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# TESTIMONY

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*"Geoengineering: Assessing the Implications of Large-Scale Climate Intervention"*
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**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 $CO_2$, 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 $CO_2$ concentrations, and whether the $CO_2$ 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 $SO_2$ (sulfur dioxide) or $H_2S$ (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 $SO_2$ (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 $SO_2$)

and Sarychev in 2009 (2 Mt $SO_2$) 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 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 $CO_2$ 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.

| 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]

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.