The size of the aerosol thus has a strong influence on the climate.

(b) *Geoengineering considerations*

To increase the mass and number of sulphate aerosols in the stratosphere, a new source must be introduced. Using Pinatubo as an analogue, Crutzen (2006) estimated a source of 5 Tg S yr^{-1} would be sufficient to balance the warming associated with a doubling of CO_2 . Wigley (2006) used an energy balance model to conclude that approximately 5 Tg S yr^{-1} in combination with emission mitigation would suffice. These studies assumed that the long-term response of the climate system to a more gradual injection would be similar to the transient response to a Pinatubo-like transient injection. A more realistic exploration can be made in a climate system model (see §2*d*).

Rasch *et al.* (2008) used a coupled climate system model to show that the amount of aerosol required to balance the warming is sensitive to particle size, and that nonlinearities in the climate system mattered. Their model suggested that 1.5 Tg S yr^{-1} might suffice to balance the GHG warming, if the particles looked like those during background conditions (unlikely, as will be seen in §2*c*), and perhaps twice that would be required if the particles looked more like volcanic aerosols. Robock *et al.* (2008) used $1.5\text{--}5 \text{ Tg S yr}^{-1}$ in a similar study, assuming larger particle sizes (which, as will be seen in §2*c*, is probably more realistic). They explored the consequences of injections in polar regions (where the aerosol would be more rapidly flushed from the stratosphere) and tropical injections.

All of these studies suggest that a source 15–30 times that of the current non-volcanic sources of sulphur to the stratosphere would be needed to balance warming associated with a doubling of CO_2 . It is important to note that in spite of this very large perturbation to the stratospheric sulphur budget, it is a rather small perturbation to the total sulphur budget of the atmosphere. This suggests that the enhanced surface deposition (as for example ‘acid rain’) from a stratospheric geoengineering aerosol would be small compared with that arising from tropospheric sources globally, although it could be important if it occurred in a region that normally experienced little deposition from other sources.

There are competing issues in identifying the optimal way to produce a geoengineering aerosol. Since ambient aerosol can be a primary scavenger of new particles and vapours, their very presence limits new particle formation. When the stratosphere is relatively clean, the H_2SO_4 supersaturation can build up, and nucleation of new particles over time occurs more easily, with less scavenging of the new particles. Thus, the engineered layer itself becomes a limiting factor in the ongoing production of optically efficient aerosols.

Many of the earlier papers on geoengineering with stratospheric aerosols have listed delivery systems that release sulphur in very concentrated regions, using artillery shells, high flying jets, balloons, etc. These will release the sulphur in relatively small volumes of air. Partial pressures of sulphuric acid gas will get quite high, with consequences to particle growth and lifetime of the aerosols (see §2*c* for more detail).

An alternative would be to use a precursor gas that is quite long-lived in the troposphere but oxidizes in the stratosphere and then allow the Earth's natural transport mechanisms to deliver that gas to the stratosphere, and diffuse it prior to oxidation. OCS might serve as a natural analogue to such a gas (Turco *et al.* 1980), although it is carcinogenic and a greenhouse gas.

Current sources of OCS are $\lesssim 1\text{--}2 \text{ Tg S yr}^{-1}$ (Montzka *et al.* 2007). Perhaps 15 per cent of that is estimated to be of anthropogenic origin. Only approximately $0.03\text{--}0.05 \text{ Tg S yr}^{-1}$ is estimated to reach the tropopause and enter the stratosphere (figure 2 and SPARC 2006). Residence times in the troposphere are estimated to be approximately 1–3 years, and much longer (3–10 years) in the stratosphere. Turco *et al.* (1980) speculated that if anthropogenic sources of OCS were to be increased by a factor of 10, then a substantial increase in sulphate aerosols would result. If we assume that lifetimes do not change (and this would require careful research in itself), then OCS concentrations would in fact need to be enhanced by a factor of 50 to produce a 1 Tg S yr^{-1} source.

It might also be possible to create a custom molecule that breaks down in the stratosphere that is not a carcinogen, but using less reactive species would produce a reservoir species that would require years to remove if society needs to stop production. Problems with this approach would be reminiscent of the climate impacts from the long-lived chlorofluorocarbons (CFCs), although lifetimes are shorter.

(c) *Aerosol injection scenarios*

An issue that has been largely neglected in geoengineering proposals to modify the stratospheric aerosol is the methodology for injecting aerosols or their precursors to create the desired reflective shield.

As exemplified in §2*d*, climate simulations to date have employed specified aerosol parameters, including size, composition and distribution, often with these parameters static in space and time. In this section, we consider transient effects associated with possible injection schemes that use aircraft platforms, and estimate the microphysical and dynamical processes that are likely to occur close to the injection point in the highly concentrated injection stream. There are many interesting physical limitations to such injection schemes for vapours and aerosols, including a very high sensitivity to the induced nucleation rates (e.g. homogeneous nucleation) that would be very difficult to quantify within injection plumes.

Two rather conservative injection scenarios are evaluated, both assume baseline emission equivalent to approximately 2.5 Tg S yr^{-1} (which ultimately forms approx. 10 Tg of particles) as follows: (i) insertion of a primary aerosol, such as fine sulphate particles, using an injector mounted aboard an aircraft platform cruising in the lower stratosphere and (ii) sulphur-enhanced fuel additives employed to emit aerosol precursors in a jet engine exhaust stream. In each case injection is assumed to occur uniformly between 15 and 25 km, with the initial plumes distributed throughout this region to avoid hot spots. Attempts to concentrate the particles at lower altitudes, within thinner layers, or regionally—at high latitudes, for example—would tend to exacerbate problems in maintaining the engineered layer, by increasing the particle number density and thus increasing coagulation.

Our generic platform is a jet-fighter-sized aircraft carrying a payload of 10 metric tons of finely divided aerosol, or an equivalent precursor mass, to be distributed evenly over a 2500 km flight path during an 4-hour flight (while few aircraft are currently capable of sustained flight at stratospheric heights, platform design issues are neglected at this point). The initial plume cross section is taken to be 1 m^2 , which is consistent with the dimensions of the platform. Note that, with these specifications, a total aerosol mass injection of 10 Tg of particles per year would call for 1 million flights, and would require several thousand aircraft operating continuously in the foreseeable future. To evaluate other scenarios or specifications, the results described below may be scaled to a proposed fleet or system.

(i) *Particle properties*

The most optically efficient aerosol for climate modification would have sizes, R_p , of the order of $0.1 \mu\text{m}$ or somewhat less (here we use radius rather than diameter as the measure of particle size, and assume spherical, homogeneous particles at all times). Particles of this size have close to the maximum backscattering cross section per unit mass; they are small enough to remain suspended in the rarefied stratospheric air for at least a year and yet are large enough and thus could be injected at low enough abundances to maintain the desired concentration of dispersed aerosol against coagulation for perhaps months (although long-term coagulation and growth ultimately degrade the optical efficiency at the concentrations required—see below). As the size of the particles increases, the aerosol mass needed to maintain a fixed optical depth increases roughly as $\sim R_p$, the local mass sedimentation flux increases as $\sim R_p^4$, and the particle infrared absorptivity increases as $\sim R_p^3$ (e.g. Seinfeld & Pandis 1997). Accordingly, to achieve, and then stabilize, a specific net radiative forcing, similar to those discussed in §2*d*, larger particle sizes imply increasingly greater mass injections, which in turn accelerate particle growth, further complicating the maintenance of the engineered layer.

This discussion assumes a monodispersed aerosol. However, an evolving aerosol, or one maintained in a steady state, exhibits significant size dispersion. Upper-tropospheric and stratospheric aerosols typically have a lognormal-like size distribution with dispersion $\sigma_{\text{LN}} \sim 1.6\text{--}2.0$ ($\ln \sigma_{\text{LN}} \sim 0.47\text{--}0.69$). Such distributions require a greater total particle mass per target optical depth than a nearly monodispersed aerosol of the same mean particle size and number concentration. Accordingly, the mass injections estimated here should be increased by a factor of approximately 2, other things remaining equal (i.e. for $\sigma_{\text{LN}} \sim 1.6\text{--}2.0$, the mass multiplier is in the range of 1.6–2.6).

(ii) *Aerosol microphysics*

A bottleneck in producing an optically efficient uniformly dispersed aerosol—assuming perfect disaggregation in the injector nozzles—results from coagulation during early plume evolution. For a delivery system with the specifications given above, for example, the initial concentration of plume particles of radius $R_{\text{po}} = 0.08 \mu\text{m}$ would be approximately $1 \times 10^9 \text{ cm}^{-3}$, assuming sulphate-like particles with a density of 2 g cm^{-3} . This initial concentration scales inversely with the plume cross-sectional area, flight distance, particle specific density and

cube of the particle radius, and also scales directly with the mass payload. For example, if R_{po} were 0.04 or 0.16 μm , the initial concentration would be approximately 1×10^{10} or $1 \times 10^8 \text{ cm}^{-3}$, respectively, other conditions remaining constant.

For an injected aerosol plume, the initial coagulation time constant is

$$t_{\text{co}} = \frac{2}{n_{\text{po}} K_{\text{co}}}, \quad (2.1)$$

where n_{po} is the initial particle concentration ($\#/\text{cm}^3$) and K_{co} is the self-coagulation kernel ($\text{cm}^3 \text{ s}^{-1}$) corresponding to the initial aerosol size. For $R_{\text{po}} \sim 0.1 \mu\text{m}$, $K_{\infty} \sim 3 \times 10^{-9} \text{ cm}^3 \text{ s}^{-1}$ (e.g. Turco *et al.* 1979; Yu & Turco 2001). Hence, in the baseline injection scenario, $t_{\text{co}} \sim 0.07\text{--}7 \text{ s}$, for $R_{\text{po}} \sim 0.04\text{--}0.16 \mu\text{m}$, respectively. To assess the role of self-coagulation, these time scales must be compared with typical small-scale mixing rates in a stably stratified environment, as well as the forced mixing rates in a jet exhaust wake.

Turco & Yu (1997, 1998, 1999) derived analytical solutions of the aerosol continuity equation which describe the particle microphysics in an evolving plume. The solutions account for simultaneous particle coagulation and condensational growth under the influence of turbulent mixing, and address the scavenging of plume vapours and particles by the entrained background aerosol. A key factor—in addition to the previous specifications—is the growth, or dilution, rate of a plume volume element (or, equivalently, the plume cross-sectional area). The analytical approach incorporates arbitrary mixing rates through a unique dimensionless parameter that represents the maximum total number of particles that can be maintained in an expanding, coagulating volume element at any time. Turco & Yu (1998, 1999) show that these solutions can be generalized to yield time-dependent particle size distributions, and accurately reproduce numerical simulations from a comprehensive microphysical code. Although aerosol properties (concentration, size) normally vary across the plume cross section (e.g. Brown *et al.* 1996; Dürbeck & Gerz 1996), uniform mixing is assumed, and only the mean behaviour is considered.

(iii) Quiescent injection plumes

An otherwise passive (non-exhaust) injection system generally has limited turbulent energy, and mixing is controlled more decisively by local environmental conditions. If the quiescent plume is embedded within an aircraft wake, however, the turbulence created by the exhaust, and wing vortices created at the wingtips, can have a major impact on near-field mixing rates (e.g. Schumann *et al.* 1998). For a quiescent plume, we adopt a linear cross-sectional growth model that represents a small-scale turbulent mixing perpendicular to the plume axis (e.g. Justus & Mani 1979). Observations and theory lead to the following empirical representation for the plume volume:

$$V(t)/V_0 = (1 + t/\tau_{\text{mix}}), \quad (2.2)$$

where V is the plume volume element of interest (equivalent to the cross-sectional area in the near-field), V_0 is its initial volume and τ_{mix} is the mixing time scale. For the situations of interest, we estimate $0.1 \leq \tau_{\text{mix}} \leq 10 \text{ s}$.

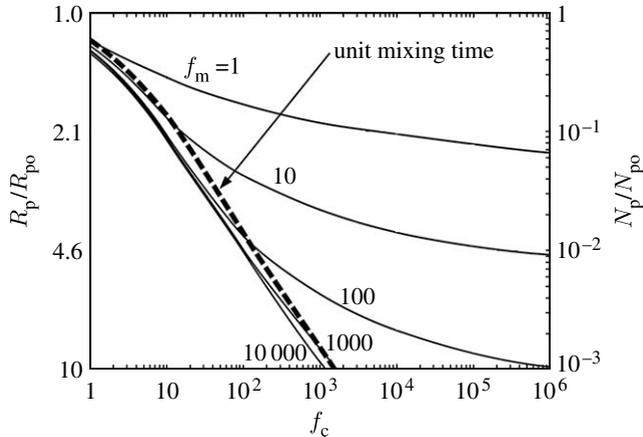


Figure 3. Evolution of the total concentration of particles N_p and the mass-mean particle radius R_p in an expanding injection plume. Both variables are scaled against their initial values in the starting plume. The time axis ($f_c = t/\tau_{co}$) is scaled in units of the coagulation time constant τ_{co} . Each solid line, corresponding to a fixed value of f_m , gives the changes in N_p and R_p for a specific mixing time scale τ_{mix} measured relative to the coagulation time scale τ_{co} or $f_m = \tau_{mix}/\tau_{co}$. The heavy dashed line shows the changes at the unit mixing time, for which $f_c = f_m$ when the plume cross-sectional area has roughly doubled; the longer the mixing time scale, the greater the reduction in particle abundance and particle radius.

Following Turco & Yu (1999, eqn (73)), we find for a self-coagulating primary plume aerosol

$$N_p(t)/N_{po} = \frac{1}{1 + f_m \ln(1 + f_c/f_m)}, \quad (2.3)$$

where N_p is the total number of particles in the evolving plume volume element at time t , and N_{po} is the initial number. We also define the scaled time, $f_c = t/\tau_{co}$, and scaled mixing rate, $f_m = \tau_{mix}/\tau_{co}$. The local particle concentration is $n_p(t) = N_p(t)/V(t)$.

In figure 3, predicted changes in particle number and size are illustrated as a function of the scaled time for a range of scaled mixing rates. The ranges of parameters introduced earlier result in an approximate range of $0.014 \leq f_m \leq 140$. At the lower end, prompt coagulation causes only a small reduction in the number of particles injected, while at the upper end reductions can exceed 90 per cent in the first few minutes. Particle self-coagulation in the plume extending over longer time scales further decreases the initial population—by a factor of a 1000 after one month in the most stable situation assumed here, but by only some 10s of per cent for highly energetic and turbulent initial plumes.

The dashed line in figure 3 shows the effect of coagulation at the ‘unit mixing time’, at which the plume volume has effectively doubled. Clearly, prompt coagulation significantly limits the number of particles that can be injected into the ambient stratosphere when stable stratification constrains early mixing. Initial particle concentrations in the range of approximately 10^{10} – 10^{11} cm^{-3} would be rapidly depleted, as seen by moving down the unit mixing time line in figure 3 (further, 10^{11} cm^{-3} of $0.08 \mu\text{m}$ sulphate particles exceed the density of

stratospheric air). A consequence of prompt coagulation is that it is increasingly difficult to compensate for plume coagulation (at a fixed mass injection rate) by reducing the starting particle size. Initial particle concentrations could simultaneously be reduced to offset coagulation, but the necessary additional flight activity would affect payload and/or infrastructure. It is also apparent that rapid mass injections *in the forms of liquids or powders* for the purpose of reducing flight times would lead to mass concentrations greatly exceeding those assumed above (generally $<1 \times 10^{-4} \text{ g cm}^{-3}$), causing large particle or droplet formation and rapid fallout.

(iv) *Aerosol injection in aircraft jet exhaust*

The effects of high-altitude aircraft on the upper troposphere and lower stratosphere have been extensively studied, beginning with the supersonic transport programmes of the 1970s and extending to recent subsonic aircraft impact assessments (under various names) in the USA and Europe (e.g. NASA-AEAP 1997). These projects have characterized aircraft emissions and jet plume dynamics, and developed corresponding models to treat the various chemical, microphysical and dynamical processes.

Enhancing aircraft fuel with added sulphur compounds (H_2S , S_n) could increase the particle mass in a jet wake. It is well established that ultrafine sulphate particles are generated copiously in jet exhaust streams during flight (e.g. Fahey *et al.* 1995). The particles appear to be nucleated by sulphuric acid on ions (hereafter chemiions, e.g. Yu & Turco (1997, 1998b)) formed in the combustion process of jet engines by radical reactions. Sulphuric acid is a by-product of sulphur residues in the fuel (typically less than 1% sulphur by weight); most of this fuel sulphur is emitted as SO_2 . The fraction emitted as H_2SO_4 decreases as the fuel sulphur content increases, and accounts for roughly 2 per cent of the total sulphur as the fuel sulphur content approaches approximately 1 per cent.

The concentrations of chemiions in jet emissions are strongly limited by ion–ion recombination along the engine train to approximately $1 \times 10^9 \text{ cm}^{-3}$ at the exit plane (e.g. Arnold *et al.* 2000). Considering a variety of direct measurements of particles in jet wakes, Kärcher *et al.* (2000) showed that chemiion nucleation is consistent with the observed relative constancy of the ultrafine volatile (non-soot) particle emission factor, $E_p \sim 1\text{--}2 \times 10^{17} \text{ kg}^{-1}$ fuel (where it should be noted that the concentrations of soot particles are typically less than 1 per cent of the total number of particles emitted). E_p is quite insensitive to the fuel sulphur content, a fact that is also consistent with a chemiion nucleation source. While vapour trails formed in jet wakes can significantly modify the injected particle properties (e.g. Yu & Turco 1998a), condensation trails are extremely rare under normally dry stratospheric conditions.

If we imagine enhanced jet fuel sulphur contents of 5 per cent by weight (10–100 times current amounts) for geoengineering purposes, then the annual consumption of approximately 50 Tg of such fuel during stratospheric flight (approx. half the amount used by current commercial aviation) could emit up to 2.5 Tg of sulphur that would eventually generate roughly 10 Tg of sulphate aerosol. The total number of particles emitted—for $E_p \sim 1 \times 10^{17} \text{ kg}^{-1}$ fuel—would amount to approximately 5×10^{27} . This number, uniformly dispersed over

a 10-km thick layer from 15 to 25 km, yields an average concentration of approximately $1 \times 10^3 \text{ cm}^{-3}$ with a particle radius of roughly $0.06 \mu\text{m}$; in other words, an ideal geoengineered solar shield. These estimates (i) assume no unexpected chemistry or microphysics in the early wake that would alter the emission factor significantly, (ii) allow for an ideal distribution of sulphate mass among the particles, and (iii) ignore coagulation following emission.

The mixing rates in a jet wake are very rapid. Schumann *et al.* (1998) fit a wide range of exhaust plume observations in the upper troposphere and lower stratosphere with a ‘universal’ mixing curve. We use their result in the form,

$$V/V_0 = 100t^{0.8}; \quad t \geq 0.0032 \text{ s.} \quad (2.4)$$

Equation (2.4) describes, roughly, plume dilution starting at the exhaust exit prior to mixing with turbine bypass air, through the jet zone, vortex region and into the ambient mixing regime. Schumann *et al.* (1998) state that the fit is best between 1 and 50 s. For the approximately $1 \times 10^9 \text{ cm}^{-3}$ incipient particles in the initial exhaust stream, the extent of self-coagulation can be projected using the more general analytical approach discussed earlier (Turco & Yu 1999). Thus, even at 10^5 s , approximately three-quarters of the initial particles remain (compared with an estimated 0.0007% if mixing were completely suppressed). Clearly, prompt coagulation is not an issue in a jet exhaust plume.

(v) Longer term plume processing

The extended microphysical processing of an injection plume can be critical owing to the long induction time before the plume becomes widely dispersed as a part of the background aerosol. Yu & Turco (1999) studied the far-wake regime of jet exhaust for upper tropospheric conditions to estimate the yield of cloud condensation nuclei from volatile aircraft particulate emissions. In their simulations, the background aerosol surface area density (SAD) ranged from 12.7 to $18.5 \mu\text{m}^2 \text{ cm}^{-3}$ for summer conditions. The resulting scavenging of fresh plume particles amounted to approximately 95 per cent after 10 days (that is, the effective emission index was decreased by a factor of 20). Moreover, only approximately 1 in 10 000 of the original particles had grown to $0.08 \mu\text{m}$ at that time, corresponding to a fuel sulphur content of 0.27 per cent by weight, with 2 per cent emitted as H_2SO_4 . For a geoengineering scheme with 5 per cent fuel sulphur, although the primary exhaust sulphuric acid fraction would probably be less than 1 per cent, the initial growth rate of the chemiions would probably be accelerated.

At typical mixing rates, background aerosol concentrations would be present in an injection plume within a minute or less. The natural stratosphere has an ambient aerosol concentration of $1\text{--}10 \text{ cm}^{-3}$, with an effective surface area of less than $1 \mu\text{m}^2 \text{ cm}^{-3}$. However, in a geoengineered stratosphere, at the desired baseline optical depth, a SAD greater than $10 \mu\text{m}^2 \text{ cm}^{-3}$ would prevail. Further, any attempt to concentrate the engineered layer regionally or vertically, or both, would greatly exacerbate both self-coagulation and local scavenging.

The coagulation kernel for collisions of the background engineered particles (assuming a minimum radius of approx. $0.1\text{--}0.2 \mu\text{m}$ following ageing) with jet exhaust nanoparticles of approximately $10\text{--}80 \text{ nm}$ is approximately 1×10^{-7} to $4 \times 10^{-9} \text{ cm}^3 \text{ s}^{-1}$, respectively (Turco *et al.* 1979). Using a mean scavenging

kernel for growing jet particles of approximately $2 \times 10^{-8} \text{ cm}^3 \text{ s}^{-1}$, and a background concentration of 120 cm^{-3} (determined for a doubling of the mass injection rate to maintain the optical depth, see below), the estimated scavenging factor is $\exp(-2.5 \times 10^{-6}t)$. After 1 day, the reduction in number is a factor of approximately 0.80, and over 10 days, approximately 0.1, consistent with the result of Yu & Turco (1999). Keeping in mind that the optical requirements of the engineered layer are roughly based on total cross section (ignoring infrared effects), while the scavenging collision kernel is also approximately proportional to the total background particle surface area (for the particle sizes relevant to this analysis), larger particles imply a lower concentration (and greater injection mass loading) but about the same overall scavenging efficiency.

The background aerosol will also affect the partitioning of any injected vapours between new and pre-existing particles. Considering the injection of SO_2 in jet exhaust as an example, it should be noted that SO_2 oxidation in the stabilized plume should occur over roughly a day, unless oxidants are purposely added to the plume. By this time the SO_2 would be so dilute and relative humidity so low that additional nucleation would be unlikely.

At approximately 1 day, the residual plume exhaust particles may have achieved sizes approaching $0.05 \mu\text{m}$ (Yu & Turco 1999). Then, considering the considerably larger surface area of the background aerosol, only a fraction of the available precursor vapours would migrate to new particles, with the rest absorbed on pre-existing aerosol. Using an approach similar to that in Turco & Yu (1999), we infer that the jet-fuel sulphur injection scenario partitions roughly 20 per cent of the injected sulphur into new particles, with the rest adding to the background mass. Considering the higher fuel sulphur content, and reduced number of condensation sites, the residual injected plume particles could grow on average to approximately $0.08 \mu\text{m}$. While this is a desirable size, the effective emission index is an order of magnitude below that needed to maintain the desired layer under the conditions studied. Either the fuel sulphur content or fuel consumption could be doubled to regain the overall target reflectivity. Nevertheless, as the expanding injection plumes merge and intermix following the early phase of coagulation scavenging, the aerosol system undergoes continuing self-coagulation as the layer approaches, and then maintains, a steady state. The consequences of this latter phase are not included in these estimates.

(vi) *Summary*

A primary conclusion of the present analysis is that the properties of aerosols injected directly into the stratosphere from a moving (or stationary) platform, or in the exhaust stream of a jet aircraft, can be severely affected by prompt and extended microphysical processing as the injection plume disperses, especially owing to self-coagulation and coagulation scavenging by the background aerosol. Early coagulation can increase mass requirements by a factor of 2 or more primarily because increased particle size leads to reduced optical efficiency. In addition, the resulting dispersion in particle sizes implies even greater mass injections by up to a factor of approximately 2. Thus, consideration of particle aggregation and size dispersion increases, at least by several fold, the estimated engineering and infrastructure development effort needed to produce a required net solar forcing. We wish to emphasize that these calculations are merely one

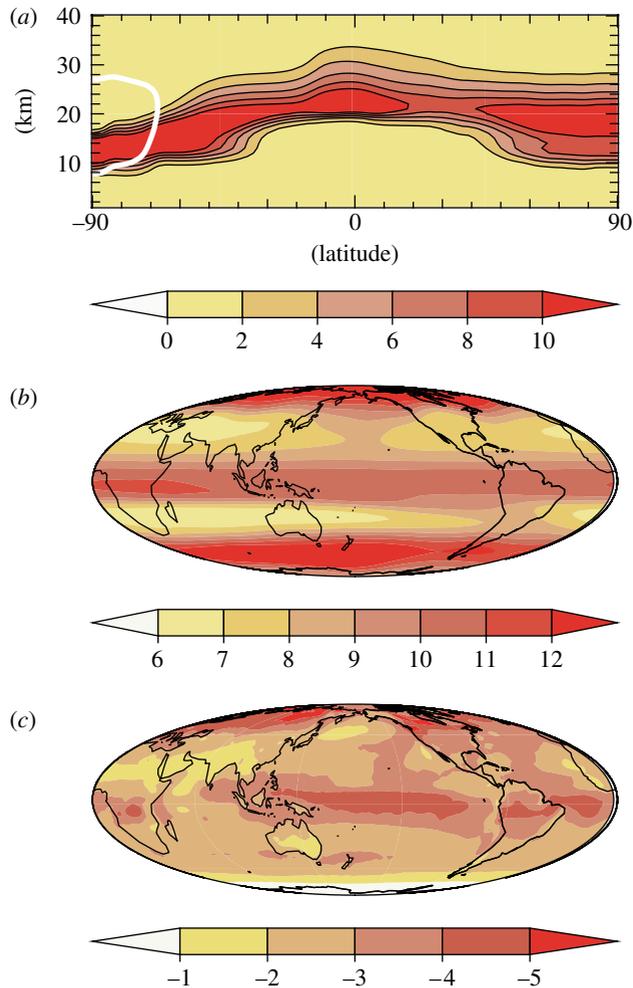


Figure 4. (a–c) Examples of distribution of the geoengineering aerosol for June, July and August from a 20-year simulation for a 2 Tg S yr^{-1} emission. The white contour in (a) shows the region where temperatures fall below 194.5 K, and indicates approximately where ozone depletion may be important (see §2*d*(i)).

exploration of an idealized set of delivery scenarios. Many others are possible, and would require similar sets of calculations, and, if deemed promising, far more elaborate studies.

(d) Global modelling

Most of the studies mentioned in the previous sections calibrated their estimates of the climate response to geoengineering aerosol (Crutzen 2006; Wigley 2006) based upon historical observations of the aerosol produced by volcanic eruptions. Crutzen and Wigley focused primarily upon the surface temperature cooling, resulting from the aerosol's shielding effect. Trenberth & Dai (2007) analysed historical data to estimate the role of the shielding on the

hydrological cycle, and concluded that there would be a substantial reduction in precipitation over land, with a consequent decrease in runoff and river discharge to the ocean.

The analogy between a volcanic eruption and geoengineering via a sulphate aerosol strategy is imperfect. The aerosol forcing from an eruption lasts a few years at most, and eruptions occur only occasionally. There are many timescales within the Earth system, and their transient response to the eruption is not likely to be the same as the response to the continuous forcing required to counter the warming associated with greenhouse gases. Furthermore, we have no precise information on the role the eruptions might have on a world warmer than today. For example, the response of the biosphere to a volcanic eruption might be somewhat different in a warmer world than it is today. It is thus of interest to explore the consequences of geoengineering using a climate model—a tool (albeit imperfect) that can simulate some of the complexities of the Earth system—and ask how the Earth's climate might change if one could successfully introduce particles into the stratosphere.

Govindasamy & Caldeira (2000, 2003), Govindasamy *et al.* (2002) and Matthews & Caldeira (2007) introduced this line of exploration, mimicking the impact of stratospheric aerosols by reducing the solar constant to diminish the energy entering the atmosphere (by 1.8%). These studies are discussed in more detail elsewhere in this volume, so we will not review them further here.

Rasch *et al.* (2008) used a relatively simple representation of the stratospheric sulphur cycle to study this problem. The aerosol and precursor distributions' evolution is controlled by production, transport and loss processes as the model atmosphere evolves. The aerosols are sensitive to changes in model climate and this allows some feedbacks to be explored (for example changes in temperature of the tropical tropopause, and lower stratosphere, and changes to cross tropopause transport). Their model used a 'bulk' aerosol formulation carrying only the aerosol mass (the particle size distribution was prescribed). They used an atmosphere ocean general circulation model, a coupled variant of the NCAR community atmosphere model (CAM3; Collins *et al.* 2006), coupled to a slab ocean model (SOM). The model was designed to produce a reasonable climate for the troposphere and middle atmosphere. The use of a SOM with a thermodynamic sea ice model precluded a dynamic response from the ocean and sea ice, which requires a more complex model such as that of Robock *et al.* (2008) discussed below.

The model was used to explore the evolution of the sulphate aerosol and the climate response to different amounts of precursor injection, and the size of the aerosol. SO₂ was injected uniformly and continuously in a 2 km thick region at 25 km between 10° N and 10° S. Owing to the difficulties of modelling the particle size evolution discussed in §2c, the study assumed the distribution to be either 'small' such as that seen during volcanically quiescent situations or 'large' such as particles seen following an eruption. Figure 4 shows the aerosol distribution and radiative forcing for an example simulation (assuming a 2 Tg S yr⁻¹ source and particle size similar to a volcanic aerosol). We have chosen to focus on the June, July, August season to highlight some features that disappear when displaying annual averages. The aerosol is not distributed uniformly in space and time. The mass of aerosol is concentrated in equatorial regions near the precursor injection source region, and in polar regions in areas where air densities are

higher, and mixing into the troposphere is less than the mid-latitudes and sub-tropics, where relatively rapid exchange with the troposphere takes place. Aerosol burdens are the highest in the winter hemisphere, but because solar insolation is lower there, radiative forcing is also lower than that in the summer hemisphere. Maximum radiative forcing occurs in the high latitudes of the summer hemisphere, acting to effectively shield the high latitudes resulting in a substantial recovery of sea ice compared with the $2\times\text{CO}_2$ scenario (Rasch *et al.* 2008).

While the largest forcing in the annually averaged sense occurs in equatorial regions, the seasonal forcing is the largest in the summer hemisphere. The most sensitivity in the response occurs at the poles, consistent with the general behaviour of climate models to uniform radiative forcing from greenhouse gases (IPCC 2007a), and also to the response to volcanic eruptions (Robock 2000), and to simpler explorations of geoengineering (Govindasamy & Caldeira 2000). Stratosphere–troposphere exchange (STE) processes respond to greenhouse gas forcing and interact with geoengineering. Nonlinear feedbacks modulate STE processes and influence the amount of aerosol precursor required to counteract CO_2 warming. Rasch *et al.* (2008) found that approximately 50 per cent more aerosol precursor must be injected than would be estimated if STE processes did not change in response to greenhouse gases or aerosols. Aerosol particle size was also found to play a role. Roughly double the aerosol mass is required to counteract greenhouse warming if the aerosol particles were as large as those seen during volcanic eruptions because larger particles are less effective at scattering incoming energy and trapping some of the outgoing energy. An estimate of 2 Tg S yr^{-1} was considered to be more than enough to balance the warming in global-mean terms from a doubling of CO_2 if particles were small (probably unlikely), but insufficient if the particles were large. Small particles were optimal for geoengineering through radiative effects, though they also provided more surface area for chemical reactions to occur. The reduced single scattering albedo of the larger particles and increased absorption in the infrared regime lessen the impact of the geoengineering, making large particle sulphate less effective in cooling the planet. That study also indicated the potential for ozone depletion. Ozone depletion issues are discussed in more detail in §2d(i).

A typical surface temperature change from present day to a doubling of current carbon dioxide levels (denoted $2\times\text{CO}_2$) scenario is shown in figure 5, along with the result of geoengineering at 2 Tg S yr^{-1} (assuming a volcanic-sized particle). The familiar CO_2 warming signal, particularly at high latitude, is evident, with a substantial reduction resulting from geoengineering. The simulation uses an emission rate that is not sufficient to completely counter-balance the warming. Geoengineering at this amplitude leaves the planet 0.25–0.5 K warmer than present over most of the globe, with the largest warming remaining at the winter pole. It is also straightforward to produce an emission that is sufficient to over-cool the model (e.g. Rasch *et al.* 2008). The polar regions and continents show the most sensitivity to the amplitude of the geoengineering.

Robock *et al.* (2008; hereafter referred to as the ‘Rutgers’ study) moved to the next level of sophistication in modelling geoengineering on the climate system. They used the GISS atmospheric model (Schmidt *et al.* 2006) and included a similar formulation for sulphate aerosols (Oman *et al.* 2005, 2006a,b) with a

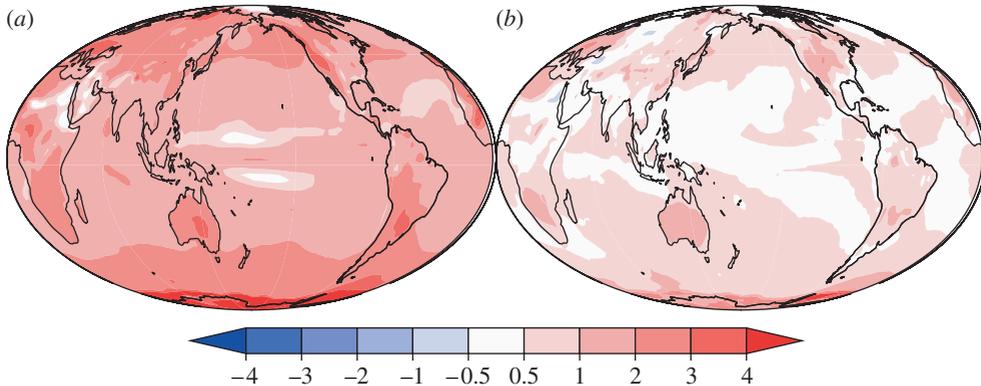


Figure 5. (a,b) The surface temperature difference from present day during June, July and August with the $2\times\text{CO}_2$ simulation and the geoengineering simulation using 2 Tg S yr^{-1} emission (which is not sufficient to entirely balance the greenhouse warming).

substantially lower horizontal ($4\times 5^\circ$) and vertical (23 layers to 80 km) spatial resolution than Rasch *et al.* (2008). Instead of using a slab ocean and sea ice model, they included a full ocean and sea ice representation. While Rasch *et al.* (2008) examined the steady-state response of the system for present and doubled CO_2 concentrations, Robock *et al.* (2008) explored solutions with transient CO_2 forcings using an IPCC A1B scenario with transient greenhouse gas forcing. They examined the consequences of injections of aerosol precursors at various altitudes and latitudes to a 20-year burst of geoengineering, between 2010 and 2030. We focus on two of their injection scenarios: (i) an injection of 2.5 Tg S yr^{-1} in the tropics at altitudes between 16 and 23 km; and (ii) an injection of 1.5 Tg S yr^{-1} at latitude 68°N between 10 and 15 km. They chose a dry mode radius of $0.25\text{ }\mu\text{m}$, intermediate to the ranges explored in the Rasch *et al.* (2008) study. The mid-latitude injection produces a shorter lifetime for the aerosol, and concentrates its impact on the Arctic, although, as they show (and as seen below), it has global consequences. This type of geoengineering scenario shares some commonalities with scenarios described by Caldeira elsewhere in this volume. Robock *et al.* (2008) also showed that geoengineering is able to return sea ice, surface temperature and precipitation patterns to values closer to the present day values in a climate system model.

As an example, we show changes in precipitation for a few scenarios from Rasch *et al.* (2008) and Robock *et al.* (2008) in figure 6, again for a JJA season. Because the signals are somewhat weaker than evident in the surface temperature changes shown above, we have hatched areas where changes exceed 2 s.d. of an ensemble of control simulations to indicate differences that are likely to be statistically important. Figure 6a,b shows results from the NCAR model from Rasch *et al.* (2008), and figure 6c,d (labelled Rutgers) shows results from the GISS model as described in Robock *et al.* (2008).

As noted in IPCC (2007b), projections of changes from forcing agents to the hydrologic cycle through climate models are difficult. Uncertainties are larger than in projections of temperature, and important deficiencies remain in the simulation of clouds, and tropical precipitation in all climate models, both

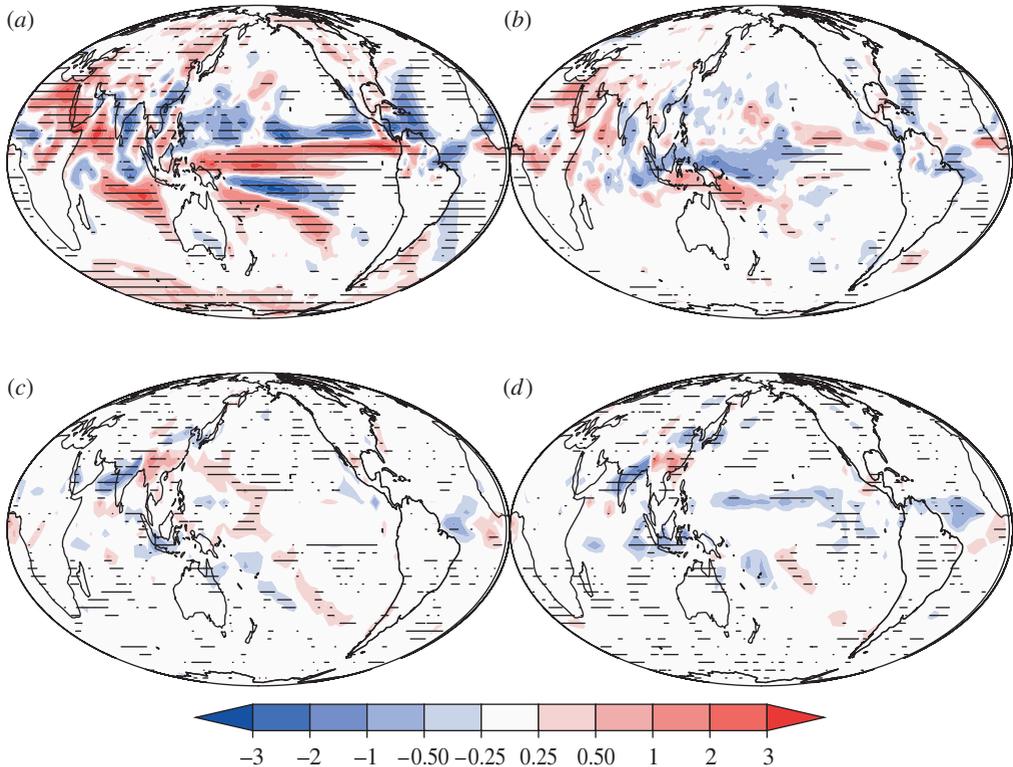


Figure 6. Change in precipitation associated with perturbations to greenhouse gases and geoengineering for two models during the June, July and August months: (a,b) shows differences between present day and doubling of CO_2 in the NCAR model CCSM using a SOM. (a) The changes induced by $2\times\text{CO}_2$. (b) The additional effect of geoengineering (with a 2 Tg S yr^{-1} source). (c,d) The precipitation changes for the GISS model using an A1B transient forcing scenario and full ocean model (between 2020 and 2030) with geoengineering. (c) The changed distribution using 1.5 Tg S yr^{-1} injection at 68° N . (d) The change introduced by a 2.5 Tg S yr^{-1} injection in the tropics. Hatching shows areas where difference exceeds 2 s.d. of an ensemble of samples from a control simulation.

regionally and globally, so results from models must be interpreted carefully and viewed cautiously. Nevertheless, climate models do provide information about the fundamental driving forces of the hydrologic cycle and its response to changes in radiative forcing (e.g. Annamalai *et al.* 2007).

The NCAR results (figure 6a), consistent with IPCC (2007c) and the 20+ models summarized there, suggest a general intensification in the hydrologic cycle in a doubled CO_2 world with substantial increases in regional maxima (such as monsoon areas) and over the tropical Pacific, and decreases in the subtropics. Geoengineering (figure 6b, in this case not designed to completely compensate for the CO_2 warming) reduces the impact of the warming substantially. There are many fewer hatched areas, and the white regions indicating differences of less than 0.25 mm d^{-1} are much more extensive.

The Rutgers simulations show a somewhat different spatial pattern, but, again, the perturbations are much smaller than those evident in an ‘ungeoengineered world’ with CO_2 warming. Figure 6c shows the precipitation

distributions for the polar injection; figure 6d shows the distributions for the equatorial injection. Both models show changes in the Indian and SE Asian monsoon regions, and common signals in the equatorial Atlantic. There are few common signals between the NCAR and Rutgers estimates. Robock *et al.* (2008) have emphasized that the perturbations that remain in the monsoon regions after geoengineering are considerable and expressed concern that these perturbations would influence the lives of billions of people. This would certainly be true. However, it is important to keep in mind that: (i) the perturbations after geoengineering are smaller than those without geoengineering; (ii) the remaining perturbations are less than or equal to 0.5 mm d^{-1} in an area where seasonal precipitation rates reach $6\text{--}15 \text{ mm d}^{-1}$; (iii) the signals differ between the NCAR and Rutgers simulations in these regions; and (iv) monsoons are a notoriously difficult phenomenon to model (Annamalai *et al.* 2007). These caveats only serve to remind the reader about the importance of a careful assessment of the consequences of geoengineering, and the general uncertainties of modelling precipitation distributions in the context of climate change.

(i) *Impact on chemistry and the middle atmosphere*

Historically, most attention has focused on the surface chemistry responsible for chlorine activation and ozone depletion taking place on Polar Stratospheric Clouds, but ozone loss also occurs on sulphate aerosols, and this is evident following volcanic eruptions (Solomon 1999; Stenchikov *et al.* 2002). Ozone depletion depends upon a complex interaction between meteorological effects (for example temperature of the polar vortex, frequency and occurrence of sudden warmings), stratospheric photochemistry and, critically, halogen concentrations connected with the release of CFCs in the last few decades. Reductions in the ozone column following Pinatubo of 2 per cent in the tropics and 5 per cent in higher latitudes were observed when particle SAD exceeded $10 (\mu\text{m})^2 \text{ cm}^{-3}$ (e.g. Solomon 1999). Rasch *et al.* (2008) noted that regions with high aerosol SAD associated with geoengineering sulphate aerosol were coincident with cold temperatures (figure 4) and indicated concern that ozone depletion might be possible, at least until most active chlorine has been flushed from the stratosphere (thought to occur after approx. 2050). Recently, Tilmes and colleagues have begun to explore some aspects of ozone depletion associated with geoengineering, and we summarize some of that work here.

Tilmes *et al.* (2007) estimated Arctic ozone depletion for the 1991–1992 winter following the eruption of Mt Pinatubo based on satellite observations and aircraft and balloon data, and found enhanced ozone loss in connection with enhanced SAD. They used an empirical relationship connecting meteorological conditions and ozone depletion to estimate 20–70 Dobson units (DU, a unit of mass of ozone in a column) of extra ozone depletion from the volcanic aerosols in the Arctic for the two winters following the eruption.

Tilmes *et al.* (2008) estimated the impact of geoengineered aerosols for future halogen conditions using a similar empirical relationship, but this time including aerosol loading and changing halogen content in the stratosphere. They based their estimates of ozone depletion on an extrapolation of present meteorological condition into the future, and assumptions about the amount and location of the geoengineering aerosol. They predicted a substantial increase of chemical ozone

depletion in the Arctic polar regions, especially for very cold winters, and a delay of 30–70 years in the recovery of the Antarctic ozone hole. This estimate of ozone depletion might be considered high, because they chose to impose a forcing (through the geoengineering aerosol) that was sufficient to counter the warming from a doubling of CO₂ even during the early twenty-first century, at a time when the halogen content is high and the CO₂ concentrations are relatively low, so a strong geoengineering is not required. However, even after 2050, accounting for the projected decline in halogens and the increase in CO₂ concentrations, they found a substantial depletion of ozone in polar regions, especially for very cold winters.

Tilmes *et al.* (submitted) extended their earlier calculation by using one of the aerosol distributions calculated in Rasch *et al.* (2008) to explore the impact of geoengineered sulphate aerosols. Rather than estimating ozone depletion using the empirical relationships, the study used the interactive chemistry climate model Whole Atmosphere Chemistry Climate Model (WACCM). The configuration included an explicit representation of the photochemistry relevant to the middle atmosphere (Kinnison *et al.* 2007), and a SOM. This model allows a first-order response of the troposphere to greenhouse warming, to changes to the middle atmosphere chemical composition and circulation structures, and exposes the interaction between the chemistry and dynamics. As in Tilmes *et al.* (2008), sulphur loading appropriate to substantially counteract the warming associated with a doubling of CO₂ was assumed, resulting in a possible overestimation of the impact of geoengineering before 2050.

Two simulations of the time period 2010–2050 were performed as follows: (i) a baseline run without geoengineering aerosols; and (ii) a simulation containing geoengineering aerosols. For the baseline run, monthly mean background values of aerosols were assumed to match background SAGEII estimates (SPARC 2006). For the geoengineering run, a repeating annual cycle of aerosols derived from the run scenario labelled as ‘volc2’ from Rasch *et al.* (2008) was employed. That scenario assumed aerosols with a particle size distribution similar to that following a volcanic eruption, and an aerosol burden produced from a 2 Tg S yr⁻¹ injection of SO₂. Both model simulations used the IPCC A1B greenhouse gas scenario and changing halogen conditions for the stratosphere. In the model simulations, the halogen content in the stratosphere was assumed to decrease to 1980 values by approximately 2060 (Newman *et al.* 2006). The study thus explored the impact of geoengineering during a period with significant amount of halogens in the stratosphere so that ozone depletion through surface chemistry is important.

In addition to the desired cooling of the surface and tropospheric temperatures, the enhanced sulphate aerosols in the stratosphere directly influence middle atmosphere temperatures, chemistry and wind fields. The temperature-dependent heterogeneous reaction rates in the stratosphere affect the amount of ozone. Ozone plays an important role in the energy budget of the stratosphere, absorbing incoming solar energy and outgoing energy in the infrared. It therefore influences temperatures (and indirectly the wind field), especially in polar regions. Additional aerosol heating also results in warmer temperatures in the tropical lower stratosphere (between 18 and 30 km). This results in an increase of the temperature gradient between tropics and polar regions (as mentioned in Robock 2000). As a consequence, the polar vortex becomes stronger and colder, and the Arctic polar vortex exists longer with geoengineering than without, which influences polar ozone depletion.

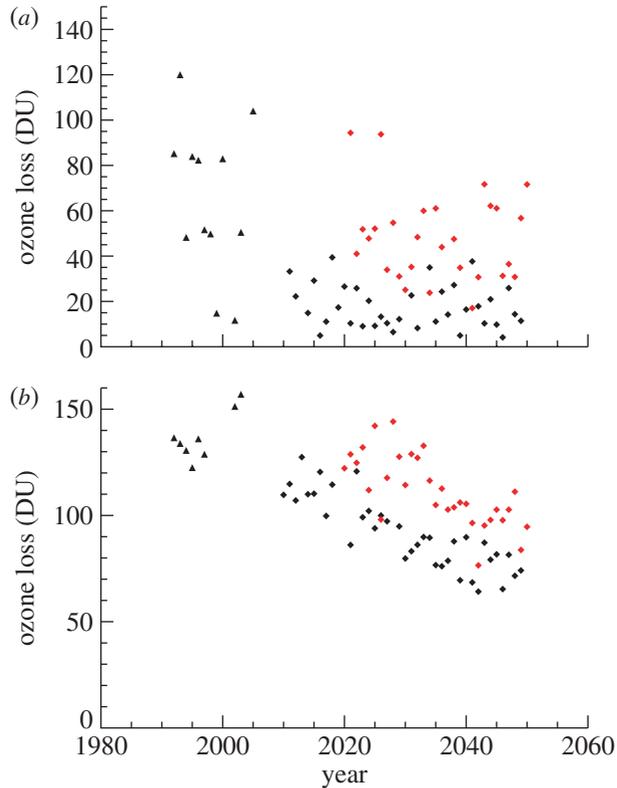


Figure 7. Partial chemical ozone depletion between 350 and 550 K in (a) the Arctic vortex core in April and (b) the Antarctic vortex core in October. The depletion is estimated using the baseline model run (black diamonds), the geoengineering run (red diamonds) and observations (Tilmes *et al.* 2006; black triangles).

In the tropics and mid-latitudes, enhanced heterogeneous reactions cause a slight increase of ozone owing to the shift of the NO_x/NO_y equilibrium towards NO_y in the region of high-aerosol loading with an increase of ozone loss rates above and below this layer owing to the higher temperatures in the geoengineering run. On average, the column ozone increases by 2–3 per cent maximum at 20–30° north and south. In polar regions, an increase in heterogeneous reaction rates has a more severe impact on the ozone layer.

Chemical ozone loss in the polar vortex between early winter and spring can be derived for both model simulations. These results can be compared with estimates derived from observations between 1991 and 1992 and 2004 and 2005 for both hemispheres (Tilmes *et al.* 2006, 2007), as displayed in figure 7. Estimates for present day depletion are indicated in black triangles. Estimates for the control simulations and geoengineered atmosphere are shown in black and red diamonds, respectively.

The WACCM model does a relatively good job of reproducing the ozone depletion for the Antarctic vortex (figure 7b). Ozone loss decreases linearly with time (black diamonds), and year to year variability in the model is similar to that of the observations. The WACCM model suggests a 40–50 DU increase in ozone depletion in the Antarctic vortex owing to geoengineering.

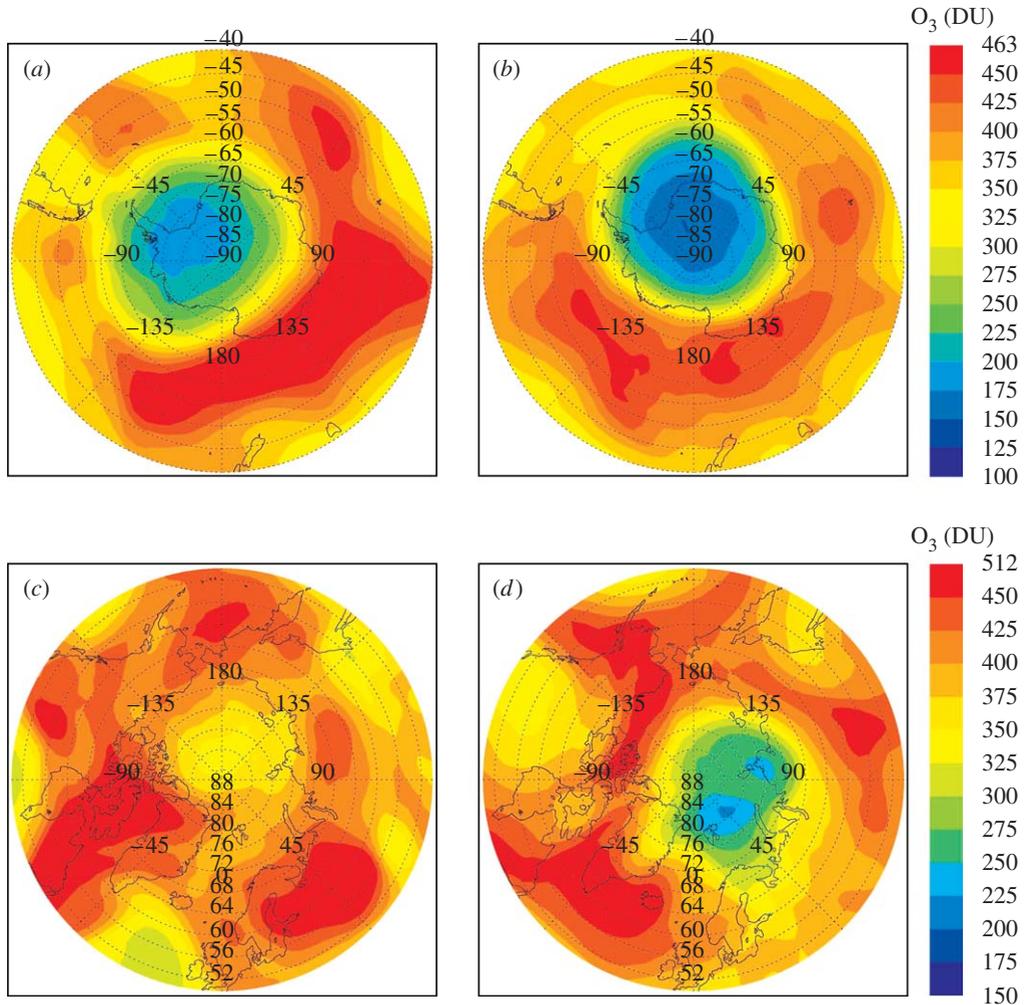


Figure 8. Column ozone for (a,c) baseline run and (b,d) geoengineering run for two meteorologically similar Antarctic winters in mid-October 2025 (a,b) and the coldest simulated Arctic winters (c,d) in the beginning of April (DU, Dobson units).

The model reproduces the depletion and variability much less realistically in the Arctic (figure 7a). Averaged temperatures in the simulated vortex are similar to observations, but the model does not reproduce the observed chemical response in ozone. The simulated polar vortex is 2–5° (in latitude) too small and the vortex boundary is not as sharp as that seen in the observations. The ozone depletion starts later in the winter owing to warmer temperatures in the beginning of the winter and there is less illumination at the edge of the smaller vortex (necessary to produce the depletion). Chemical ozone depletion for the WACCM3 baseline run in the Arctic is less than half of that derived from observations. Underestimates of bromine concentrations may also contribute to the underestimation of chemical ozone loss.

Examples of spatial changes in ozone depletion are shown in figure 8, which displays the difference between the baseline and geoengineering runs for Antarctica (figure 8a,b) for two winters with similar temperature structure and

for the coldest winter of each simulation in the Arctic (figure 8c,d). Antarctic winters show approximately 30 DU smaller column ozone values for the geoengineering simulation. Larger ozone losses occur over a wider area of the vortex for the geoengineering model run.

The geoengineering simulation suggests that ozone depletion will be somewhat larger in the Arctic. The amplitude of the variability in ozone depletion is increased in the geoengineering simulation, and colder vortex temperatures occur during winter and spring. The coldest three winters of the geoengineering run are 1–2.5°C colder than the coldest winter in the baseline run (between 20 and 25 km in altitude) between mid-December and March. The warm Arctic winter in the baseline case shows little ozone depletion (figure 8c). The colder temperatures and larger vortex in the geoengineering run result in increased depletion compared with the control. The Arctic ozone column falls below 250 DU in the vortex core and reaches latitudes of 70° N. Note that the inability of the model to reproduce the chemical signal of observed ozone depletion in the unperturbed calculation means one must be cautious in interpreting the model estimates for the Arctic.

These studies (Tilmes *et al.* 2008, submitted) thus indicate that geoengineering may have a significant impact on the ozone layer, with a possible decrease in ozone by an additional 40–50 DU when geoengineering is employed, and a possible delay of a few decades before the ozone recovery would begin again. More precise quantification of these effects will require a better specification of the aerosol evolution, and more realistic representations for the model dynamics and chemistry.

3. Summary, discussion and conclusions

Geoengineering by stratospheric aerosols as a possible means of mitigating the climate change associated with increased greenhouse gases has been reviewed. Sulphate aerosols in the stratosphere will increase the reflectivity of the planet and counteract some of the effects of CO₂ warming. Part of the attraction of using stratospheric aerosols arises because volcanic eruptions form a natural but imperfect analogue to geoengineering. Observations following major volcanic eruptions have demonstrated that sulphate aerosol, in sufficient amounts, will cool the planet, and that the Earth system can survive this kind of perturbation. Although the topic has been discussed over the last 30 years, only very recently have attempts been made to understand the interactions between various components of the climate system using modern tools for understanding climate consequences. These tools provide opportunities to quantify the interactions and consequences, and to explore those consequences on time scales that are much longer than the influence of a single volcanic eruption.

We have shown that state-of-the-art climate models used to simulate the Earth system produce the intended physical response to geoengineering, i.e. the Earth does cool, and many components of the system return to a state more like an unperturbed Earth. However,

- Our studies have shown that the delivery of aerosols or their precursors, at least using our hypothetical aircraft, is a formidable task. For the conservative scenarios we have explored, it would take of the order of a million flights of 4-hour duration (2500 km) per year to deliver the nominal

amount of aerosol ($10 \text{ Tg particles yr}^{-1} = 2.5 \text{ Tg S yr}^{-1}$) needed to balance the warming associated with increasing greenhouse gas emissions. These numbers are still quite rough, and it is possible that up to four times as much sulphur might be required. We have not investigated the entire spectrum of delivery systems. The issues and methodology we have suggested may be relevant to other proposed delivery systems (artillery shells, balloons, hoses, other aircraft), although details will certainly be different. It may be possible to design more efficient methods for delivery, but all will require careful attention to detail and the difficulty of designing a system that produces particles of the right size over broad regions of the stratosphere should not be underestimated.

- Although it is possible to cool the Earth to approximately the same globally averaged surface temperature, it is not likely that all aspects of the physical system will return to a state such as that prior to human-induced CO_2 increases. It is important to emphasize the uncertainties in our characterization of these issues. We have made initial exploratory forays into understanding the consequences of geoengineering, but much work remains to be done. The high sensitivity of polar regions to processes regulating energy in and out of the system would make it difficult to reproduce precisely the seasonal cycle of the polar climate for a pre-industrial (or even present day) world with geoengineering.

A recent study by Stenchikov *et al.* (2006) showed that models have difficulty in capturing the regional response of the climate system to volcanic eruptions. They argued that volcanoes' influence on the Arctic Annular Oscillation is associated with the extra heating in the equatorial lower stratosphere, changing the temperature gradient in the lower stratosphere vortex and producing stronger westerlies and a winter warming over northern Eurasia and North America. Models identified in that paper (which were reviewed in the IPCC report) tended to underestimate, and misplace the Northern Hemisphere winter surface temperature warming seen over Siberia in the observations following an eruption. This suggests that while the zeroth-order response of a surface cooling is likely to be robust, the first-order response of other components of the climate systems is a difficult problem and that model regional responses to stratospheric forcing changes must be viewed with caution.

As discussed in §2*d*, there are also hints that rainfall patterns would be different from an undisturbed Earth, although it is likely that they would be much closer to that distribution than in a world with $2\times\text{CO}_2$ and no geoengineering.

- An increase in aerosol burden is likely to increase ozone depletion. We have shown that current chemistry climate models have difficulty in reproducing quantitatively the dynamics and chemistry of the arctic middle atmosphere. Better coupled chemistry climate models would allow an improved estimate of ozone, sulphate aerosol and dynamical interactions. The first step is to improve the models' capability in reproducing present day ozone representation, particularly for the Northern Hemisphere.
- Reductions in ozone will lead to increases in solar ultraviolet-B radiation reaching the Earth's surface with a potential impact on human health (Ambach & Blumthaler 1993; Madronich & de Gruijl 1993) and biological populations (Blaustein *et al.* 1994). The increase in UV associated with ozone depletion could be compensated for by increased light extinction and attenuation by the aerosol

cloud itself; Vogelmann *et al.* (1992) and Wetzell *et al.* (2003) explored the compensation between these effects. Vogelmann *et al.* (1992) studied the effect for volcanic eruptions and concluded that, for stratospheric aerosol with an optical depth of 0.1–0.2 (approx. the value required for geoengineering), ozone and aerosol effects approximately compensated. At higher aerosol amounts, the aerosol attenuation did not balance the enhancement from ozone, and UV was enhanced at the surface. This kind of calculation should be repeated with a focus upon geoengineering and global warming, since ozone distributions and aerosol spatial and particle size distributions might differ significantly for geoengineering scenarios compared with their volcanic eruption counterpart.

- Gu *et al.* (2003) showed that volcanic aerosols from the Pinatubo eruption substantially increase diffuse radiation worldwide, with a resulting enhancement to photosynthesis and uptake of CO₂. The same effect is to be anticipated with the geoengineering shield. Govindasamy *et al.* (2002) explored some aspects of interactions between the physical Earth system and the biosphere. They showed that stabilizing the temperature but not CO₂ induced a change in Net Primary Productivity. Their study had a number of limitations as follows: (i) they used a prescribed CO₂ concentration, eliminating important feedbacks, (ii) they did not use a biospheric model that included nutrient limitation, (iii) they did not include an ocean biosphere, and (iv) their model was not sensitive to changes in the ratio of direct to diffuse radiation.

While ecosystems can survive occasional volcanic eruptions, it is not clear whether the consequences to ecosystems would be from long-term changes in direct/diffuse energy, or increases in UV radiation. These issues argue for more attention on the consequences of stratospheric aerosols to ecosystems.

The change in ratio of direct to diffuse radiation will also have an effect on solar energy production with technologies that make use of solar concentrators. Advances in solar energy production which operate efficiently in the presence of diffuse radiation are also possible, but a different technology is needed. Characterizing the consequences of geoengineering for these technologies is worthwhile.

- As mentioned in §§1 and 2*b,d*, larger aerosol particles exhibit significant absorption in the infrared part of the energy spectrum. The cooling resulting from the scattering of incoming solar energy is thus partly compensated for by the absorption in the infrared. The proclivity of this geoengineering method to form large particles makes it a less efficient solution than it would be if small particles were easily generated and maintained.
- There are also occasional concerns voiced about increases to acid rain from this type of geoengineering. We have shown that, although the perturbations to the stratospheric sulphur cycle are quite large (increasing the background sources there by a factor of 15–30), they are perhaps 2 per cent of the total (troposphere + stratosphere) sulphur sources. Therefore it is unlikely that geoengineering will have a significant impact on acid deposition and the global increment could easily be balanced by a small reduction in tropospheric emissions. On the other hand, it is possible that the deposition of the geoengineering aerosol could influence a region that normally sees little sulphate deposition from tropospheric sources if it occurs there. This should be looked into.

- It is obvious that current models of the sulphur cycle could be substantially improved. It would be desirable to move beyond the bulk aerosol formulations used here to models that included the evolution of the particle size distribution, accounting explicitly for aerosol growth and coagulation. This would include a mechanism to move from the source as determined by the delivery system, to evolution within the plume and finally to scales resolved by a global model.
- It is clear that this geoengineering method will not alleviate the problems engendered by absorption of CO₂ in the oceans, with a resulting decrease in ocean pH.

Substantial reductions in greenhouse gas emissions must take place soon to avoid large and undesirable climate impacts. This study has reviewed one technique that might be used in a planetary emergency to mitigate some of the effects of a projected global warming. We emphasize that, while the studies highlighted here are a step along the way, we believe no proposal (including the ideas explored here) has yet completed the series of steps required for a comprehensive and thoroughly studied geoengineering mitigation strategy occurring in the peer reviewed literature (Cicerone 2006). Our review of studies of geoengineering by sulphate aerosols suggests it will ameliorate some consequences of global warming. The study highlights some positive aspects of the strategy. However, many uncertainties remain in understanding the influence of geoengineering on the climate system (particularly on aspects related to likely impacts on the biosphere). More work is required to understand the costs, benefits and risks involved, and to reconcile the legal, political and ethical issues of geoengineering.

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References

- Ambach, W. & Blumthaler, M. 1993 Biological effectiveness of solar UV in humans. *Cell. Mol. Life Sci.* **49**, 747–753.
- Annamalai, H., Hamilton, K. & Sperber, K. R. 2007 South Asian summer monsoon and its relationship with ENSO in the IPCC AR4 simulations. *J. Climate* **20**, 1071–1092. (doi:10.1175/JCLI4035.1)
- Arnold, F., Kiendler, A., Wiedemer, V., Aberle, S., Stilp, T. & Busen, R. 2000 Chemiion concentration measurements in jet engine exhaust at the ground: implications for ion chemistry and aerosol formation in the wake of a jet aircraft. *Geophys. Res. Lett.* **27**, 1723–1726. (doi:10.1029/1999GL011096)
- Bauman, J. J., Russell, P. B., Geller, M. A. & Hamill, P. 2003 A stratospheric aerosol climatology from SAGE II and CLAES measurements: 2. Results and comparisons, 1984–1999. *J. Geophys. Res.* **108**, 4383. (doi:10.1029/2002JD002993)

- Bengtsson, L. 2006 Geo-engineering to confine climate change: is it at all feasible? *Clim. Change* **77**, 229–234. (doi:10.1007/s10584-006-9133-3)
- Blaustein, A. R., Hoffman, P. D., Hokit, D. G., Kiesecker, J. M., Walls, S. C. & Hays, J. B. 1994 UV repair and resistance to solar UV-B in amphibian eggs: a link to population declines? *Proc. Natl Acad. Sci. USA* **91**, 1791–1795. (doi:10.1073/pnas.91.5.1791)
- Brown, R. C., Miake-Lye, R. C., Anderson, M. R., Kolb, C. E. & Resch, T. J. 1996 Aerosol dynamics in near-field aircraft plumes. *J. Geophys. Res.* **101**, 22 939–22 953. (doi:10.1029/96JD01918)
- Budyko, M. I. 1974 *Izmeniia Klimata*. Gidrometeoizdat, also published as: Budyko, M. I. 1977 *Climatic changes* (transl. *Izmeniia Klimata* Leningrad: Gidrometeoizdat, 1974). Washington, DC: American Geophysical Union.
- Cicerone, R. J. 2006 Geoengineering: encouraging research and overseeing implementation. *Clim. Change* **77**, 221–226. (doi:10.1007/s10584-006-9102-x)
- Collins, W. D. et al. 2004 Description of the NCAR community atmosphere model: CAM3.0. Technical report NCAR/TN-464+STR, National Center for Atmospheric Research, Boulder, Colorado, USA, pp. 226. See <http://www.cesm.ucar.edu/models/atm-cam>.
- Collins, W. D. et al. 2006 The formulation and atmospheric simulation of the community atmosphere model: CAM3. *J. Climate* **19**, 2144–2161. (doi:10.1175/JCLI3760.1)
- Crutzen, P. J. 2006 Albedo enhancement by stratospheric sulfur injections: a contribution to resolve a policy dilemma? *Clim. Change* **77**, 211–220. (doi:10.1007/s10584-006-9101-y)
- Dürbeck, T. & Gerz, T. 1996 Dispersion of aircraft exhaust in the free troposphere. *J. Geophys. Res.* **101**, 26 007–26 015.
- Fahey, D. W. et al. 1995 Emission measurements of the Concorde supersonic aircraft in the lower stratosphere. *Science* **270**, 70–74. (doi:10.1126/science.270.5233.70)
- Fleming, J. R. 1990 *Meteorology in America, 1800–1870*, pp. 24–31. Baltimore, MD: Johns Hopkins University Press.
- Govindasamy, B. G. & Caldeira, K. 2000 Geoengineering Earth's radiation balance to mitigate CO₂-induced climate change. *Geophys. Res. Lett.* **27**, 2141–2144. (doi:10.1029/1999GL006086)
- Govindasamy, B. G. & Caldeira, K. 2003 Geoengineering Earth's radiation balance to mitigate climate change from a quadrupling of CO₂. *Glob. Planet. Change* **37**, 157–168. (doi:10.1016/S0921-8181(02)00195-9)
- Govindasamy, B. G., Thompson, S., Duffy, P., Caldeira, K. & Delire, C. 2002 Impact of geoengineering schemes on the terrestrial biosphere. *Geophys. Res. Lett.* **29**, 2061. (doi:10.1029/2002GL015911)
- Gu, L., Baldocchi, D. D., Wofsy, S. C., Munger, J. W., Michalsky, J. J., Urbanski, S. P. & Boden, T. A. 2003 Response of a deciduous forest to the Mount Pinatubo eruption: enhanced photosynthesis. *Science* **299**, 2035–2038. (doi:10.1126/science.1078366)
- Hoffert, M. I. et al. 1998 Energy implications of future stabilization of atmospheric CO₂ content. *Nature* **395**, 881–884. (doi:10.1038/27638)
- IPCC 2007a Summary for policymakers. In *Climate change 2007: the physical science basis. Contribution of working group I to the fourth assessment report of the Intergovernmental Panel on Climate Change* (eds S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. Avery, M. Tignor & H. Miller), pp. 1–18. Cambridge, UK: Cambridge University Press.
- IPCC 2007b Climate models and their evaluation. In *Climate change 2007: the physical science basis. Contribution of working group I to the fourth assessment report of the Intergovernmental Panel on Climate Change* (eds D. A. Randall et al.), pp. 589–662. Cambridge, UK: Cambridge University Press.
- IPCC 2007c Global climate projections In *Climate change 2007: the physical science basis. Contribution of working group I to the fourth assessment report of the Intergovernmental Panel on Climate Change* (eds G. A. Meehl et al.), ch. 10, pp. 749–845. Cambridge, UK: Cambridge University Press.
- Justus, C. G. & Mani, K. K. 1979 A model for the simulation of turbulent and eddy diffusion processes at heights of 0–65 km. *PAGEOPH* **117**, 513–530.

- Kärcher, B., Turco, R., Yu, F., Danilin, M., Weisenstein, D., Miake-Lye, R. & Busen, R. 2000 A unified model for ultrafine aircraft particle emissions. *J. Geophys. Res.* **105**, 29 379–29 386. (doi:10.1029/2000JD900531)
- Keith, D. W. 2000 Geoengineering the climate: history and prospect. *Annu. Rev. Energy Environ.* **25**, 245–284. (doi:10.1146/annurev.energy.25.1.245)
- Kiehl, J. T. 2006 Geoengineering climate change: treating the symptom over the cause? *Clim. Change* **77**, 227–228. (doi:10.1007/s10584-006-9132-4)
- Kinnison, D. E. *et al.* 2007 Sensitivity of chemical tracers to meteorological parameters in the MOZART-3 chemical transport model. *J. Geophys. Res.* **112**, D20302. (doi:10.1029/2006JD007879)
- Lawrence, M. J. 2006 The geoengineering dilemma: to speak or not to speak. *Clim. Change* **77**, 245–248. (doi:10.1007/s10584-006-9131-5)
- MacCracken, M. C. 2006 Geoengineering: worthy of cautious evaluation? *Clim. Change* **77**, 235–243. (doi:10.1007/s10584-006-9130-6)
- Madronich, S. & de Gruijl, F. R. 1993 Skin cancer and UV radiation. *Nature* **366**, 23. (doi:10.1038/366023a0)
- Matthews, H. D. & Caldeira, K. 2007 Transient climate-carbon simulations of planetary geoengineering. *Proc. Natl Acad. Sci. USA* **104**, 9949–9954. (doi:10.1073/pnas.0700419104)
- Montzka, S. A., Calvert, P., Hall, B. D., Elkins, J. W., Conway, T. J., Tans, P. P. & Sweeny, C. 2007 On the global distribution, seasonality, budget of atmospheric carbonyl sulfide (COS) and some similarities to CO₂. *J. Geophys. Res.* **112**, D09302. (doi:10.1029/2006JD007665)
- NAS92 1992 *Panel on Policy Implications of Greenhouse Warming, Committee on Science, Engineering and Public Policy: policy implications of greenhouse warming: mitigation, adaptation and the science base*. Washington, DC: National Academy Press.
- NASA-AEAP 1997 In *The atmospheric effects of subsonic aircraft: interim assessment report of the advanced subsonic technology program* (ed. R. R. Friedl), pp. 168. Washington, DC: NASA Reference Publication 1400.
- Newman, P. A., Nash, E. R., Kawa, S. R., Montzka, S. A. & Schauffler, S. M. 2006 When will the Antarctic ozone hole recover? *Geophys. Res. Lett.* **33**, L12814. (doi:10.1029/2005GL025232)
- Oman, L., Robock, A., Stenchikov, G. L., Schmidt, G. A. & Ruedy, R. 2005 Climatic response to high latitude volcanic eruptions. *J. Geophys. Res.* **110**, D13103. (doi:10.1029/2004D005487)
- Oman, L., Robock, A., Stenchikov, G. L. & Thordarson, T. 2006a High latitude eruptions cast shadow over the African monsoon and the flow of the Nile. *Geophys. Res. Lett.* **33**, L13711. (doi:10.1029/2006GL027665)
- Oman, L., Robock, A., Stenchikov, G. L., Thordarson, T., Koch, D., Shindell, D. & Gao, C. 2006b Modelling the distribution of the volcanic aerosol cloud from the 1783–1784 Laki eruptions. *J. Geophys. Res.* **111**, D12209. (doi:10.1029/2005JD0006899)
- Pinto, J. R., Turco, R. & Toon, O. 1998 Self-limiting physical and chemical effects in volcanic eruption clouds. *J. Geophys. Res.* **94**, 11 165–11 174. (doi:10.1029/JD094iD08p11165)
- Rasch, P. J., Barth, M., Kiehl, J. T., Benkovitz, C. M. & Schwartz, S. E. 2000 A description of the global sulfur cycle and its controlling processes in the National Center for Atmospheric Research Community Climate Model, version 3. *J. Geophys. Res.* **105**, 1367–1385. (doi:10.1029/1999JD900777)
- Rasch, P. J., Crutzen, P. J. & Coleman, D. B. 2008 Exploring the geoengineering of climate using stratospheric sulfate aerosols: the role of particle size. *Geophys. Res. Lett.* **35**, L02809. (doi:10.1029/2007GL032179)
- Robock, A. 2000 Volcanic eruptions and climate. *Rev. Geophys.* **38**, 191–219. (doi:10.1029/1998RG000054)
- Robock, A. 2008 Twenty reasons why geoengineering might be a bad idea. *Bull. Atom. Sci.* **64**, 14–18. (doi:10.2968/064002006)
- Robock, A., Oman, L. & Stenchikov, G. L. 2008 Regional climate responses to geoengineering with tropical and Arctic SO₂ injections. *J. Geophys. Res.* **113**, D16101. (doi:10.1029/2008JD010050)
- Schmidt, G. A. *et al.* 2006 Present day atmospheric simulations using GISS ModelE: comparisons to *in-situ*, satellite and reanalysis data. *J. Clim.* **19**, 153–193. (doi:10.1175/JCLI3612.1)

- Schumann, U., Schlager, H., Arnold, F., Bauman, R., Haschberger, P. & Klemm, O. 1998 Dilution of aircraft exhaust plumes at cruise altitudes. *Atmos. Environ.* **32**, 3097–3103. (doi:10.1016/S1352-2310(97)00455-X)
- Seinfeld, J. H. & Pandis, S. N. 1997 *Atmospheric chemistry and physics*. New York, NY: Wiley.
- Solomon, S. 1999 Stratospheric ozone depletion: a review of concepts and history. *Rev. Geophys.* **37**, 275–316. (doi:10.1029/1999RG900008)
- SPARC 2006 Assessment of stratospheric aerosol properties (ASAP). Technical report WCRP-124/WMO/TD-No. 1295/SPARC report no. 4, SPARC, Toronto, Ontario, CA, pp. 322.
- Steele, H. M. & Turco, R. P. 1997 Separation of aerosol and gas component in halogen occultation experiments and the stratospheric aerosol and gas experiment SAGE II extinction measurements: implications of SAGE II ozone concentrations and trends. *J. Geophys. Res.* **102**, 19 665–19 681. (doi:10.1029/97JD01263)
- Stenchikov, G. L., Kirchner, I., Robock, A., Graf, H. F., Antuna, J. C., Grainger, R. G., Lambert, A. & Thomason, L. 1998 Radiative forcing from the 1991 Mount Pinatubo volcanic eruption conditions. *J. Geophys. Res.* **103**, 13 837–13 857. (doi:10.1029/98JD00693)
- Stenchikov, G. A., Robock, A., Ramaswamy, V., Schwarzkopf, M. D., Hamilton, K. & Ramachandran, S. 2002 Arctic oscillation response to the 1991 Mount Pinatubo eruption: effect of volcanic aerosols and ozone depletion. *J. Geophys. Res.* **107**, 4803. (doi:10.1029/2002JD002090)
- Stenchikov, G., Hamilton, K., Stouffer, R. J., Robock, A., Ramaswamy, V., Santer, B. & Graf, H.-F. 2006 Arctic oscillation response to volcanic eruptions in the IPCC AR4 climate models. *J. Geophys. Res.* **111**, D07107. (doi:10.1029/2005JD0068286)
- Tilmes, S., Müller, R., Engel, A., Rex, M. & Russell III, J. M. 2006 Chemical ozone loss in the Arctic and Antarctic stratosphere between 1992 and 2005. *Geophys. Res. Lett.* **33**, LK20812. (doi:10.1029/2006GL026925)
- Tilmes, S., Müller, R., Salawitch, R. J., Schmidt, U., Webster, C. R., Oelhaf, H., Russell III, J. M. & Camy-Peyret, C. C. 2007 Chemical ozone loss in the Arctic winter 1991–1992. *Atmos. Chem. Phys.* **7**, 10 097–10 129.
- Tilmes, S., Müller, R. & Salawitch, R. 2008 The sensitivity of polar ozone depletion to proposed geo-engineering schemes. *Science* **320**, 1201–1204. (doi:10.1126/science.1153966)
- Tilmes, S., Garcia, R. R., Kinnison, E. D., Gettelman, A. & Rasch, P. J. Submitted. Impact of geo-engineered aerosols on troposphere and stratosphere using the whole atmosphere climate model WACCM3.
- Trenberth, K. E. & Dai, A. 2007 Effects of Mount Pinatubo volcanic eruption on the hydrological cycle as an analog of geoengineering. *Geophys. Res. Lett.* **34**, L15702. (doi:10.1029/2007GL030524)
- Turco, R. P. 1995 *Global environmental engineering: prospects and pitfalls*, ch. 7, pp. 93–113. Sudbury, MA: Jones and Bartlett.
- Turco, R. & Yu, F. 1997 Aerosol invariance in expanding coagulating plumes. *Geophys. Res. Lett.* **24**, 1223–1226. (doi:10.1029/97GL01092)
- Turco, R. & Yu, F. 1998 Aerosol size distribution in a coagulating plume: analytical behavior and modeling applications. *Geophys. Res. Lett.* **25**, 927–930. (doi:10.1029/98GL00324)
- Turco, R. & Yu, F. 1999 Particle size distributions in an expanding plume undergoing simultaneous coagulation and condensation. *J. Geophys. Res.* **104**, 19 227–19 241. (doi:10.1029/1999JD900321)
- Turco, R. P., Hamill, P., Toon, O. B., Whitten R. C. & Kiang, C. S. 1979 The NASA Ames Research Center stratospheric aerosol model. I. Physical processes and numerical analogs. NASA Technical Report No. 1362.
- Turco, R. P., Whitten, R. C., Toon, O. B., Pollack, J. B. & Hamill, P. 1980 OCS, stratospheric aerosols and climate. *Nature* **283**, 283–285. (doi:10.1038/283283a0)
- Vogelmann, A. M., Ackerman, T. P. & Turco, R. P. 1992 Enhancements in biologically effective ultraviolet radiation following volcanic eruptions. *Nature* **359**, 47–49. (doi:10.1038/359047a0)
- Wetzel, M. A., Shaw, G. E., Slusser, J. R., Borys, R. D. & Cahill, C. F. 2003 Physical, chemical, and ultraviolet radiative characteristics of aerosol in central Alaska. *J. Geophys. Res.* **108**, 4418. (doi:10.1029/2002JD00320)

- Wigley, T. M. L. 2006 A combined mitigation/geoengineering approach to climate stabilization. *Science* **314**, 452–454. (doi:10.1126/science.1131728)
- WRMSR 2007 Workshop report on managing solar radiation (eds L. Lane, K. Caldeira, R. Chatfield & S. Langhoff). NASA, NASA/CP-2007-214558, pp. 31.
- Yu, F. & Turco, R. 1997 The role of ions in the formation and evolution of particles in aircraft plumes. *Geophys. Res. Lett.* **24**, 1927–1930. (doi:10.1029/97GL01822)
- Yu, F. & Turco, R. 1998a Contrail formation and impacts on aerosol properties in aircraft plumes: effects of fuel sulfur content. *Geophys. Res. Lett.* **25**, 313–316. (doi:10.1029/97GL03695)
- Yu, F. & Turco, R. 1998b The formation and evolution of aerosols in stratospheric aircraft plumes: numerical simulations and comparisons with observations. *J. Geophys. Res.* **103**, 25 915–25 934. (doi:10.1029/98JD02453)
- Yu, F. & Turco, R. P. 1999 Evolution of aircraft-generated volatile particles in the far wake regime: potential contributions to ambient CCN/IN. *Geophys. Res. Lett.* **26**, 1703–1706. (doi:10.1029/1999GL900324)
- Yu, F. & Turco, R. P. 2001 From molecular clusters to nanoparticles: the role of ambient ionization in tropospheric aerosol formation. *J. Geophys. Res.* **106**, 4797–4814. (doi:10.1029/2000JD900539)



Sulfuric acid deposition from stratospheric geoengineering with sulfate aerosols

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[1] We used a general circulation model of Earth's climate to conduct geoengineering experiments involving stratospheric injection of sulfur dioxide and analyzed the resulting deposition of sulfate. When sulfur dioxide is injected into the tropical or Arctic stratosphere, the main additional surface deposition of sulfate occurs in midlatitude bands, because of strong cross-tropopause flux in the jet stream regions. We used critical load studies to determine the effects of this increase in sulfate deposition on terrestrial ecosystems by assuming the upper limit of hydration of all sulfate aerosols into sulfuric acid. For annual injection of 5 Tg of SO₂ into the tropical stratosphere or 3 Tg of SO₂ into the Arctic stratosphere, neither the maximum point value of sulfate deposition of approximately 1.5 mEq m⁻² a⁻¹ nor the largest additional deposition that would result from geoengineering of approximately 0.05 mEq m⁻² a⁻¹ is enough to negatively impact most ecosystems.

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1. Introduction

[2] Faced with the problem of climate change due to increasing global temperatures, some scientists and policy makers have suggested the deliberate modification of Earth's climate, an activity that has been termed geoengineering. There have been many different suggestions for geoengineering, both recently [e.g., Angel, 2006; Bower *et al.*, 2006] as well as historically [Fleming, 2007]. However, one method that has received a great deal of recent attention is the suggestion of Budyko [1974, 1977], Dickinson [1996], and Crutzen [2006] to inject gaseous aerosol precursors into the stratosphere. The creation of highly reflective sulfate aerosols in the lower stratosphere would result in some warming of the stratosphere, but the aerosol cloud would also tend to increase the planetary albedo, resulting in cooling of the troposphere and the surface [Rasch *et al.*, 2008a]. Rasch *et al.* [2008b] and Robock *et al.* [2008] calculated climate responses to this aerosol cloud using general circulation models.

[3] Geoengineering will, however, invariably have certain undesirable consequences. Tilmes *et al.* [2008] and Robock [2008a] discussed the negative impact these sulfate aerosols will have on polar stratospheric ozone. Robock [2008b] listed 20 potential side effects that could result from this

method. Our purpose here is to evaluate one of Robock's concerns, quantifying the amount of sulfur deposition that would result from two potential scenarios of geoengineering with sulfate aerosols. This is of concern because the sulfate aerosol can hydrate to form sulfuric acid, meaning geoengineering with sulfate aerosols can potentially result in an increase in acid deposition.

[4] Acid rain has been studied extensively in terms of its effects on ecosystems. Sulfur is a necessary nutrient for some plants, and the need to add sulfur to crops has long been recognized by farmers [Hart and Peterson, 1911]. However, an increase in sulfur deposition will not universally benefit ecosystems, especially ones that are poorly buffered against an increase in acidity. For example, excess acid can decrease or even eliminate freshwater fish populations [Leivestad and Muniz, 1976], cause foliar leaching [Wood and Bormann, 1975], affect plant-parasite interaction [Shriner, 1977], significantly reduce lake bacteria populations [Rao and Dutka, 1983], and, through forest dieback and reduced food supply, can affect forest bird communities [Graveland, 1998]. These, among other potential problems, could present significant ecological concerns, and serve as our motivation for the study of sulfate deposition due to geoengineering.

[5] Whether sulfate deposition (both dry and wet) is harmful depends on the amount of sulfur introduced into the system, the amount of sulfate that is hydrated to form sulfuric acid, and the sensitivity of the ecosystem. We will base our calculations on an upper limit, i.e., that all the sulfur deposition is sulfuric acid. This is likely an overestimation, since wet deposition in the model accounts for approximately 65% of total sulfate deposition, and dry deposition accounts for the remainder. Moreover, not all

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sulfate deposition will result in an increase in acid rain. Here we calculate how much additional sulfate would reach the surface from proposed geoengineering and compare this to critical load thresholds for different regions.

[6] As of now, most of the discussion of geoengineering with sulfate aerosols has focused on using SO_2 as the preferred sulfate aerosol precursor. Volcanic eruptions can inject a large pulse of SO_2 into the lower stratosphere, and previous geoengineering studies have considered volcanic eruptions as an analog of geoengineering. However, other precursors, such as hydrogen sulfide, carbonyl sulfide, and ammonium sulfate, could also potentially be used. Regardless, the important factor in determining sulfate deposition is the amount of sulfur injected into the stratosphere. As such, the results presented in this paper need only be scaled appropriately according to the aerosol precursor's molecular weight.

2. Experiment

[7] We studied geoengineering with stratospheric sulfate aerosols using ModelE, a general circulation model developed by the National Aeronautics and Space Administration Goddard Institute for Space Studies [Schmidt *et al.*, 2006]. We used the stratospheric version with 4° latitude by 5° longitude horizontal resolution and 23 vertical levels up to 80 km. It is fully coupled to a 4° latitude by 5° longitude dynamic ocean with 13 vertical levels [Russell *et al.*, 1995].

[8] The aerosol module [Koch *et al.*, 2006] accounts for SO_2 conversion to sulfate aerosols, as well as transport and removal of the aerosols. The chemical model calculates the sulfur cycle in the stratosphere, where the conversion rate of SO_2 to sulfate is based on the respective concentrations of SO_2 and the hydroxyl radical, the latter of which is prescribed [Oman *et al.*, 2006]. The dry aerosol effective radius is specified to be $0.25 \mu\text{m}$, and the model hydrates the aerosols on the basis of ambient humidity values, resulting in a distribution of hydrated aerosols with an effective radius of approximately $0.30\text{--}0.35 \mu\text{m}$. Radiative forcing from the aerosols is fully interactive with the atmospheric circulation.

[9] Koch *et al.* [2006] thoroughly analyzed the performance of ModelE concerning sulfur deposition from tropospheric sources. The model has some biases in that it produces 50–67% of the observed sulfur deposition in Europe and the east coast of the United States. In the western United States, the model overpredicts the actual amount by 50–100%, but that region has little sulfur deposition anyway. There are also some other local differences between model output and observed values, but none of these biases is in a location that will affect our conclusions.

[10] We proceeded with further analysis of climate simulations performed by Robock *et al.* [2008]. We began with a three-member control ensemble of 20-year runs over which time global greenhouse gas concentrations increased according to the Intergovernmental Panel on Climate Change's A1B scenario [IPCC, 2007]. The greenhouse gas concentrations at the beginning of the simulation were prescribed to be 2007 levels, and they increased to the A1B scenario's estimation of 2026 levels by the end of the simulation.

[11] In addition, we used two ensembles, each with three members of 20-year climate simulations, covering the same time period. One involved daily injections of SO_2 into the tropical lower stratosphere (longitude 120°E , latitude 0° , 16–23 km altitude) for a total of 5 Tg per year in addition to the forcing prescribed by the A1B scenario, and one involved daily injections of SO_2 into the Arctic lower stratosphere (longitude 120°E , latitude 68°N , 10–15 km altitude) for a total of 3 Tg per year in addition to the forcing prescribed by the A1B scenario. The value of 5 Tg per year was chosen to correspond to a Mount Pinatubo-sized eruption every 4 years, which was a value determined by Robock *et al.* [2008] as being sufficient to cause substantial enough cooling to offset the climatic effects of an increase in greenhouse gas concentrations. The smaller value of 3 Tg per year was also chosen by Robock *et al.*, since the goal of the original experiment was to limit the climate response only in the Arctic. The longitude value chosen is arbitrary and irrelevant, since the prevailing general circulation will transport the gas/aerosol cloud around the globe within a matter of weeks.

[12] The results of Robock *et al.* [2008] showed a globally averaged warming of approximately 0.5°C by 2026 over the current climate under the A1B scenario. Under the 3 Tg a^{-1} Arctic injection case, the globally averaged temperature immediately reduced to 2000 levels and only warmed 0.3°C over the current climate by 2026. Under the 5 Tg a^{-1} tropical injection case, the globally averaged temperature reduced to 1980 levels and held relatively constant at that level through 2026, resulting in cooling by 0.3°C .

3. Results

[13] Figure 1 shows the annual percent increase in total sulfate deposition, averaged over the second decade of geoengineering. In the tropical injection case, there is an increase in sulfate deposition over much of the globe, with the exception of the tropics (owing to poleward stratospheric transport before mixing into the troposphere). As expected, in the Arctic injection, the increase in deposition is mostly confined to the Northern Hemisphere. The majority of the increase is in the form of wet deposition (not shown). In the polluted midlatitudes of the Northern Hemisphere, the increases of sulfate deposition are not noticeable, but in pristine areas, such as Antarctica, they are readily apparent. Although all shaded values in Figure 1 are statistically significant at a 95% confidence level, for the Arctic injection case, many of the shaded values in the Southern Hemisphere are most likely due to weather noise.

[14] Since pristine areas, such as Antarctica, Greenland, and the Southern Pacific Ocean, received very little sulfate deposition in the baseline (A1B) case, additional deposition of tens of percent may not be consequential, so we must evaluate the actual amount of deposition. Figure 2 shows that the increases in actual deposition are strongest in midlatitude bands, some as high as $10^{-3} \text{ kg m}^{-2} \text{ a}^{-1}$, owing to strong cross-tropopause flux in the jet stream region. Downwind of large urban and industrial areas, we find the largest areas of absolute deposition, since these urban areas are a significant source of sulfate, but they are also the areas of the largest increase in deposition due to geoengineering because they are the jet exit regions, meaning the flux from

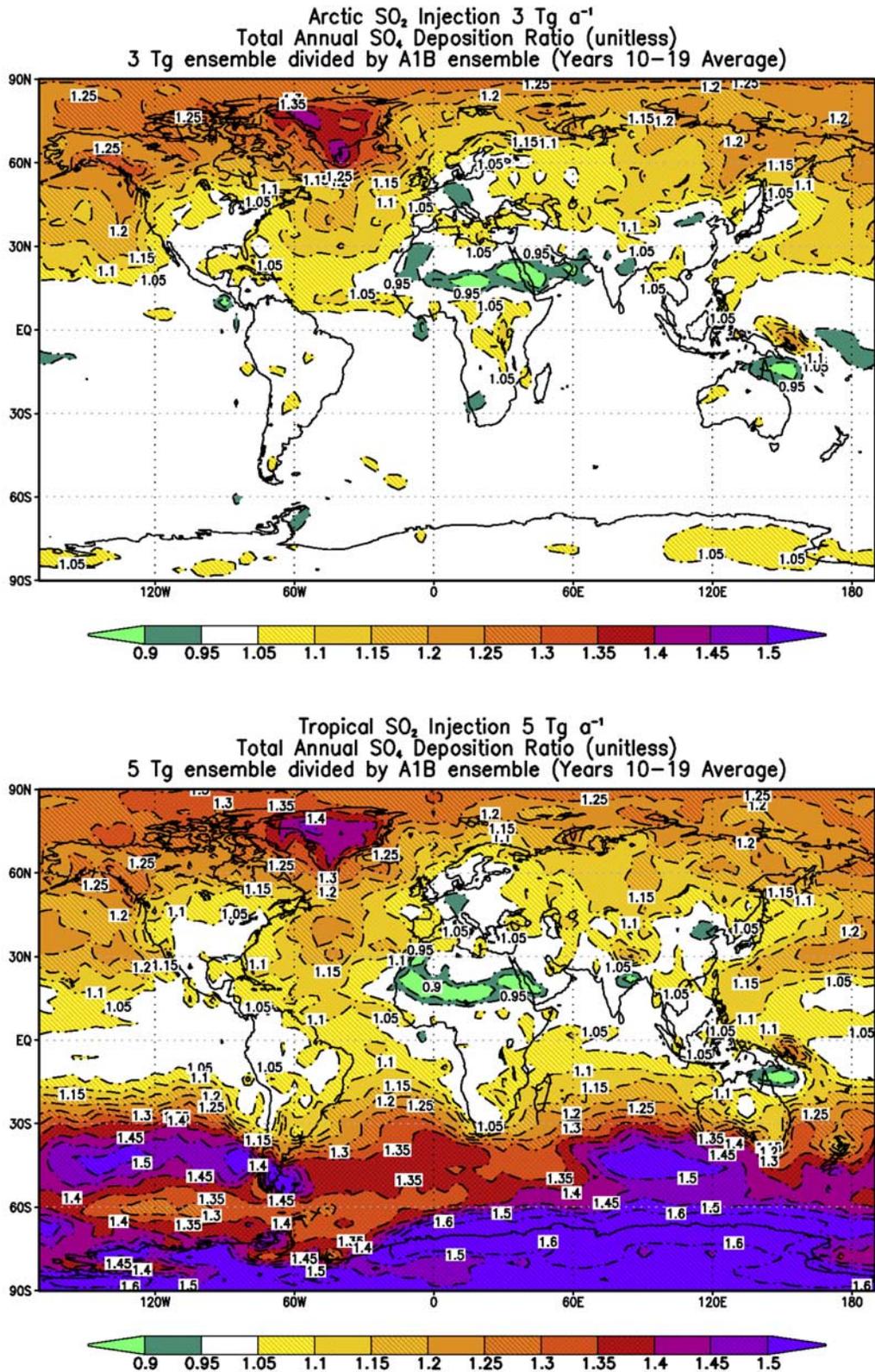


Figure 1. Ratios of the geoengineering ensembles of (top) Arctic 3 Tg SO₂ a⁻¹ injection and (bottom) tropical 5 Tg SO₂ a⁻¹ injection to the baseline (A1B) ensemble. Shown are annually averaged total sulfate deposition averaged over years 10–19 for each experiment. These plots are made from the model output of the climate simulations performed by Robock *et al.* [2008]. All shaded values are statistically significant at a 95% confidence level.

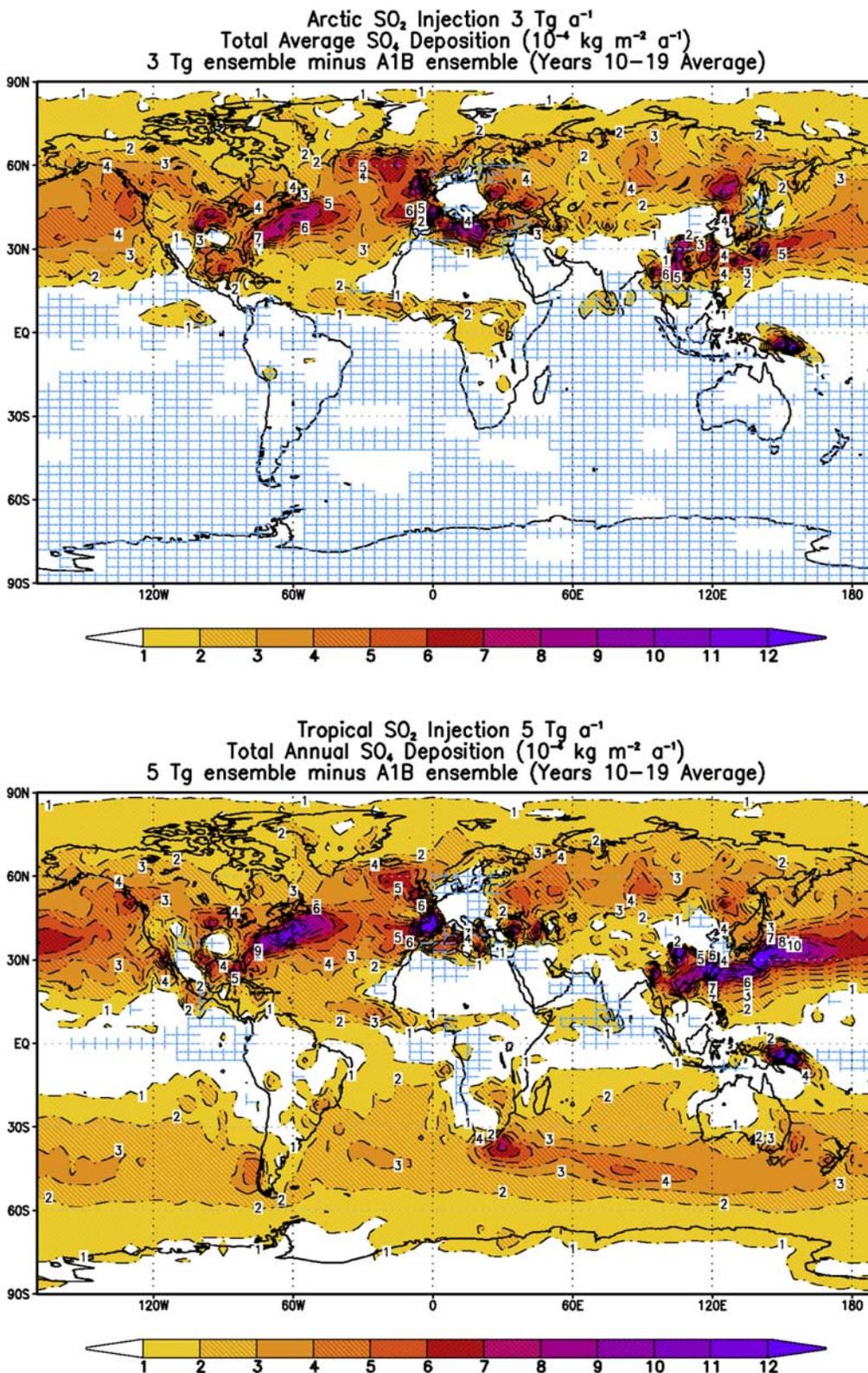


Figure 2. Annually averaged total sulfate deposition anomalies (injection minus baseline, revealing only the additional deposition from geoengineering) for the geoengineering scenarios of (top) Arctic 3 Tg SO₂ a⁻¹ and (bottom) tropical 5 Tg SO₂ a⁻¹ injection into the lower stratosphere. The results are averaged over three ensemble members and for years 10–19 of each experiment. These plots are made from the model output of the climate simulations performed by Robock *et al.* [2008]. Values not statistically significant at a 95% confidence level are denoted by blue hatching.

stratosphere to troposphere is comparatively large in these areas.

[15] For the purpose of establishing a reference value for comparison, the baseline surface sulfur emission levels are 135.8 Tg a^{-1} globally [Koch *et al.*, 2006]. Since the additional stratospheric injections are 1–2 orders of magnitude smaller, we might not expect them to be important in any case on a global basis. Dividing the surface emissions by the surface area of Earth, we get an average of $5.41 \times 10^{-5} \text{ kg m}^{-2} \text{ a}^{-1}$. Also according to Koch *et al.*, this sulfate has an average atmospheric lifetime of 6.2 days, meaning levels would be expected to be much higher than this reference value downwind of large urban and industrial areas and much lower (or practically negligible) in unpopulated areas.

[16] The notable absence of deposition over some of the continental areas (for example, the Sahara and Western Australia) is because most of the additional sulfate deposition is in the form of wet deposition, and these areas receive little rain. Other seeming gaps in deposition over continents are merely due to the values being small enough that they are obscured by the choice in contouring levels. Model bias may also play a certain role in either enhancing or obscuring these gaps, but we do not have sufficient information to make a detailed analysis of effects due to this.

[17] Figure 1 only shows annually averaged results. There are small regions of larger deposition for certain seasons, but the annual average is sufficient for this analysis. However, as greenhouse gas concentrations increase in the future, the strength of the Brewer-Dobson circulation will also increase, resulting in a shorter lifetime for stratospheric aerosols and the need for more sulfur to produce the same climate response [Rasch *et al.*, 2008b], which would cause an increase in sulfate deposition. We have not evaluated the effects that an increase in the strength of stratospheric circulation would have with regard to our study.

4. Impacts of Additional Acid Deposition

[18] The significance of the sulfate deposition increases depends on their potential effects on the ecosystems over which the deposition occurs. Section 5 is devoted to the potential effects on the ocean, so in this section, we concentrate on terrestrial ecosystems. Although the graphs only show sulfate deposition, for the purposes of establishing an upper limit to potential negative effects, we will assume that all sulfate due to geoengineering reacts to form sulfuric acid.

[19] *Kuylenstierna et al.* [2001] used a modeling approach to perform a critical load study on a global scale in which they rank areas by sensitivity to increased acid deposition, a value they determine by evaluating the buffering capacity of each region's soil. Our units of sulfate deposition, $\text{kg m}^{-2} \text{ a}^{-1}$, must be converted to the units used by *Kuylenstierna et al.* of $\text{mEq m}^{-2} \text{ a}^{-1}$. We use the definitions

$$\text{mEq} = \frac{\text{mass(grams)}}{\text{mEq mass(grams)}} \text{ and}$$

$$\text{mEq mass(grams)} = \frac{\text{atomic weight(g/mol)}}{\text{valence} \times 1000}.$$

[20] The SO_4^{2-} ion has atomic weight 96 g/mole and a valence of 2, giving us mEq mass (grams) of 0.048. So

$$\frac{1 \text{ kg}}{\text{m}^2 \cdot \text{a}} \cdot \frac{1000 \text{ g}}{1 \text{ kg}} \cdot \frac{1 \text{ mEq} \times 0.048}{1 \text{ g}} = 48 \frac{\text{mEq}}{\text{m}^2 \cdot \text{a}}.$$

[21] Figure 3 refers to the 5 Tg a^{-1} injection scenario. It shows total annual sulfate deposition (taken as an ensemble average over the second decade of geoengineering) and the annual sulfate deposition just due to geoengineering (injection minus baseline), both in terms of these new units. The 5 Tg a^{-1} injection scenario was chosen because it has larger sulfate deposition than the Arctic 3 Tg a^{-1} scenario, although the results presented in Figure 3 are similar for the Arctic 3 Tg a^{-1} injection case. The maximum point value for total deposition is approximately $1.5 \text{ mEq m}^{-2} \text{ a}^{-1}$, and the largest point value which is solely the result of geoengineering (injection minus baseline) is approximately $0.05 \text{ mEq m}^{-2} \text{ a}^{-1}$. According to the critical loading studies of *Kuylenstierna et al.* [2001], the most sensitive areas of the globe can receive $25\text{--}50 \text{ mEq m}^{-2} \text{ a}^{-1}$ of sulfate deposition before potentially being negatively impacted.

[22] In another study, *Skeffington* [2006] takes a very conservative approach to critical loading. He uses models for many of his results, but he also uses experimental and field evidence when available. In addition, his purpose is to estimate uncertainty in measurements of critical loading, so the low ends of his ranges for which loads are considered critical can be seen as conservative estimates.

[23] *Skeffington's* [2006] results are given in terms of $\text{kEq ha}^{-1} \text{ a}^{-1}$, so we must again perform a conversion:

$$\frac{1 \text{ kEq}}{\text{ha} \cdot \text{a}} \cdot \frac{10^6 \text{ mEq}}{1 \text{ kEq}} \cdot \frac{1 \text{ ha}}{10^4 \text{ m}^2} = 100 \frac{\text{mEq}}{\text{m}^2 \cdot \text{a}}.$$

These results, with our conversion factor taken into account, show that our values for acid deposition over a year, with the possible exception of poorly buffered terrestrial waterways, are well below critical loading levels (Table 1). In addition, the area in which the total sulfate deposition exceeds $1 \text{ mEq m}^{-2} \text{ a}^{-1}$ is, according to our model results, very small. However, because of our grid size, which is especially large when compared to the size of most terrestrial waterways, there may be localized areas of enhanced deposition from individual precipitation events that we cannot assess.

5. Ocean Acidification

[24] One well-known consequence of an increase in carbon dioxide concentrations in the atmosphere is an increase in the acidity of the oceans, as carbon dioxide dissolves in the oceans, forming carbonic acid. We wish to compare this resultant acidification with our results for sulfate deposition to further evaluate significance of our results.

[25] *Raven et al.* [2005] estimated that over 500 Gt ($5 \times 10^{17} \text{ g}$) of carbon dioxide has dissolved in the oceans over the past 200 years. Knowing that carbonic acid is a weak acid and that the atomic weight of carbon dioxide is 44 g/mol, we can put this value in terms of mEq by using our

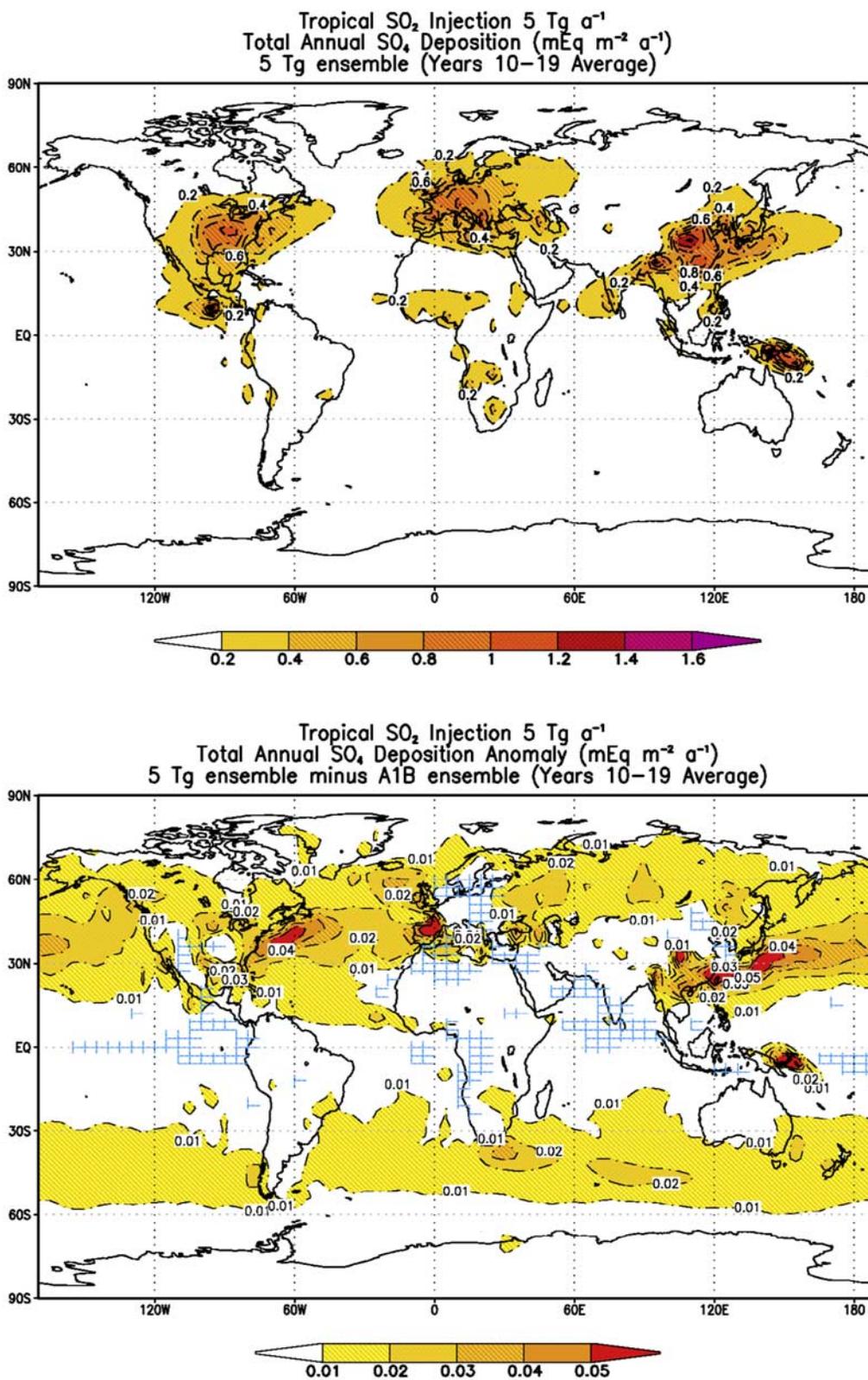


Figure 3. Results for a tropical 5 Tg a⁻¹ injection. (top) Total sulfate deposition (geoengineering plus baseline). (bottom) Sulfate deposition anomaly (injection minus baseline, revealing only the additional deposition from geoengineering). The largest total sulfate deposition point value is approximately 1.5 mEq m⁻² a⁻¹, and the largest anomaly point value is approximately 0.05 mEq m⁻² a⁻¹. These plots are made from the model output of the climate simulations performed by Robock *et al.* [2008], averaged over three ensemble members and years 10–19 for each experiment. Values not statistically significant at a 95% confidence level are denoted by blue hatching.

Table 1. Ranges of Critical Loading of Pollutant Deposition, Including Sulfur, for Various Sites in Europe as Reported by Skeffington [2006]

| Region | Critical Load (mEq m ⁻² a ⁻¹) |
|---|--|
| Coniferous forests in southern Sweden | 13–61 |
| Deciduous forests in southern Sweden | 15–72 |
| Varied sites in UK | 24–182 |
| Aber in north Wales | 32–134 |
| Uhlirska in Czech Republic | 260–358 |
| Fåråhall in Sweden | 29–134 |
| Several varied sites in China (sulfur only) | 63–880 |
| Waterways in Sweden | 1–44 |

previous definitions. Thus we conclude that 1×10^{19} mEq of carbon dioxide has dissolved in the ocean. Since the ocean covers approximately 70% of the Earth's surface, we can divide by the surface area covered by the ocean, as well as dividing by the 200 years over which this process occurred, to get

$$\frac{1 \times 10^{19}}{(0.7)(4\pi R_E^2)(200)} = 140 \text{ mEq m}^{-2} \text{ a}^{-1},$$

where R_E is the radius of Earth. This deposition is 2 orders of magnitude larger than our highest potential value of sulfuric acid deposition, again assuming all sulfate due to geoengineering is reacted to form sulfuric acid, leading us to conclude that the increase in acid deposition resulting from geoengineering with stratospheric sulfate aerosols is not enough to negatively impact the oceans.

6. Conclusions

[26] Analysis of our results and comparison to the results of Kuylensstierna et al. [2001] and Skeffington [2006] lead to the conclusion that the additional sulfate deposition that would result from geoengineering will not be sufficient to negatively impact most ecosystems, even under the assumption that all deposited sulfate will be in the form of sulfuric acid. However, although these model results are feasible, should geoengineering with sulfate aerosols actually be conducted, local results due to weather variability may differ from the results presented here. With the exception of terrestrial waterways, every region has a critical loading value a full order of magnitude above the largest potential total amount of acid deposition that would occur under the geoengineering scenarios presented in this paper. Furthermore, our results show that additional sulfate deposition tends to preferentially occur over oceans, meaning the chance of such a sensitive ecosystem receiving enough additional sulfate deposition to suffer negative consequences is very small.

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References

Angel, R. (2006), Feasibility of cooling the Earth with a cloud of small spacecraft near the inner Lagrange point (L1), *Proc. Natl. Acad. Sci. U. S. A.*, *103*, 17,184–17,189, doi:10.1073/pnas.0608163103.

- Bower, K., T. Choulaton, J. Latham, J. Sahaeri, and S. Salter (2006), Computational assessment of a proposed technique for global warming mitigation via albedo-enhancement of marine stratocumulus clouds, *Atmos. Res.*, *82*, 328–336, doi:10.1016/j.atmosres.2005.11.013.
- Budyko, M. I. (1974), *Climate and Life*, 508 pp., Academic Press, San Diego, Calif.
- Budyko, M. I. (1977), *Climatic Changes*, 261 pp., AGU, Washington, D. C.
- Crutzen, P. (2006), Albedo enhancement by stratospheric sulfur injections: A contribution to resolve a policy dilemma?, *Clim. Change*, *77*, 211–219, doi:10.1007/s10584-006-9101-y.
- Dickinson, R. E. (1996), Climate engineering: A review of aerosol approaches to changing the global energy balance, *Clim. Change*, *33*, 279–290, doi:10.1007/BF00142576.
- Fleming, J. R. (2007), The climate engineers, *Wilson Q.*, Spring, 46–60.
- Graveland, J. (1998), Effects of acid rain on bird populations, *Environ. Rev.*, *6*(1), 41–54, doi:10.1139/er-6-1-41.
- Hart, E. B., and W. H. Peterson (1911), The sulfur requirements of farm crops in relation to the soil and air supply, *J. Am. Chem. Soc.*, *33*(4), 549–564, doi:10.1021/ja02217a015.
- Intergovernmental Panel on Climate Change (IPCC) (2007), *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by S. Solomon et al., Cambridge Univ. Press, Cambridge, U. K.
- Koch, D., G. A. Schmidt, and C. V. Field (2006), Sulfur, sea salt, and radionuclide aerosols in GISS ModelE, *J. Geophys. Res.*, *111*, D06206, doi:10.1029/2004JD005550.
- Kuylensstierna, J. C. I., H. Rodhe, S. Cinderby, and K. Hicks (2001), Acidification in developing countries: Ecosystem sensitivity and the critical load approach on a global scale, *Ambio*, *30*, 20–28.
- Leivestad, H., and I. P. Muniz (1976), Fish kill at low pH in a Norwegian river, *Nature*, *259*, 391–392, doi:10.1038/259391a0.
- Oman, L., A. Robock, G. L. Stenchikov, T. Thordarson, D. Koch, D. T. Shindell, and C. Gao (2006), Modeling the distribution of the volcanic aerosol cloud from the 1783–1784 Laki eruption, *J. Geophys. Res.*, *111*, D12209, doi:10.1029/2005JD006899.
- Rao, S. S., and B. J. Dutka (1983), Influence of acid precipitation on bacterial populations in lakes, *Hydrobiologia*, *98*(2), 153–157, doi:10.1007/BF02185633.
- Rasch, P. J., et al. (2008a), An overview of geoengineering of climate using stratospheric sulphate aerosols, *Philos. Trans. R. Soc. A*, *366*, 4007–4037, doi:10.1098/rsta.2008.0131.
- Rasch, P. J., P. J. Crutzen, and D. B. Coleman (2008b), Exploring the geoengineering of climate using stratospheric sulfate aerosols: The role of particle size, *Geophys. Res. Lett.*, *35*, L02809, doi:10.1029/2007GL032179.
- Raven, J. A., et al. (2005), Ocean acidification due to increasing atmospheric carbon dioxide, policy document, 68 pp., R. Soc., London.
- Robock, A. (2008a), Whither geoengineering?, *Science*, *320*, 1166–1167, doi:10.1126/science.1159280.
- Robock, A. (2008b), 20 reasons why geoengineering may be a bad idea, *Bull. At. Sci.*, *64*(2), 14–18, 59, doi:10.2968/064002006.
- Robock, A., L. Oman, and G. Stenchikov (2008), Regional climate responses to geoengineering with tropical and Arctic SO₂ injections, *J. Geophys. Res.*, *113*, D16101, doi:10.1029/2008JD010050.
- Russell, G. L., J. R. Miller, and D. Rind (1995), A coupled atmosphere-ocean model for transient climate change, *Atmos. Ocean*, *33*, 683–730.
- Schmidt, G. A., et al. (2006), Present-day atmospheric simulations using GISS ModelE: Comparison to in situ, satellite and reanalysis data, *J. Clim.*, *19*, 153–192, doi:10.1175/JCLI3612.1.
- Shriner, D. S. (1977), Effects of simulated rain acidified with sulfuric acid on host-parasite interactions, *Water Air Soil Pollut.*, *8*, 9–14, doi:10.1007/BF00156719.
- Skeffington, R. A. (2006), Quantifying uncertainty in critical loads: (A) literature review, *Water Air Soil Pollut.*, *169*, 3–24, doi:10.1007/s11270-006-0382-6.
- Tilmes, S., R. Müller, and R. Salawitch (2008), The sensitivity of polar ozone depletion to proposed geoengineering schemes, *Science*, *320*, 1201–1204, doi:10.1126/science.1153966.
- Wood, T., and F. H. Bormann (1975), Increases in foliar leaching caused by acidification of an artificial mist, *Ambio*, *4*, 169–171.

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Benefits, risks, and costs of stratospheric geoengineering

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[1] Injecting sulfate aerosol precursors into the stratosphere has been suggested as a means of geoengineering to cool the planet and reduce global warming. The decision to implement such a scheme would require a comparison of its benefits, dangers, and costs to those of other responses to global warming, including doing nothing. Here we evaluate those factors for stratospheric geoengineering with sulfate aerosols. Using existing U.S. military fighter and tanker planes, the annual costs of injecting aerosol precursors into the lower stratosphere would be several billion dollars. Using artillery or balloons to loft the gas would be much more expensive. We do not have enough information to evaluate more exotic techniques, such as pumping the gas up through a hose attached to a tower or balloon system. Anthropogenic stratospheric aerosol injection would cool the planet, stop the melting of sea ice and land-based glaciers, slow sea level rise, and increase the terrestrial carbon sink, but produce regional drought, ozone depletion, less sunlight for solar power, and make skies less blue. Furthermore it would hamper Earth-based optical astronomy, do nothing to stop ocean acidification, and present many ethical and moral issues. Further work is needed to quantify many of these factors to allow informed decision-making. **Citation:** Robock, A., A. Marquardt, B. Kravitz, and G. Stenchikov (2009), Benefits, risks, and costs of stratospheric geoengineering, *Geophys. Res. Lett.*, 36, L19703, doi:10.1029/2009GL039209.

1. Introduction

[2] Global warming will continue for decades due to anthropogenic emissions of greenhouse gases and aerosols [Intergovernmental Panel on Climate Change (IPCC), 2007a], with many negative consequences for society [IPCC, 2007b]. Although currently impossible, as there are no means of injecting aerosols or their precursors into the stratosphere, the possibility of geoengineering the climate is now being discussed in addition to the conventional potential responses of mitigation (reducing emissions) and adaptation [IPCC, 2007c]. While originally suggested by Budyko [1974, 1977], Dickinson [1996], and many others (see Robock *et al.* [2008] and Rasch *et al.* [2008a] for a comprehensive list), Crutzen [2006] and Wigley [2006] rekindled interest in stratospheric geoengineering using sulfate aerosols. This proposal for “solar radiation management,” to reduce insolation with an anthropogenic stratospheric aerosol cloud in the same manner as episodic explosive volcanic eruptions,

will be called “geoengineering” here, recognizing that others have a more inclusive definition of geoengineering that can include tropospheric cloud modification, carbon capture and sequestration, and other proposed techniques.

[3] The decision to implement geoengineering will require a comparison of its benefits, dangers, and costs to those of other responses to global warming. Here we present a brief review of these factors for geoengineering. It should be noted that in the three years since Crutzen [2006] and Wigley [2006] suggested that, in light of no progress toward mitigation, geoengineering may be necessary to reduce the most severe impacts of global warming, there has still been no global progress on mitigation. In fact, Mauna Loa data show that the rate of CO₂ increase in the atmosphere is actually rising. However, the change of U.S. administration in 2009 has completely changed the U.S. policy on global warming. In the past eight years, the U.S. has stood in the way of international progress on this issue, but now President Obama is planning to lead a global effort toward a mitigation agreement in Copenhagen in December 2009. If geoengineering is seen as a potential low-cost and easy “solution” to the problem, the public backing toward a mitigation agreement, which will require some short-term dislocations, may be eroded. This paper, therefore, is intended to serve as useful information for that process.

[4] Crutzen [2006], Wigley [2006], and others who have suggested that geoengineering be considered as a response to global warming have emphasized that mitigation is the preferable response and that geoengineering should only be considered should the planet face a climate change emergency. However, there are no international governance mechanisms or standards that would allow the determination of such an emergency. Furthermore, should geoengineering begin, it would have to continue for decades, and the decision to stop would be even more difficult, what with commercial and employment interests in continuing the project as well as concerns for the additional warming that would result.

[5] Robock [2008a] presented 20 reasons why geoengineering may be a bad idea. Those reasons are updated here. However, there would also be benefits of geoengineering, against which the risks must be weighed. So first we discuss those benefits, then the risks, and finally the costs. As the closest natural analog, examples from the effects of volcanic eruptions are used to illustrate the benefits and costs.

2. Benefits

[6] The benefits of stratospheric geoengineering are listed in Table 1. Both observations of the response of climate to large explosive volcanic eruptions [Robock, 2000] and all modeling studies conducted so far [e.g., Teller *et al.*, 1997, 1999, 2002; Govindasamy and Caldeira, 2000; Govindasamy

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Table 1. Benefits and Risks of Stratospheric Geoengineering^a

| Benefits | Risks |
|--|---|
| 1. Cool planet | 1. Drought in Africa and Asia |
| 2. Reduce or reverse sea ice melting | 2. Continued ocean acidification from CO ₂ |
| 3. Reduce or reverse land ice sheet melting | 3. Ozone depletion |
| 4. Reduce or reverse sea level rise | 4. No more blue skies |
| 5. Increase plant productivity | 5. Less solar power |
| 6. Increase terrestrial CO ₂ sink | 6. Environmental impact of implementation |
| | 7. Rapid warming if stopped |
| | 8. Cannot stop effects quickly |
| | 9. Human error |
| | 10. Unexpected consequences |
| | 11. Commercial control |
| | 12. Military use of technology |
| | 13. Conflicts with current treaties |
| | 14. Whose hand on the thermostat? |
| | 15. Ruin terrestrial optical astronomy |
| | 16. Moral hazard – the prospect of it working would reduce drive for mitigation |
| | 17. Moral authority – do we have the right to do this? |

^aThe right column is an update of Robock [2008a].

et al., 2002, 2003; Wigley, 2006; Rasch *et al.*, 2008a, 2008b; Robock *et al.*, 2008; Lenton and Vaughan, 2009] show that with sufficient stratospheric sulfate aerosol loading, back-scattered insolation will cool Earth. The amount of cooling depends on the amount of aerosols and how long the aerosol cloud is maintained in the stratosphere. Many negative impacts of global warming are strongly correlated with global average surface air temperature, so it would in theory be possible to stop the rise of global-average temperature or even lower it, thus ameliorating these impacts. For example, reduced temperature would slow or reverse the current downward trend in Arctic sea ice, the melting of land glaciers, including Greenland, and the rise of sea level.

[7] Observations after large volcanic eruptions show that stratospheric sulfate aerosols drastically change the partitioning of downward solar flux into direct and diffuse [Robock, 2000]. After the 1982 El Chichón eruption, observations at the Mauna Loa Observatory in Hawaii on mornings with clear skies, at a solar zenith angle of 60° equivalent to two relative air masses, showed a peak change of downward direct insolation, from 515 W m⁻² to 340 W m⁻², while diffuse radiation increased from 40 W m⁻² to 180 W m⁻² [Robock, 2000]. A similar effect was observed after the 1991 Mt. Pinatubo eruption. While the change of net radiation after El Chichón was a reduction of 35 W m⁻², this shift to an increase of the diffuse portion actually produced an increase of the growth of terrestrial vegetation, and an increase in the terrestrial CO₂ sink. Gu *et al.* [1999, 2002, 2003], Roderick *et al.* [2001], and Farquhar and Roderick [2003] suggested that increased diffuse radiation allows plant canopies to photosynthesize more efficiently, increasing the CO₂ sink. Gu *et al.* [2003] actually measured this effect in trees following the 1991 Pinatubo eruption. While some of the global increase in CO₂ sinks following volcanic eruptions may have been due to the direct temperature effects of the eruptions, Mercado *et al.* [2009] showed that the diffuse radiation effect produced an increase sink of about 1 Pg C a⁻¹ for about one year following the Pinatubo eruption. The effect of a

permanent geoengineering aerosol cloud would depend on the optical depth of the cloud, and these observed effects of episodic eruptions may not produce a permanent vegetative response as the vegetation adjusts to this changed insolation. Nevertheless, this example shows that stratospheric geoengineering may provide a substantial increased CO₂ sink to counter anthropogenic emissions. This increase in plant productivity could also have a positive effect on agriculture.

3. Risks

[8] The potential benefits of stratospheric geoengineering must be evaluated in light of a large number of potential negative effects [Robock, 2008a]. While most of those concerns are still valid, three of them can now be removed. As discussed above, the effects of the change in diffuse and direct radiation on plants would in general be positive. Kravitz *et al.* [2009] have shown that the excess sulfate acid deposition would not be enough to disrupt ecosystems. And below we show that there are potentially airplane-based injection systems that would not be overly costly as compared to the cost of mitigation. But there still remains a long list of negative effects (Table 1).

[9] Two of the reasons in the list have been strengthened by recent work. Tilmes *et al.* [2008] used a climate model to show that indeed stratospheric geoengineering would produce substantial ozone depletion, prolonging the end of the Antarctic ozone hole by several decades and producing ozone holes in the Arctic in springs with a cold lower stratosphere. Murphy [2009] used observations of direct solar energy generation in California after the 1991 Pinatubo eruption and showed that generation went from 90% of peak capacity in non-volcanic conditions to 70% in summer 1991 and to less than 60% in summer 1992.

[10] One additional problem with stratospheric geoengineering has also become evident. There would be a major impact on terrestrial optical astronomy. Astronomers spend billions of dollars to build mountain-top observatories to get above pollution in the lower troposphere. Geoengineering would put permanent pollution above these telescopes.

4. Costs

[11] Robock [2008a] suggested that the construction and operation of a system to inject aerosol precursors into the stratosphere might be very expensive. Here we analyze the costs of three suggested methods of placing the aerosol precursors into the stratosphere: airplanes, artillery shells, and stratospheric balloons (Figure 1 and Table 2). Because such systems do not currently exist, the estimates presented here are rough but provide quantitative starting points for further discussions of the practicality of geoengineering. Even if sulfate aerosol precursors could be injected into the stratosphere, it is not clear that aerosols could be created of a size range with an effective radius of about 0.5 μm, like volcanic aerosols, that would be effective at cooling the planet. Some of these issues were discussed by Rasch *et al.* [2008a]. Can injectors be designed to give appropriate initial aerosol sizes? If injected into an existing sulfate cloud, would the existing aerosols just grow at the expense



Figure 1. Proposed methods of stratospheric aerosol injection. A mountain top location would require less energy for lofting to stratosphere. Drawing by Brian West.

of smaller ones? These important topics are currently being investigated by us, and here we limit the discussion to just getting the precursor gases into the stratosphere.

[12] Figure 1 is drawn with the injection systems on a mountain and with the supplies arriving up the mountain by train. If the injection systems were placed on a mountain top, the time and energy needed to get the material from the surface to the stratosphere would be less than from sea level.

Gunnbjorn Mountain, Greenland, is the highest point in the Arctic, reaching an altitude of 3700 m. In the tropics, there are multiple high altitude locations in the Andes.

[13] The 1991 Mt. Pinatubo eruption injected 20 Tg SO₂ into the tropical lower stratosphere [Bluth *et al.*, 1992], which formed sulfate aerosols and cooled the climate for about two years. As discussed by Robock *et al.* [2008], the equivalent of one Pinatubo every 4–8 years would be

Table 2. Costs for Different Methods of Injecting 1 Tg of a Sulfur Gas Per Year Into the Stratosphere^a

| Method | Payload (tons) | Ceiling (km) | Number of Units | Purchase Price (2008 Dollars) | Annual Cost |
|------------------------|----------------|--------------|------------------------|-------------------------------|-----------------------------------|
| F-15C Eagle | 8 | 20 | 167 with 3 flights/day | \$6,613,000,000 | \$4,175,000,000 ^b |
| KC-135 Tanker | 91 | 15 | 15 with 3 flights/day | \$784,000,000 | \$375,000,000 |
| KC-10 Extender | 160 | 13 | 9 with 3 flights/day | \$1,050,000,000 | \$225,000,000 ^b |
| Naval Rifles | 0.5 | | 8,000 shots per day | included in annual cost | \$30,000,000,000 |
| Stratospheric Balloons | 4 | | 37,000 per day | included in annual cost | \$21,000,000,000–\$30,000,000,000 |

^a Airplane data from Air Combat Command (2008), Air Mobility Command (2008a, 2008b). See text for sources of data for airplanes. Costs in last two lines from COSEPUP [1992]. Conversion from 1992 and 1998 dollars to 2008 dollars (latest data available) using the Consumer Price Index (<http://www.measuringworth.com/uscompare/>).

^b If operation costs were the same per plane as for the KC-135.



a.



b.

Figure 2. U.S. military planes that could be used for geoengineering. (a) F-15C Eagle (<http://www.af.mil/shared/media/photodb/photos/060614-F-8260H-310.JPG>), (b) KC-10 Extender (http://www.af.mil/shared/media/factsheet/kc_10.jpg).

required to stop global warming or even reduce global temperature in spite of continued greenhouse gas emissions.

[14] While volcanic eruptions inject mostly SO_2 into the stratosphere, the relevant quantity is the amount of sulfur. If H_2S were injected instead, it would oxidize quickly to form SO_2 , which would then react with water to form H_2SO_4 droplets. Because of the relative molecular weights, only 2.66 Tg of H_2S (molecular weight 34 g mol^{-1}) would be required to produce the same amount of sulfate aerosols as 5 Tg of SO_2 (molecular weight 64 g mol^{-1}). Since there are choices for the desired sulfate aerosol precursor, our calculations will be in terms of stratospheric injection of any gas. H_2S , however, is more corrosive than SO_2 [e.g., Kleber *et al.*, 2008] and is very dangerous, so it would probably not be the gas of choice. Exposure to 50 ppm of H_2S can be fatal [Kilburn and Warshaw, 1995]. H_2S was even used for a time as a chemical warfare agent in World War I [Croddy *et al.*, 2001]. However, 100 ppm of SO_2 is also considered “immediately dangerous to life and health” [Agency for Toxic Substances and Disease Registry, 1998].

[15] If the decision were ever made to implement geoengineering, the amount of gas to loft, the timing and location of injections, and how to produce aerosols, would have to be considered, and these are issues we address in

other work [Rasch *et al.*, 2008a]. Here we just examine the question of the cost of lofting 1 Tg of a sulfur gas per year into the stratosphere. Other more speculative geoengineering suggestions, such as engineered aerosols [e.g., Teller *et al.*, 1997], are not considered here.

[16] Our work is an update and expansion of the first quantitative estimates by *Committee on Science Engineering and Public Policy (COSEPUP)* [1992]. While they listed “Stratospheric Bubbles; Place billions of aluminized, hydrogen-filled balloons in the stratosphere to provide a reflective screen; Low Stratospheric Dust; Use aircraft to maintain a cloud of dust in the low stratosphere to reflect sunlight; Low Stratospheric Soot; Decrease efficiency of burning in engines of aircraft flying in the low stratosphere to maintain a thin cloud of soot to intercept sunlight” among the possibilities for geoengineering, they did not evaluate the costs of aircraft or stratospheric bubble systems.

[17] Rather than cooling the entire planet, it has been suggested that we only try to modify the Arctic to prevent a sea ice-free Arctic summer and to preserve the ice sheets in Greenland while mitigation is implemented [Lane *et al.*, 2007; Caldeira and Wood, 2008]. A disadvantage of Arctic injection is that the aerosols would only last a few months rather than a couple years for tropical injection [Robock *et al.*, 2008]. An advantage is that they would only need to be injected in spring, so their strongest effects would occur over the summer. They would have no effect in the dark winter. One important difference between tropical and Arctic injections is the height of the tropopause, which is about 16 km in the tropics but only about 8 km in the Arctic. These different heights affect the capability of different injection schemes to reach the lower stratosphere, and we consider both cases here.

[18] In addition to these costs would be the cost of the production and transport to the deployment point of the sulfur gas. *COSEPUP* [1992] estimated the price of SO_2 to be \$50,000,000 per Tg in 1992 dollars, and H_2S would be much cheaper, as it is currently removed from oil as a pollutant, so the price of the gases themselves would be a minor part of the total. The current bulk price for liquid SO_2 is \$230/ton or \$230,000,000 per Tg [Chemical Profiles, 2009].

4.1. Airplanes

[19] Existing small jet fighter planes, like the F-15C Eagle (Figure 2a), are capable of flying into the lower stratosphere in the tropics, while in the Arctic, larger planes, such as the KC-135 Stratotanker or KC-10 Extender (Figure 2b), are capable of reaching the required altitude. Specialized research aircraft such as the American Lockheed ER-2 and the Russian M55 Geophysica, both based on Cold War spy planes, can also reach 20 km, but neither has a very large payload or could be operated continuously to deliver gases to the stratosphere. The Northrop Grumman RQ-4 Global Hawk can reach 20 km without a pilot but costs twice as much as an F-15C. Current designs have a payload of 1–1.5 tons. Clearly it is possible to design an autonomous specialized aircraft to loft sulfuric acid precursors into the lower stratosphere, but the current analysis focuses on existing aircraft.

[20] Options for dispersing gases from planes include the addition of sulfur to the fuel, which would release the

aerosol through the exhaust system of the plane, or the attachment of a nozzle to release the sulfur from its own tank within the plane, which would be the better option. Putting sulfur in the fuel would have the problem that if the sulfur concentration were too high in the fuel, it would be corrosive and affect combustion. Also, it would be necessary to have separate fuel tanks for use in the stratosphere and in the troposphere to avoid sulfate aerosol pollution in the troposphere.

[21] The military has already manufactured more planes than would be required for this geoengineering scenario, potentially reducing the costs of this method. Since climate change is an important national security issue [Schwartz and Randall, 2003], the military could be directed to carry out this mission with existing aircraft at minimal additional cost. Furthermore, the KC-135 fleet will be retired in the next few decades as a new generation of aerial tankers replaces it, even if the military continues to need the in-flight refueling capability for other missions.

[22] Unlike the small jet fighter planes, the KC-135 and KC-10 are used to refuel planes mid-flight and already have a nozzle installed. In the tropics, one option might be for the tanker to fly to the upper troposphere, and then fighter planes would ferry the sulfur gas up into the stratosphere (Figure 2b). It may also be possible to have a tanker tow a glider with a hose to loft the exit nozzle into the stratosphere.

[23] In addition to the issues of how to emit the gas as a function of space and time to produce the desired aerosols, another concern is the maximum concentration of sulfate aerosols through which airplanes can safely fly. In the past, noticeable damage has occurred to airplanes that fly through plumes of volcanic ash containing SO_2 . In June, 1982, after the eruption of Galunggung volcano in Java, Indonesia, two passenger planes flew through a volcanic cloud. In one case the windows were pitted, volcanic ash entered the engines and thrust was lost in all four engines. In the other case, the same thing happened, with the plane descending 7.5 km before the engines could be restarted [McClelland *et al.*, 1989]. While the concentration of sulfate in the stratosphere would be less than in a plume like this, and there would be no ash, there could still be sulfuric acid damage to airplanes. In the year after the 1991 Pinatubo eruption, airplanes reported acid damage to windows and other parts. An engineering study would be needed to ascertain whether regular flight into a stratospheric acid cloud would be safe, and how much harm it would do to airplanes.

[24] The calculations for airplanes are summarized in Table 2. We assume that the sulfur gas will be carried in the cargo space of the airplane, completely separate from the fuel tank. The cost of each plane comes from Air Combat Command (F-15 Eagle, Air Force Link Factsheets, 2008, available at <http://www.af.mil/information/factsheets/factsheet.asp?id=101>) for the F-15C (\$29.9 million), Air Mobility Command (KC-10 Extender, Air Force Link Factsheets, 2008, available at <http://www.af.mil/information/factsheets/factsheet.asp?id=109>) for the KC-10 (\$88.4 million), and Air Mobility Command (KC-135 Stratotanker, Air Force Link Factsheets, 2008, available at <http://www.af.mil/information/factsheets/factsheet.asp?id=110>) for the KC-135 (\$39.6 million), in 1998 dollars, and in Table 2 is then converted to 2008 dollars (latest data available) by multiply-

ing by a factor of 1.32 using the Consumer Price Index (S. H. Williamson, Six ways to compute the relative value of a U.S. dollar amount, 1774 to present, MeasuringWorth, 2008, available at <http://www.measuringworth.com/uscompare/>). If existing aircraft were converted to geoengineering use, the cost would be much less and would only be for retrofitting of the airplanes to carry a sulfur gas and installation of the proper nozzles. The annual cost per aircraft for personnel, fuel, maintenance, modifications, and spare parts for the older E model of the KC-135 is \$4.6 million, while it is about \$3.7 million for the newer R model, based on an average of 300 flying hours per year [Curtin, 2003].

[25] We postulate a schedule of three flights per day, 250 days per year, for each plane. If each flight were 2 hours, this would be 1500 hours per year. As a rough estimate, we take \$5 million per 300 hours times 5, or \$25 million per year in operational costs per airplane. If we use the same estimates for the KC-10 and the F-15C, we can get an upper bound on the annual costs for using these airplanes for geoengineering, as we would expect the KC-10 to be cheaper, as it is newer than the KC-135, and the F-15C to be cheaper, just because it is smaller and would require less fuel and fewer pilots.

4.2. Artillery Shells

[26] COSEPUP [1992] made calculations using 16-inch (41-cm) naval rifles, assuming that aluminum oxide (Al_2O_3) dust would be injected into the stratosphere. They envisaged 40 10-barrel stations operating 250 days per year with each gun barrel replaced every 1500 shots. To place 5 Tg of material into the stratosphere, they estimated the annual costs, including ammunition, gun barrels, stations, and personnel, as \$100 billion (1992 dollars), with the cost of the Al_2O_3 only \$2.5 million of the total. So the cost for 1 Tg would be \$30 billion (2008 dollars). It is amusing that they conclude, with a total lack of irony, "The rifles could be deployed at sea or in empty areas (e.g., military reservations) where the noise of the shots and the fallback of expended shells could be managed."

4.3. Stratospheric Balloons

[27] Requiring no fuel, weather balloons are launched on a daily basis to high levels of the atmosphere. Balloons can be made out of either rubber or plastic, but plastic would be needed due to the cold temperatures at the tropical tropopause or in the Arctic stratosphere, as rubber balloons would break prematurely. Weather balloons are typically filled with helium, but hydrogen (H_2) is less expensive and more buoyant than helium and can also be used safely to inflate balloons.

[28] Balloons could be used in several ways for geoengineering. As suggested by L. Wood (personal communication, 2008), a tethered balloon could float in the stratosphere, suspending a hose to pump gas upwards. Such a system has never been demonstrated and should probably be included in the next section of this paper on exotic future ideas. Another idea is to use aluminized long-duration balloons floating as reflectors [Teller *et al.*, 1997], but again, such a system depends on future technology development. Here we discuss two options based on current technology: lofting a payload under a balloon or mixing H_2 and H_2S inside a balloon. In the first case, the additional mass of the balloon and its gas would be a weight penalty,

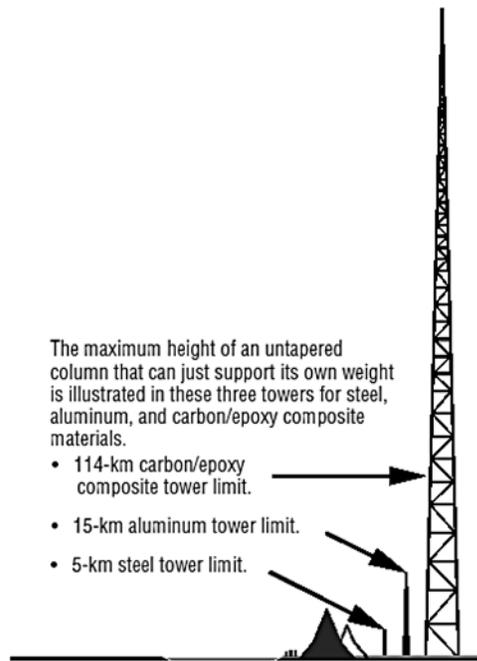


Figure 3. The maximum height of an untapered tower that can support its own weight, showing that one tower on the Equator could be used for stratospheric geoengineering. (From “Space Elevator Schematics” page at end of *Smitherman* [2000]).

but in the second case, when the balloons burst, the H_2S would be released into the stratosphere.

[29] *COSEPUP* [1992] discussed a system to loft a payload under large H_2 balloons, smaller multi-balloon systems, and hot air balloons. To inject 1 Tg of H_2S into the stratosphere with H_2 balloons, the cost including balloons, dust, dust dispenser equipment, hydrogen, stations, and personnel, was estimated to be \$20 million, which would be \$30 million in 2008 dollars. Hot air balloon systems would cost 4 to 10 times that of using H_2 balloons.

[30] We examined another idea, of mixing H_2 and H_2S inside a balloon, and then just releasing the balloons to rise themselves and burst in the stratosphere, releasing the gases. The H_2S would then oxidize to form sulfate aerosols, but the H_2 would also have stratospheric impacts. Since H_2S has a molecular weight of 34 g/mol, as compared to 29 g/mol for air, by mixing it with H_2 , balloons can be made buoyant. The standard buoyancy of weather balloons as compared to air is 20%. The largest standard weather balloon available is model number SF4-0.141-.3/0-T from Aerostar International, with a maximum volume of 3990 m^3 , and available in quantities of 10 or more for \$1,711 each. The balloons would burst at 25 mb.

[31] To calculate the mix of gases, if the temperature at 25 mb is 230 K and the balloon is filled at the surface at a pressure of 1000 mb and a temperature of 293 K, then the volume of the balloon would be:

$$V = 3990 \text{ m}^3 \times \frac{25 \text{ mb}}{1000 \text{ mb}} \times \frac{293 \text{ K}}{230 \text{ K}} = 127 \text{ m}^3 \quad (1)$$

The mass of air displaced would be:

$$m = \frac{pV}{RT} = \frac{1000 \text{ mb} \times 127 \text{ m}^3}{287 \frac{\text{J}}{\text{kg K}} \times 293 \text{ K}} = 151 \text{ kg} \quad (2)$$

To produce the required buoyancy, the balloon with its mixture of H_2 and H_2S would have a mass $m' = m/1.2 = 125.9 \text{ kg}$. Normally a weather balloon is filled with He, allowing it to lift an additional payload beneath it. In our case, the payload will be the H_2S inside the balloon. Since each balloon has a mass of 11.4 kg, the total mass of the gases would be 114.5 kg. To produce that mass in that volume would require a mixture of 37.65% H_2 and 62.35% H_2S by volume, for a total mass of H_2S of 110.6 kg. To put 1 Tg of gas into the stratosphere per year would therefore require 9 million balloons, or 36,000 per day (using 250 days per year). This would cost \$15.5 billion per year just for the balloons. According to *COSEPUP* [1992], the additional costs for infrastructure, personnel, and H_2 would be \$3,600,000,000 per year, or \$5.5 billion in 2008 dollars, for their balloon option, and as rough guess we adopt it for ours, too. So our balloon option would cost \$21 billion per year in 2008 dollars.

[32] The option above would also inject 0.04 Tg H_2 into the stratosphere each year. This is 2 to 3 orders of magnitude less than current natural and anthropogenic H_2 emissions [*Jacobson*, 2008], so would not be expected to have any detectable effects on atmospheric chemistry.

[33] Because about 1/10 of the mass of the balloons would actually be the balloons, this would mean 100 million kg of plastic falling to Earth each year. As *COSEPUP* [1992] said, “The fall of collapsed balloons might be an annoying form of trash rain.”

[34] We repeated the above calculations using SO_2 . Since SO_2 has a molecular weight of 64 g/mol, it would require a much higher ratio of H_2 to the sulfur gas to make the balloons buoyant. The number of balloons and the cost to loft 1 Tg of S as SO_2 would be approximately twice that as for H_2S , as it would be for the other means of lofting.

4.4. Ideas of the Future

[35] All the above systems are based on current technology. With small changes, they would all be capable of injecting gases into the stratosphere within a few years. However, more exotic systems, which would take longer to realize, could also be considered.

4.4.1. Tall Tower

[36] The tallest structure in the world today is the KTHI-TV transmission tower in Fargo, North Dakota, at 629 m high [*Smitherman*, 2000]. However, as *Smitherman* [2000] explains, the heights of this tower and current tall buildings are not limited by materials or construction constraints, but only because there has been no need. Currently, an untapered column made of aluminum that can just support its own weight could be built to a height of 15 km. One made of carbon/epoxy composite materials could be built to 114 km (Figure 3). If the tower were tapered (with a larger base), had a fractal truss system, were stabilized with guy wires (like the KTHI-TV tower), or included balloons for buoyancy, it could be built much higher.

[37] We can imagine such a tower on the Equator with a hose to pump the gas to the stratosphere. The weather on the Equator would present no strong wind issues, as tornadoes and hurricanes cannot form there, but icing issues for the upper portion would need to be addressed. If the gas were pushed up a hose, adiabatic expansion would cool it to temperatures colder than the surrounding atmosphere, exacerbating icing problems. Because such a tower has never been built, and many engineering issues would need to be considered, from the construction material to the pumping needed, we cannot offer an estimate of the cost. Only one tower would be needed if the hoses were large enough to pump the required amount of gas, but one or two additional backup systems would be needed if the planet were to depend on this to prevent climate emergencies. Weather issues, such as strong winds, would preclude such a tower at high latitudes, even though it would not need to be as tall. (A tethered balloon system would have all the same issues, but weather would be even more of a factor.)

4.4.2. Space Elevator

[38] The idea of a geostationary satellite tethered to Earth, with an elevator on the cable was popularized by *Clarke* [1978]. A material for the cable that was strong enough to support its own weight did not exist at the time, but now carbon nanotubes are considered a possibility [Smitherman, 2000; Pugno, 2006]. Such a space elevator could use solar power to lift material to stratospheric levels for release for geoengineering. However, current designs for such a space elevator would have it anchored to Earth by a tower taller than the height to which we would consider doing geoengineering [Smitherman, 2000]. So a tall tower would suffice without an exotic space elevator.

5. Conclusions

[39] Using existing airplanes for geoengineering would cost several billion dollars per year, depending on the amount, location, and type of sulfur gas injected into the stratosphere. As there are currently 522 F-15C Eagles, 481 KC-135 Stratotankers, and 59 KC-10 Extenders, if a fraction of them were dedicated to geoengineering, equipment costs would be minimal. Systems using artillery or balloons would cost much more and would produce additional potential problems of falling spent artillery shells or balloons, or H₂ injections into the stratosphere. However, airplane systems would still need to address several issues before being practical, including the effects of acid clouds on the airplanes, whether nozzles could be designed to produce aerosol particles of the desired size distributions, and whether injection of sulfur gases into an existing sulfuric acid cloud would just make existing droplets grow larger rather than producing more small droplets. All the systems we evaluate would produce serious pollution issues, in terms of additional CO₂, particles, and noise in the production, transportation, and implementation of the technology at the location of the systems.

[40] Several billion dollars per year is a lot of money, but compared to the international gross national product, this amount would not be a limiting factor in the decision of whether to proceed with geoengineering. Rather, other concerns, including reduction of Asian monsoon rainfall, ozone depletion, reduction of solar power, psychological

effects of no more blue skies, and political and ethical issues (Table 1), will need to be compared to the potential advantages before society can make this decision. As *COSEPUP* [1992] already understood, “The feasibility and possible side-effects of these geoengineering options are poorly understood. Their possible effects on the climate system and its chemistry need considerably more study and research. They should not be implemented without careful assessment of their direct and indirect consequences.”

[41] Table 1 gives a list of the potential benefits and problems with stratospheric geoengineering. But for society to make a decision as to whether to eventually implement this response to global warming, we need somehow to quantify each item on the list. While it may be impossible for some of them, additional research can certainly provide valuable information about some of them. For example, reduction of summer precipitation in Asia and Africa could have a negative impact on crop productivity, and this is why this climate change is a potential major concern. But exactly how much will precipitation go down? How will the effects of increased diffuse insolation and increased CO₂ ameliorate the effects of reduced soil moisture on agricultural production?

[42] If stratospheric geoengineering were to be implemented, it would be important to be able to observe the resulting stratospheric aerosol cloud. After the 1991 Pinatubo eruption, observations with the Stratospheric Aerosol and Gas Experiment II (SAGE II) instrument on the Earth Radiation Budget Satellite [Russell and McCormick, 1989] showed how the aerosols spread, but there was a blind spot in the tropical lower stratosphere where there was so much aerosol that too little sunlight got through to make measurements [Antuña *et al.*, 2002]. To be able to measure the vertical distribution of the aerosols, a limb-scanning design, such as that of SAGE II, is optimal. Right now, the only limb-scanner in orbit is the Optical Spectrograph and InfraRed Imaging System (OSIRIS), a Canadian instrument on Odin, a Swedish satellite. SAGE III flew from 2002 to 2006, and there are no plans for a follow on mission. A spare SAGE III sits on a shelf at a NASA lab, and could be used now. Certainly, a dedicated observational program would be needed as an integral part of any geoengineering implementation.

[43] As already pointed out by *Robock* [2008b] and the *American Meteorological Society* [2009], a well-funded national or international research program, perhaps as part of the currently ongoing Intergovernmental Panel on Climate Change Fifth Scientific Assessment, would be able to look at several other aspects of geoengineering and provide valuable guidance to policymakers trying to decide how best to address the problems of global warming. Such research should include theoretical calculations as well as engineering studies. While small-scale experiments could examine nozzle properties and initial formation of aerosols, they could not be used to test the climatic response of stratospheric aerosols. Because of the natural variability of climate, either a large forcing or a long-term (decadal) study with a small forcing would be necessary to detect a response above climatic noise. Because volcanic eruptions occasionally do the experiment for us and climate models have been validated by simulating volcanic eruptions, it would not be important to fully test the climatic impact of stratospheric geoengineering in situ as part of a decision about implementation. However, the evolution

of aerosol properties, including size distribution, for an established stratospheric aerosol cloud would need careful monitoring during any full-scale implementation.

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References

- Agency for Toxic Substances and Disease Registry (1998), Toxicological profile for sulfur dioxide, 223 pp., U.S. Dep. of Health and Hum. Serv., Public Health Serv., Atlanta, Ga. (Available at <http://www.atsdr.cdc.gov/toxprofiles/tp116.pdf>)
- American Meteorological Society (2009), Geoengineering the climate system: A policy statement of the American Meteorological Society, *Bull. Am. Meteorol. Soc.*, 90(9), 1369–1370.
- Antuña, J. C., A. Robock, G. L. Stenchikov, L. W. Thomason, and J. E. Barnes (2002), Lidar validation of SAGE II aerosol measurements after the 1991 Mount Pinatubo eruption, *J. Geophys. Res.*, 107(D14), 4194, doi:10.1029/2001JD001441.
- Bluth, G. J. S., S. D. Doiron, S. C. Schnetzler, A. J. Krueger, and L. S. Walter (1992), Global tracking of the SO₂ clouds from the June, 1991 Mount Pinatubo eruptions, *Geophys. Res. Lett.*, 19, 151–154, doi:10.1029/91GL02792.
- Budyko, M. I. (1974), *Climate and Life*, 508 pp., Academic, New York.
- Budyko, M. I. (1977), *Climatic Changes*, 261 pp., AGU, Washington, D. C.
- Caldeira, K., and L. Wood (2008), Global and Arctic climate engineering: Numerical model studies, *Philos. Trans. R. Soc., Ser. A*, 366, 4039–4056, doi:10.1098/rsta.2008.0132.
- Chemical Profiles (2009), Sulfur dioxide, in *Chemical Market Reporter*, Schnell, New York. (Available at <http://www.the-innovation-group.com/ChemProfiles/SulfurDioxide.htm>)
- Clarke, A. C. (1978), *The Fountains of Paradise*, 261 pp., Harcourt Brace Jovanovich, New York.
- Committee on Science Engineering and Public Policy (COSEPUP) (1992), Geoengineering options, Appendix Q, in *Policy Implications of Greenhouse Warming: Mitigation, Adaptation, and the Science Base*, pp. 433–464, Natl. Acad. Press, Washington, D. C.
- Croddy, E., C. Perez-Armendariz, and J. Hart (2001), *Chemical and Biological Warfare: A Comprehensive Survey for the Concerned Citizen*, 306 pp., Springer, New York.
- Crutzen, P. (2006), Albedo enhancement by stratospheric sulfur injections: A contribution to resolve a policy dilemma?, *Clim. Change*, 77, 211–219, doi:10.1007/s10584-006-9101-y.
- Curtin, N. P. (2003), Information on Air Force aerial refueling tankers, testimony before the Subcommittee on Projection Forces, Committee on Armed Services, House of Representatives, *Rep. GAO-03-938T*, 8 pp., Gov. Account. Off., Washington, D. C. (Available at <http://www.gao.gov/new.items/d03938t.pdf>)
- Dickinson, R. E. (1996), Climate engineering: A review of aerosol approaches to changing the global energy balance, *Clim. Change*, 33, 279–290, doi:10.1007/BF00142576.
- Farquhar, G. D., and M. L. Roderick (2003), Pinatubo, diffuse light, and the carbon cycle, *Science*, 299, 1997–1998, doi:10.1126/science.1080681.
- Govindasamy, B., and K. Caldeira (2000), Geoengineering Earth's radiation balance to mitigate CO₂-induced climate change, *Geophys. Res. Lett.*, 27, 2141–2144, doi:10.1029/1999GL006086.
- Govindasamy, B., S. Thompson, P. B. Duffy, K. Caldeira, and C. Delire (2002), Impact of geoengineering schemes on the terrestrial biosphere, *Geophys. Res. Lett.*, 29(22), 2061, doi:10.1029/2002GL015911.
- Govindasamy, B., K. Caldeira, and P. B. Duffy (2003), Geoengineering Earth's radiation balance to mitigate climate change from a quadrupling of CO₂, *Global Planet. Change*, 37, 157–168, doi:10.1016/S0921-8181(02)00195-9.
- Gu, L., J. D. Fuentes, H. H. Shugart, R. M. Staebler, and T. A. Black (1999), Responses of net ecosystem exchanges of carbon dioxide to changes in cloudiness: Results from two North American deciduous forests, *J. Geophys. Res.*, 104, 31,421–31,434, doi:10.1029/1999JD901068.
- Gu, L., D. Baldocchi, S. B. Verma, T. A. Black, T. Vesala, E. M. Falge, and P. R. Dowty (2002), Advantages of diffuse radiation for terrestrial ecosystem productivity, *J. Geophys. Res.*, 107(D6), 4050, doi:10.1029/2001JD001242.
- Gu, L., D. Baldocchi, S. C. Wofsy, J. W. Munger, J. J. Michalsky, S. P. Urbanski, and T. As. Boden (2003), Response of a deciduous forest to the Mount Pinatubo eruption: Enhanced photosynthesis, *Science*, 299, 2035–2038, doi:10.1126/science.1078366.
- Intergovernmental Panel on Climate Change (IPCC) (2007a), *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by S. Solomon et al., Cambridge Univ. Press, Cambridge, U. K.
- Intergovernmental Panel on Climate Change (IPCC) (2007b), *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by E. Hanson et al., Cambridge Univ. Press, Cambridge, U. K.
- Intergovernmental Panel on Climate Change (IPCC) (2007c), *Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by B. Metz et al., Cambridge Univ. Press, Cambridge, U. K.
- Jacobson, M. Z. (2008), Effects of wind-powered hydrogen fuel cell vehicles on stratospheric ozone and global climate, *Geophys. Res. Lett.*, 35, L19803, doi:10.1029/2008GL035102.
- Kilburn, K. H., and R. H. Warshaw (1995), Hydrogen sulfide and reduced-sulfur gases adversely affect neurophysiological functions, *Toxicol. Ind. Health*, 11(2), 185–197.
- Kleber, C., et al. (2008), Initial oxidation of silver surfaces by S²⁻ and S⁴⁺ species, *Corros. Sci.*, 50, 1112–1121, doi:10.1016/j.corsci.2007.12.001.
- Kravitz, B., A. Robock, L. Oman, G. Stenchikov, and A. B. Marquardt (2009), Sulfuric acid deposition from stratospheric geoengineering with sulfate aerosols, *J. Geophys. Res.*, 114, D14109, doi:10.1029/2009JD011918.
- Lane, L., K. Caldeira, R. Chatfield, and S. Langhoff (Eds.) (2007), Workshop report on managing solar radiation, *NASA Conf. Publ. NASA/CP-2007-214558*, 31 pp., NASA, Washington, D. C.
- Lenton, T. M., and N. E. Vaughan (2009), The radiative forcing potential of different climate geoengineering options, *Atmos. Chem. Phys.*, 9, 5539–5561.
- McClelland, L., T. Simkin, M. Summers, E. Nielsen, and T. C. Stein (Eds.) (1989), *Global Volcanism 1975–1985: The First Decade Reports from the Smithsonian Institution's Scientific Event Alert Network (SEAN)*, 655 pp., Prentice Hall, Englewood Cliffs, N. J.
- Mercado, L. M., et al. (2009), Impact of changes in diffuse radiation on the global land carbon sink, *Nature*, 458, 1014–1018, doi:10.1038/nature07949.
- Murphy, D. M. (2009), Effect of stratospheric aerosols on direct sunlight and implications for concentrating solar power, *Environ. Sci. Technol.*, 43(8), 2784–2786, doi:10.1021/es802206b.
- Pugno, N. M. (2006), On the strength of the carbon nanotube-based space elevator cable, from nanomechanics to megamechanics, *J. Phys. Condens. Matter*, 18, S1971–S1990, doi:10.1088/0953-8984/18/33/S14.
- Rasch, P. J., et al. (2008a), An overview of geoengineering of climate using stratospheric sulphate aerosols, *Philos. Trans. R. Soc., Ser. A*, 366, 4007–4037, doi:10.1098/rsta.2008.0131.
- Rasch, P. J., P. J. Crutzen, and D. B. Coleman (2008b), Exploring the geoengineering of climate using stratospheric sulfate aerosols: The role of particle size, *Geophys. Res. Lett.*, 35, L02809, doi:10.1029/2007GL032179.
- Robock, A. (2000), Volcanic eruptions and climate, *Rev. Geophys.*, 38, 191–219, doi:10.1029/1998RG000054.
- Robock, A. (2008a), 20 reasons why geoengineering may be a bad idea, *Bull. At. Sci.*, 64, 14–18, doi:10.2968/064002006.
- Robock, A. (2008b), Whither geoengineering?, *Science*, 320, 1166–1167, doi:10.1126/science.1159280.
- Robock, A., L. Oman, and G. Stenchikov (2008), Regional climate responses to geoengineering with tropical and Arctic SO₂ injections, *J. Geophys. Res.*, 113, D16101, doi:10.1029/2008JD010050.
- Roderick, M. L., G. D. Farquhar, S. L. Berry, and I. R. Noble (2001), On the direct effect of clouds and atmospheric particles on the productivity and structure of vegetation, *Oecologia*, 129, 21–30, doi:10.1007/s004420100760.
- Russell, P. B., and M. P. McCormick (1989), SAGE II aerosol data validation and initial data use: An introduction and overview, *J. Geophys. Res.*, 94, 8335–8338, doi:10.1029/JD094iD06p08335.
- Schwartz, P., and D. Randall (2003), An abrupt climate change scenario and its implications for United States national security, report, 22 pp., U.S. Dep. of Def., Washington, D. C. (Available at <http://www.gbn.com/articles/pdfs/Abupt%20Climate%20Change%20February%202004.pdf>)
- Smitherman, D. V., Jr. (2000), Space elevators: An advanced Earth-space infrastructure for the new millennium, *Rep. NASA/CP-2000-210429*, 48 pp., NASA Marshall Space Flight Cent., Huntsville, Ala.
- Teller, E., L. Wood, and R. Hyde (1997), Global warming and ice ages: I. Prospects for physics-based modulation of global change, *Publ. UCRL-JC-128715*, 18 pp., Lawrence Livermore Natl. Lab., Livermore, Calif.
- Teller, E., et al. (1999), Long-range weather prediction and prevention of climate catastrophes: A status report, *Publ. UCRL-JC-135414*, 44 pp., Lawrence Livermore Natl. Lab., Livermore, Calif.

Teller, E., R. Hyde, and L. Wood (2002), Active climate stabilization: Practical physics-based approaches to prevention of climate change, *Publ. UCRL-JC-148012*, 8 pp., Lawrence Livermore Natl. Lab., Livermore, Calif.

Tilmes, S., R. Müller, and R. Salawitch (2008), The sensitivity of polar ozone depletion to proposed geoengineering schemes, *Science*, *320*, 1201–1204, doi:10.1126/science.1153966.

Wigley, T. M. L. (2006), A combined mitigation/geoengineering approach to climate stabilization, *Science*, *314*, 452–454, doi:10.1126/science.1131728.

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