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Workshop Report on Managing Solar Radiation

Compiled and Edited by:

Lee Lane

*Consultant, CRA International,
Boston, Massachusetts*

Ken Caldeira

*Department of Global Ecology, Carnegie Institution of Washington,
at Stanford, California*

Robert Chatfield

*Earth Sciences Division, NASA Ames Research Center,
Moffett Field, California*

Stephanie Langhoff

*Chief Scientist, NASA Ames Research Center,
Moffett Field, California*

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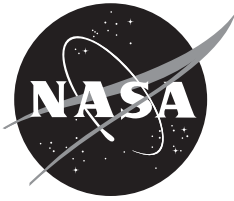
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National Aeronautics and
Space Administration

Ames Research Center
Moffett Field, California 94035-1000

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Executive Summary

In November of 2006 the NASA Ames Research Center and the Carnegie Institution of Washington Department of Global Ecology at Stanford University sponsored an expert workshop on the use of solar radiation management as a strategy for coping with the challenge of climate change.

The basic concept of managing Earth's radiation budget is to reduce the amount of incoming solar radiation absorbed by the Earth so as to counterbalance the heating of the Earth that would otherwise result from the accumulation of greenhouse gases.

The workshop did not seek to decide whether or under what circumstances solar radiation management should be deployed or which strategies or technologies might be best, if it were deployed. Rather, the workshop focused on defining what kinds of information might be most valuable in allowing policy makers more knowledgeably to address the various options for solar radiation management. The report concludes with an appendix that describes important environmental science, engineering, and policy research issues.

Solar radiation management concepts

The volcanic eruptions of El Chichón and Pinatubo injected enough sulfate aerosol into the stratosphere to decrease temperatures in the Northern Hemisphere for 1 to 3 years by several tenths of a degree Celsius. Repeating the aerosol injections and optimizing them for cooling could amplify the impacts on global temperatures. Further research could assess whether this approach could safely counter the significant increases in temperature that could occur by 2100 if anthropogenic greenhouse gas emissions continue unabated. Research could determine, for example, whether injections of sulfates or other materials into the stratosphere could diminish cooling in the Arctic region, an area of seemingly high vulnerability to climate change.

Workshop participants also considered other approaches to solar radiation management, such as a plan to raise the reflectivity of low altitude marine clouds. Work has begun on designing seagoing hardware capable of producing the upward directed spray of mixed air and seawater intended to increase cloud reflectivity. Another proposed approach was to block some sunlight with an orbiting space sunshade. The inner Lagrange L1 point is in an orbit with the same one-year period as the Earth, in-line with the sun at a distance where the penumbra shadow covers, and thus cools, the entire planet. A presentation on this concept proposed several approaches for overcoming the various engineering and economic challenges a sunshade presented although those challenges remain daunting.

These concepts have been the subject of some preliminary theoretical analysis, but none have been tested in the field under controlled experimental conditions.

Solar radiation management as climate policy

Research into solar radiation management approaches could develop information related to effectiveness and unintended consequences. Research could proceed in a carefully graduated series of theoretical studies and experiments. If the deployment of such technologies were ever to come under consideration, having generated detailed knowledge about the consequences of each option could be extremely valuable. On the other hand, research may show that solar radiation management strategies would not be feasible for any of a number of reasons.

Although the workshop did not address the issue of the circumstances under which solar radiation management should be deployed, participants' views on this matter appeared to span the gamut including (i) never, (ii) only in the event of an imminent climate catastrophe, (iii) as part of a transition to a low-carbon-emission economy, and (iv) in lieu of strong reductions in greenhouse gas emissions. More importantly, the discussion illuminated important differences in the economic and political implications of solar radiation management depending on whether deployment occurred in the face of imminent climate emergency or was implemented preemptively well in advance of crisis conditions. Thus the circumstances under which solar radiation management might be deployed could have major implications for its economic and policy implications.

Possible risks, uncertainties, and objections

One major focus of the workshop was to identify the factors that might militate against research or deployment of solar radiation management technology. Participants noted several such potential objections. These included:

- Solar radiation management systems are unlikely to perfectly reverse all climate consequences of greenhouse gases and could introduce new changes in regional or seasonal climate, so some climate change might be expected even with the deployment of such systems.
- Modeling indicates that if a solar radiation management system were shut down suddenly after prolonged operation the climate system could warm very rapidly.
- Injecting sulfur into the stratosphere would likely diminish spring Northern Hemisphere stratospheric polar ozone levels, although the amount of diminution is currently uncertain and extreme Antarctic-style depletion is unlikely.
- Solar radiation management will neither reverse nor exacerbate non-climate effects of CO₂ including fertilization of the land biosphere and acidification of the ocean.

The workshop scope focused on preliminary characterization of some elements of a possible solar radiation management research program. Research into solar radiation management could have implications for other approaches to addressing climate change and could have various political consequences, both domestically and internationally. These considerations may be important, but were beyond the scope of our workshop.

The Ames / Carnegie Solar Radiation Management Workshop: Goals and Background

1.0 Workshop Background

In November of 2006 the NASA Ames Research Center and the Carnegie Institution of Washington Department of Global Ecology at Stanford University sponsored an expert workshop on the use of solar radiation management as a strategy for coping with the challenge of climate change. The workshop was held at NASA Ames Research Laboratory.

The concept of solar radiation management has recently received considerable attention in both scientific and popular news media. Recent publications by such distinguished scientists as Ralph Cicerone, Paul Crutzen, and Tom Wigley, have suggested the concept needs further study. Prominent economists such as William Nordhaus and Thomas Schelling have long argued that the concept warranted further exploration as well.

1.1 Workshop Goal: defining a research agenda for solar radiation management

The workshop sought to generate research questions and approaches that could help in evaluating engineered systems designed to lessen potential harm from climate change by reducing the amount of solar radiation absorbed by the Earth. This could counterbalance increased heat retained by the Earth due to increased greenhouse gases. Workshop participants sought to identify potentially important unknowns about the consequences of solar radiation management. They also proposed a preliminary portfolio of research tasks that could narrow the existing uncertainties. This research agenda was intended to be the workshop's primary output. The initial steps toward a research agenda as generated by the workshop's three breakout groups are given in the Appendix.

The workshop did not seek to decide whether or under what circumstances solar radiation management should be deployed or which strategies or technologies might be best, if it needed to be deployed. Furthermore, the workshop did not seek to achieve consensus, as participants held a wide range of opinions. Instead, the focus was on defining important research questions to lessen uncertainty and to mature potential engineered systems.

Scientists drawn from several relevant fields as well as experts in economics, history, and political science attended the workshop. It was conducted over the weekend of November 18-19 at the Ames Conference Center. In all, some thirty experts participated.

1.2 Limitations of the workshop's goals

The workshop addressed only solar radiation management and not other forms of geoengineering. It did not address non-climate effects of increased CO₂, such as the acidification of the oceans. Many solar radiation management strategies could be devised. The workshop only considered a few of these, concentrating on those that have received recent attention. Participants also noted that other options might be available and that a systematic effort to devise other options might well produce strategies superior to any under current consideration.

Additionally, a small workshop conducted relatively early in the development of interest in the subject could not possibly hope to generate a definitive research agenda. Instead participants sought to identify questions likely to demonstrate that the subject warranted investigation and to steer further investigations toward high priority issues. Much of the discussion emphasized that a more comprehensive research agenda was likely to emerge only as initial investigations proceeded and delineated additional lines of inquiry. Final discussions moved towards a realization of the strong

commonalities between research on solar radiation management and research on climate sensitivity, such as temperature-precipitation responses to global or local increases in greenhouse gases.

2. The Basics of Solar Radiation Management

2.1 Anthropogenic climate change

The workshop explored solar radiation management as a possible tool for coping with climate change. In principle, solar radiation management could either cool the planet or warm it. Workshop discussion, however, focused on proposals designed to use solar radiation management to cope with greenhouse warming.

2.2 Solar radiation management

This workshop addressed methods to reduce absorption of sunlight so as to counteract the climate effects of increasing anthropogenic greenhouse gases. Reducing the amount of absorbed solar radiation could potentially compensate for some of the climate effects of increasing absorption by greenhouse gases of outgoing longwave radiation.

The ability of solar radiation management to counteract the global warming influence of greenhouse gases depends on being able to deflect sufficient sunlight. Current General Circulation Models predict that for a doubling of atmospheric CO₂ content, approximately 1.7% to 1.8% of solar radiation would need to be deflected. This would require placing light-scatterers in a layer in the atmosphere deflecting sunlight from a total of about 8 million square kilometers; one quarter of this area, or about 2 million square kilometers, would need to be deflected from at a suitable spot about 1.5 million km out in space between the Earth and Sun.

The feasibility of making geoengineering schemes that deflect sunlight on a large scale depends on making the components very small or thin. While further research is required to determine the optimal particle size, scattering particles of about 0.1 μm ($= 10^{-7}$ m) in size might be preferred, because they would scatter incoming sunlight while allowing outgoing long wave radiation to escape to space. In the stratosphere, for example, an array of 0.1 μm particles with a combined cross sectional area of 8 million km² would be a volume of about 800,000 m³. Given the size of the Earth, this is a modest volume: it corresponds to the volume of a cube of material of only 90 m on a side.

Solar Radiation Management Technologies

Presentations at the workshop described several technological options for managing solar radiation. Participants described technologies based in the stratosphere, in the lower troposphere and in space.

1. The Potential for Solar Radiation Management to Reduce Environmental Risk

As one workshop presentation noted, substantial Earth brightness (planetary albedo) increases have been observed repeatedly in our own time. They include the volcanic eruptions of Tambora, Krakatau, El Chichón, and Pinatubo. The cooling effects of the large Pinatubo event are heavily documented, and cooling associated with many major volcanic eruptions was described (Robock and Mao, 1995). The stratospheric aerosol layer resulting from the Pinatubo volcanic eruption is shown in Figure 1.



Figure 1. Stratospheric sulfate aerosol layer resulting from the massive Pinatubo volcanic eruption.

These uncontrolled experiments that occur in nature suggest the possibility of using solar radiation management technologies to diminish the threat of deleterious climate change. Views differed among meeting participants regarding when it might be appropriate to deploy such systems. The range of views considered included (i) never, (ii) only in the event of an imminent climate catastrophe, (iii) as part of a transition to a low-carbon-emission economy, and (iv) in lieu of strong reductions in greenhouse gas emissions.

Engineering schemes that increased the Earth's albedo could stabilize global mean temperature while atmospheric greenhouse gas levels continue to rise. If temperature stability could be achieved amid rising greenhouse gas concentrations without producing large negative environmental consequences, this would offer great advantages.

Much of the uncertainty voiced at the workshop regarding stratospheric solar radiation management revolved around comparing the effects of these major-volcanic episodes to a limited, but continual particle injection. A key question was whether limited injections sufficient to obtain the desired climate change would induce other undesirable effects, such as midwinter ozone-layer depletion, tropospheric chemistry effects, or regional climate effects.

The tropical volcanic eruption of Pinatubo injected enough sulfate aerosols into the stratosphere to *decrease* temperatures in the Northern Hemisphere for 1 to 3 years by several tenths of a degree Celsius, albeit these temperature changes vary with latitude and season. Because of the thermal inertia of the ocean, this cooling would have been much greater if the volcanic eruptions were repeated on the 1 to 3 year time scale. However, the volcano-produced particles were not optimally sized for maximum efficiency in scattering sunlight (Rasch *et al.*, 2007), suggesting the possibility that an optimized system might achieve this cooling with much less mass. More detail regarding volcanic effects is found in the appendix.

A well-designed system of climate modification might use sub-micron particles deployed in the stratosphere to scatter sunlight back to space. These particles do not fall out readily from air masses into which they are initially deployed, as does volcanic ash. Eventually, they would descend from the stratosphere into the lower atmosphere, especially in the polar vortices at high latitudes. There was brief discussion that particles might not persist in the stratosphere as described, and might

have undesirable aspects even if they did, since it would take a long time to clear the atmosphere if there were undesired consequences. Once in the lower atmosphere, they would be expected to “rain out”. The total mass of such particles removed from the lower atmosphere by rain or snow is expected to be small, equivalent to a few percent of today’s sulfur emissions from power plants. However, additional research is needed to confirm optimal particle size and possible impacts on ecosystems. The term “optimal” in this context is dependent on what criteria are being optimized, such as the effectiveness at scattering solar radiation per unit mass, the lifetime of the particles in the atmosphere, cost, or minimization of environmental side effects. The “optimal” particle size is also highly dependent on the nature of the materials. From a purely scattering point of view, the optimal particle size is about 0.5 microns. However, absorbing particles can be much smaller and still have appreciable atmospheric lifetimes (Kasten, 1968).

Several kinds of scatterers could bring about the desired cooling. The simplest and cheapest per unit mass may be substances that interact minimally with electromagnetic radiation (dielectrics). These include sub-micron oxide particles, including sulfur oxides. These materials are contained in standard volcanic aerosols and Earth crustal ‘dust’, although the particles used in solar radiation management would likely be smaller and without chemical impurities. As such, they may be safe, since materials, such as sulfate and ash, are relatively well understood as one can predict with confidence how their properties change throughout their months-to-years travel time through the stratosphere. The surface properties of other materials must be studied to determine their response to the very acidic and oxidizing environment, in the presence of highly energetic ultraviolet light. Alternatives to dielectrics have been suggested, such as metallic or resonant particles (see, for example, Teller, 1997). Metals interact with electromagnetic radiation strongly and might conceivably require much less particle mass than would non-conducting (dielectric) particles.

In addition to changing the materials used in the scatterers, materials might be shaped to preferentially scatter particular wavelength regions of the optical spectrum. More exotic and as yet untested concepts include tiny super-pressure self-deploying balloons engineered to hover at a particular altitude. If designed to be top-bottom oriented they could be ‘coated’ for preferred optical properties. These concepts take one step further the trade-off between unit input costs and mass efficiency. It should be noted, however, that the stratosphere is a harsh environment due to the extremely oxidizing nature of its constituents such as ozone, oxygen, chlorine, and OH radicals, strong acidity (concentrated nitric and sulfuric acids can condense onto surfaces), and harsh ultraviolet radiation. Studies could be conducted to better understand the fate of scatterers in this harsh environment and what might happen if these particles became significantly altered during their months-to-decades residence times in the stratosphere.

Injecting the particles near the equator and at higher altitudes lengthens their life in the atmosphere. A longer atmospheric life reduces the total mass that must be put into the stratosphere in order to achieve a given change in global mean temperature. If adverse effects appeared following the introduction of such a scheme, most of these effects would be expected to dissipate once the particles were removed from the stratosphere.

The workshop also considered ways in which particles could be self-lofted; absorption of solar radiation causes some particles like black carbon to loft (Pueschel et al., 2000). Particles may even loft very high to 70 km if they can survive the harsh chemical environment (Rohatschek, 1996). One untested idea was to mix small amounts of absorbing aerosol like black carbon with sulfate so as to produce a long-lasting aerosol with a designer mix of heating and cooling effects in the upper stratosphere at 40 km. At very high altitudes even pure absorbing aerosols can produce cooling effects near ground level.

Several options exist or are conceivable for deploying the radiation reflecting materials into the stratosphere. These include naval artillery, high-altitude transport aircraft, and unpiloted vehicles. It may be possible to construct an anthropogenic mini-volcano. A large scale engineered combustor situated on an equatorial mountain top could create a thermal plume lofting aerosol precursors to the stratosphere. Kites or hovering drones might lift a thin 25 km pipe through which aerosols could be blown into the stratosphere. None of these options is currently operational, and further research is needed to determine their feasibility.

2. An Experiment in Arctic Cooling

Many predict that more severe warming will affect the Arctic and the planet within a few decades. There is evidence that widespread melting of polar ice about 125,000 years ago contributed to a rise in global sea level 13 to 20 feet (4 to 6 meters) higher than today's level. Polar temperatures were about 5 to 9 degrees Fahrenheit (3 to 5 degrees Celsius) higher than they are today (IPCC, 2007). Thus, the Arctic seems to be particularly vulnerable to climate warming.

Experiments performed at a scale that is too small to affect climate could yield much information about potential climate and chemical effects of solar radiation management schemes. Particles deployed in the lower stratosphere near the North Pole in the late spring would be expected to be substantially removed from the stratosphere in the next polar winter, so unexpected adverse effects would be unlikely to persist for more than a single year.

Such reversible regional-scale testing would allow better understanding of the consequences of solar radiation management approaches without requiring commitment to prolonged or global-scale interventions.

Relatively low tech experiments to accelerate our understanding of climate science could begin soon. One approach is to focus first on the Arctic with a particulate shield experiment. Perhaps the simplest idea uses the dispersion of tiny (less than one micron) particles in stratospheric air parcels that would be expected to descend into the troposphere and precipitate out within approximately 6 months. Research could demonstrate how well atmospheric circulation patterns confine most of the deployed particles to the Arctic.

Temperatures could be measured with sensors and sea-ice extent could be monitored from space. Changes in sea ice cover could provide a clear, visual signature of regional cooling. Ground measurements could give more refined understanding.

A first experiment could use just enough of the tiny particles to create a readily measurable radiation shielding effect. A second experiment could use enough particles and be of long enough duration to produce a detectable cooling effect. (Because of climate variability, a clear cooling signal would be more difficult to detect than a change in reflected sunlight.) These experiments could occur north of 70 degrees latitude, over the Arctic Ocean.

Because sulfates interact chemically with the high altitude air, one might consider the use of less chemically reactive particles in an experimental protocol. The aim would be to attenuate incoming sunlight, while minimizing interference with atmospheric chemistry. It should be noted, however, that all particles serve as surfaces promoting coatings of stratospheric constituents and thus heterogeneous chemistry, which can release chlorine that destroys ozone.

Such experiments may uncover unanticipated negative consequences and provide a clear statement that solar radiation management approaches cannot be used to reverse adverse effects of global warming. On the other hand, ideas and the scientific knowledge gained from such experiments

could provide information to help improve possible future technologies. There could be many useful variables in such a climate technology, including particle size, particle nature, altitude deployed (and therefore duration in the atmosphere), and much else. Other relationships and feedbacks would doubtless emerge from the experiment.

Such an experiment would disclose much about the possibility of arresting Arctic warming and reversing the loss of sea ice. Repeating the experiment over several years would advance scientific understanding of the climate system's workings and improve confidence that the effect was not just normal yearly variations in climate. Public discussion could run in parallel, providing the opportunity for free public airing of the complex and momentous issues involved in such an undertaking.

If the Arctic deployment results in environmental benefits that clearly outweigh environmental hazards, and the effects of greenhouse gas induced global climate change prove to be unacceptably large, solar radiation management could be cautiously scaled up. In that case, other side effects might emerge. Careful monitoring would be essential. If the positive effects of such deployment do not clearly outweigh the negative effects, such deployment could be terminated.

3. Cooling through enhanced oceanic cloud albedo

Latham (1990) and Bower *et al.* (2006) have discussed a possible technique for ameliorating global warming by controlled enhancement of the droplet concentration in low level non-overlapped marine stratiform cloud cover. Such clouds make a significant cooling contribution to the radiative balance of the Earth. Increased droplet concentration would increase cloud albedo and possibly increase cloud longevity, thereby producing a cooling effect. This approach to increase oceanic cloud albedo has never been tested in the field.

The proposed technique involves production of an extremely fine mist of sea water droplets which are lofted upwards, eventually forming moist sea salt aerosol particles of diameter less than one micron. These particles provide sites for cloud droplets to form once they rise to the marine cloud layer, adding to the effects of natural sea salt and other small particles, all of which are called collectively 'cloud condensation nuclei'. The effect of added particles, pollutant or natural, has been considered to brighten the clouds, since many small droplets scatter light back to the source better than fewer, larger droplets. Sean Twomey in 1974 pioneered a description of this phenomenon. Particles emitted from ship engines have long been thought to create definitely brighter clouds, and perhaps magnify their areal extent. Figure 2 shows variations in the prevalence and brightness of low-level oceanic clouds supposed to be produced in the atmosphere by ship engine exhaust emissions of small aerosol particles (two views of the same scene). Ship exhaust effects are complex and arguably extend beyond simple particle emission effects. For further discussion see the papers by Twomey (1974), Charlson *et al.* (1992), Wigley (1989), Slingo (1990), and Ackerman *et al.*, (2004), in the bibliography.

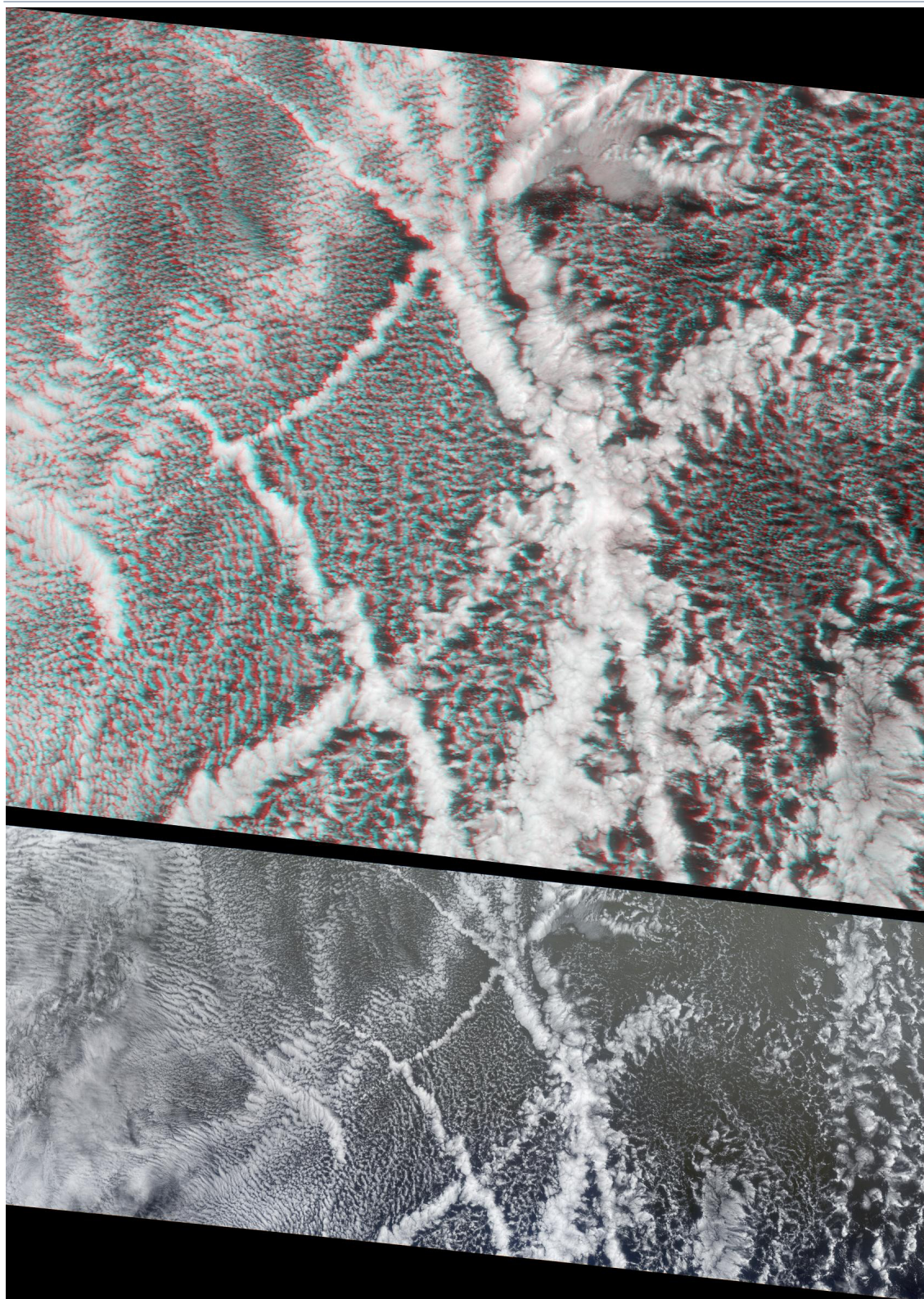


Figure 2. Interaction between aerosols and clouds in marine low stratocumulus clouds. These striking linear patterns are known as “ship tracks,” and are produced when fine aerosols from the ships’ exhaust float into a moist layer of atmosphere. The particles may either produce new cloud particles where none existed before, or may attract water from existing cloud particles, creating a brighter cloud composed of smaller droplets. Sample: west of San Francisco, July 18, 2001. Credit: NASA MISR (Multi-angle Imaging SpectroRadiometer, JPL/GSFC/LaRC)
<http://eosweb.larc.nasa.gov/HPDOCS/misr/misr_html/ship_tracks.html>

Doubling of droplet number concentration in all marine stratocumulus could produce a cooling, which would compensate for the global warming associated with a doubling of the atmospheric carbon dioxide concentration. Unpublished simple computations of Jones, Latham and Smith using the Hadley Centre's (UK Meteorological Office) HadGAM1 general circulation model reinforce the quantitative validity of this scheme. The studies indicate that the associated change in planetary albedo is 0.01 (3.5%): and in top of cloud albedo about 0.06 (12%). These albedo changes would roughly compensate for the positive forcing caused by increased greenhouse gas concentrations since the beginning of the industrial period—when taking account of the negative forcing due to the production of anthropogenic aerosol to date.

Recent sensitivity studies (Bower *et al.* 2006) used a simple marine stratocumulus model to explore the effectiveness of this concept. Albedo changes exceeding the value of 0.06 were computed for an appreciable fraction of conditions considered if the clouds are formed in pure air but not in highly polluted air. This suggests that seeding a fraction—perhaps only a few tenths—of oceanic cloud coverage could compensate for CO₂ doubling in principle. However, dissemination efficiency and other considerations indicate that the optimal marine stratus fraction may be in the 50 to 75% range. Computations suggest provisionally that the additional cooling resulting from enhanced cloud longevity of seeded clouds (due to drizzle inhibition) might be significant (perhaps around 30%) for realistically achievable values of droplet concentration in clouds formed in pure air, but not in clouds formed in polluted air.

Advantages of this proposed global warming mitigation technique, were it to be deployed operationally, include:

- Albedo control could be exercised by measuring cloud albedo from satellites, and switching seawater droplet disseminators on or off as required;
- The only raw material needed is seawater;
- The droplet disseminators and the vessels that carry them (see later) would derive their energy from the wind;
- The system could be switched off with the expectation that conditions would return to normal within a few days.

Work has begun at Edinburgh University in Scotland on the design of practical seagoing hardware for an initial field demonstration. The proposal is to use a fleet of unmanned, wind driven spray vessels equipped with satellite navigation, positioned at suitable points around the oceans. They would sail back and forth across the local wind and drag oversize propellers through the water to act as turbines to generate the energy for spray. Periodically, they would be directed to new positions.

The current concept is to discharge the spray as an upward directed mix of air and water. Turbulence in the marine boundary layer will tend to produce an even distribution of the salty residues left from partial evaporation of the drops. Only a fraction of the nuclei (perhaps 5%) will reach the reflective region of the cloud tops, but only a small number of nuclei are needed due to their efficiency in reflecting solar radiation. While this method has promise, research is needed to determine whether salt will have the desired effect on cloud albedo and lifetime, and whether boundary layer circulation will get the salt into the clouds. Another question is the degree to which the response will be regional versus global in extent. Specific questions arising in the workshop discussion may be found in the appendix.

4. A space-based sunshade for Earth

Professor Roger Angel's presentation at the workshop described his concept to block 1.8% of the solar flux with space "sunshades" orbited near the inner Lagrange point (L1). The L1 point is the preferred location, since it is at a position where objects may track with period as the Earth, in-line with the sun at a distance where the penumbra shadow covers and thus cools the entire planet. As shown in Figure 3, it is necessary to place the flyers inside the L1 point to compensate for the radiation pressure on the sunshades. The radiation pressure also necessitates the use of a transparent material designed to deflect the sunlight rather than absorb it.

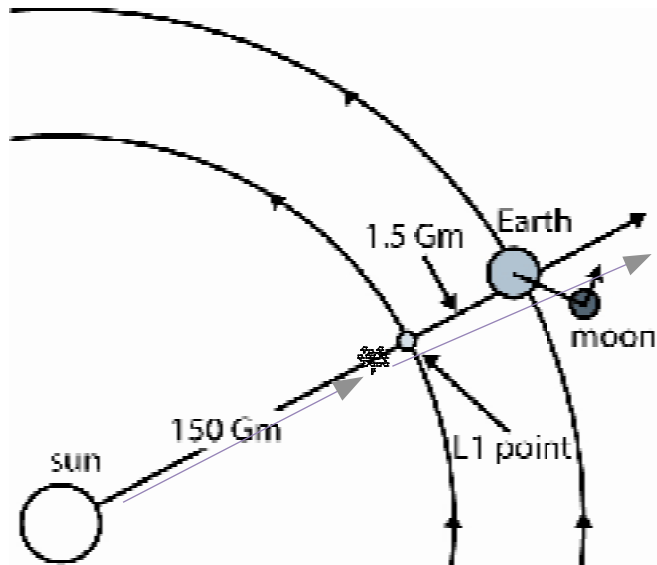


Figure 3. Location of small flyers just within the Lagrange 1 or L1 point.

Three advances aimed at a practical implementation were presented. First was an optical design for a very thin refractive screen with low reflectivity, leading to a total sunshade mass of ~20 million tons. The "sunshades" actually described were many transparent "diffusers" behaving somewhat like light-diverging lenses, but more robust in construction. Second was a concept aimed at reducing transportation cost to \$50/kg, by using electromagnetic acceleration to escape Earth's gravity, then using ion propulsion to maneuver diffusers into orbit. Third was the implementation of the sunshade as a cloud of many spacecraft, autonomously stabilized from wandering by modulating solar radiation pressure (Angel, 2006).

Advantages of the approach include potentially a lifetime of many decades. Assuming that modulating solar pressure could stabilize the spacecraft, the system would not need expendable propellants. Displacing the orbit of the sunshade would allow the program managers to stop cooling at any time. Another advantage is the high degree of predictability of effects on Earth, since only the flux of solar radiation is altered (see Govindasamy references). However, the main advantage of this approach is that the composition of the atmosphere and ocean would not be further modified, beyond their loading with greenhouse gases.

Disadvantages of the approach include the enormous area and mass required, which makes it technically challenging to construct such a sunshade. Dr. Angel focused on a relatively near-term ap-

proach in which the sunshade was manufactured and launched from Earth in the form of many autonomous spacecraft. Considerable discussion of the technical challenges was presented including materials issues, launch costs, and propulsion and station keeping issues. The cost was estimated at 1 trillion dollars. Extensive details of this approach are given in the original literature (Angel, 2006).

Clearly if this approach were technically feasible and cost competitive it would be compelling although it would not address non-climate effects of carbon dioxide, such as ocean acidification.

Solar Radiation Management and Climate Policy

In addition to discussing technologies for implementing solar radiation management and potential disadvantages of those technologies, the workshop discussed how solar radiation management approaches might relate to other climate policy options including mitigation approaches.

1.1 The need for early research

Theoretical studies of geoengineering schemes with computer models and laboratory experiments could advance our understanding of these approaches. If the time to deploy solar radiation management technologies were to arrive, research that had matured the concepts might prove to be extremely valuable.

Experiments could begin small with paper and modeling exercises. They could graduate to small scale physical tests. Assuming that no 'show-stoppers' emerged, tests could gradually scale up. The ability to proceed cautiously is an important rationale for beginning experimentation early. An early start is especially important in some solar radiation management deployment strategies.

1.2 The risk that mitigation might 'fail'

Mitigation policies might partially or completely fail to avoid harmful climate change. If solar radiation management is feasible, therefore, it could represent a potentially valuable tool for coping with this possible policy failure. Participants' opinions about the likelihood of such a failure clearly differed.

1.3 Research to disprove solar radiation management's feasibility

Research may show that solar radiation management schemes would not be feasible, for any of a variety of reasons. Thus, solar radiation management research may conclusively remove solar radiation management as a policy option.

Early tests could hasten the process of understanding whether solar radiation might be a feasible policy option under some conceivable set of circumstances. However, this research could take resources from more pressing matters.

1.4 Research on solar radiation management and mitigation efforts

Research on solar radiation management could be performed concurrently with research on or deployment of other mitigation approaches. Delaying research could risk depriving policy makers of a potentially valuable tool. Should abrupt harmful climate change occur, pressure to resort to solar radiation management or other geoengineering technology could become strong. Failure to conduct early research could diminish the chances of a successful deployment while increasing the probability of unanticipated environmental hazards.

2. Future deployment strategies

The workshop participants discussed the question of how and under what circumstances solar radiation management might be deployed and how differing possible future deployment strategies

might affect research needs. There are many ways of categorizing the nuances of views expressed, but they can be broadly categorized into two rival strategic visions. One of these, which might be called the parachute strategy, would foresee deployment only in the event of a climate change emergency. The second, preemptive deployment strategy, would implement solar radiation management technologies as soon as research firmly established their safety and efficacy.

2.1 The rival strategic visions

One vision, the 'parachute strategy,' would deploy solar radiation management only if strong evidence appeared that harmful and perhaps irreversible consequences of climate change were imminent. In this situation, politically, the decision to deploy solar radiation management would be relatively straightforward. Once abrupt climate change began, mitigation policies could be much too slow to avoid serious harm. The choice would be among solar radiation management, other forms of geoengineering, adaptation, or some combination. Several participants expressed the view that, should such circumstances arise, society could decide to deploy some form of geoengineering.

In this strategic vision, research and development efforts would test the feasibility of various solar radiation management technologies, explore their consequences, and hone their cost-effectiveness. The most promising concepts would be "put on the shelf" for use in case of emergency. Emission abatement strategies would presumably proceed. Political, economic, social, and scientific events would dictate their success or lack of it. Solar radiation management technologies would represent a parachute for use in an emergency.

An alternative strategy would deploy solar radiation management preemptively as soon as experimentation proved it to be safe. Underlying this strategy is the assumption that implementing effective international agreements on greenhouse gas reduction requires prior development of new, far lower cost emission abatement technologies. Developing new technology and forging international consensus will require time. Successful deployment of solar radiation management could buy that time by holding global mean temperatures to safe levels and limiting the rate of temperature increase.

The alternative strategy was seen as a temporary measure to buy time for emission reductions. Scientists like Wigley (2006) have cautiously suggested this option. In principle and under favorable circumstances, this strategy could be consistent with an economically efficient climate policy. Economic efficiency requires minimizing the present value of the sum of the damages from climate change and the costs of reducing those damages. By constraining the rise in temperature, solar radiation management deployment could reduce the damages of climate change. At the same time, postponing the deepest emission cuts until cheaper abatement technology is available is a key to abatement cost-effectiveness. On the other hand, the perception of a technological "fix" to the global warming problem could diminish the incentive to reduce greenhouse gas emissions. In Figure 4 we have plotted the fossil fuel carbon emissions in billions of tons of carbon per year versus time. The figure compares the Business as Usual (BAU) case (shaded curve) with various reduction schemes proposed in the paper by Wigley, Richels, and Edmonds (WRE) published in 1996. The number following WRE refers to the long-term concentration of CO₂ in parts per million. This demonstrates that a delay in effect of carbon dioxide emission reductions occurs even with very rapid deployment of economic resources to emission reductions (WRE 450 and WRE 550).

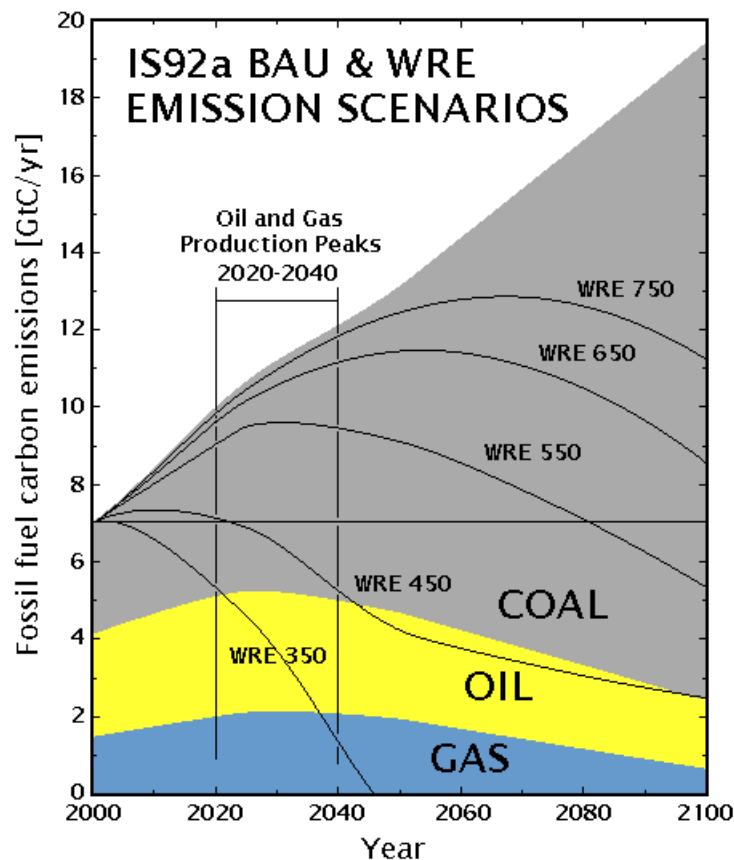


Figure 4. Delay in effect of carbon dioxide emission reductions even with very rapid deployment of economic resources to emission reductions (WRE 450 and WRE 550). The emissions scenarios and graph are described in Wigley, Richels, and Edmonds (1996) and described in simplified form in Hoffert (2002).

2.2 Implications for policy and research

The two rival policy visions described in the preceding section pose rather different policy choices, and they may imply somewhat different research priorities. The parachute strategy has both advantages and disadvantages.

If solar radiation management were to be deployed only in case of a clear climate emergency, there would be relatively little practical value in research about current political objections and resistance to solar radiation management. (In a crisis, ideological objections to solar radiation management may be swept aside.) Also, comparisons between the costs and benefits of solar radiation management versus emissions reduction would be irrelevant. If it were assumed that the potential crisis lies far in the future, the relevance of ozone depletion would be slight.

Along with these obvious political advantages, the parachute strategy exhibits some potential drawbacks. These include the following factors:

- A late and hurried deployment is likely to be less than ideally efficient.
- Substantial damage from climate change may accumulate before the widespread perception of imminent emergency comes to prevail.
- If deployment is perceived as lying many decades in the future, solar radiation management research projects might fare poorly in the contest for scarce research and development resources.
- Should an emergency arise and the solar radiation management deployment fail, the consequences could be very negative.
- By the time the threat of climate catastrophe is widely recognized, it may be too late to prevent or reverse.

The advantages and disadvantages of preemptive deployment are largely the mirror image of those of the parachute strategy. Proposals to deploy solar radiation management without overwhelming evidence of imminent crisis could encounter strong resistance both domestically and abroad. Whatever the proponents' actual intentions with regard to mitigation policies, many will perceive solar radiation management as a rival strategy, the use of which will inevitably sap the will to undertake greenhouse gas abatement measures. The earlier the deployment of solar radiation management, the more likely it is to stimulate concerns about ozone depletion.

Nevertheless, should experimentation confirm the efficacy and safety of solar radiation management, a preemptive deployment offers major advantages. These include:

- The opportunity for efficient deployment growing logically and progressively out of testing;
- The possibility of lowering the present value of both damages from climate change and the costs of greenhouse gas abatement;
- A more direct rationale for near term research and development;
- More time to implement other policies should deployment of full-scale solar radiation management produce disappointing results or unacceptable side effects.

Possible risks, uncertainties, and objections to solar radiation management

Workshop participants explored many possible risks uncertainties and objections to solar radiation management. Some of these issues were scientific, most relating to the possibility of undesirable side effects.

1. Environmental issues

1.1 System failure

Modeling results indicate that should the solar radiation management system fail or be shut down, the climate system could warm very rapidly. Conceivably, the solar radiation management system might encounter limits to its effectiveness, undesirable side effects might suddenly appear, technical problems may arise, or the political decisions might change. Any of these developments might prompt a rapid system shut down.

If the solar radiation management system were shut down, the climate could warm rapidly, soon approaching average temperatures that would have prevailed without solar radiation management. Unless precautions had been taken, a shut down could drastically compress both human and natural systems' time for adaptation. With reduced reaction time, the transition cost to the new climate regime could exceed that implied by adaptation in parallel with the gradual rise in atmospheric concentrations of greenhouse gases.

If the solar radiation management system retained its effectiveness, and despite other changes, these high transition costs could argue against a rapid shut down. While a gradual phase-out could partially dampen the otherwise steep transition cost penalty, it also could imply that once greenhouse gas concentrations had risen significantly, transitioning away from solar radiation management could require a substantial amount of time.

1.2 Possible changes in regional and seasonal climates

Solar radiation management could, if deployed, reduce global mean temperatures, but different climate models simulating different scenarios have generated different results for regional climates. The most relevant simulations to date have indicated that solar radiation management might re-

verse much of the regional and seasonal effects otherwise predicted because of rising greenhouse gas concentrations (see, for example, Govindasamy and Caldeira, 2000 and Rasch *et al.*, 2007).

Other simulations have indicated that at least some approaches might alter regional and/or seasonal climates. Indeed, one simulation set, mimicking historical volcanic aerosol emissions, has predicted regional fluctuation of climate. It should be noted that these simulations have been highly preliminary and no attempt has been made, for example, to optimize particle emplacement to minimize regional or seasonal climate change.

Regional climatic changes, such as a shift in precipitation patterns, could entail large transition costs. The transition cost problem, should it arise, is likely to be more salient in less developed countries or economic sectors that are especially climate dependent like agriculture or forestry. Some regional climatic systems are economically important like the Indian Ocean monsoon. A simulation of past volcanic-eruption particle release produced indicated shifts in precipitation and a possible weakening of the Indian Ocean Monsoon. Changes in regional and local climates may also affect unmanaged ecosystems in ways that may be regarded as either desirable or undesirable.

1.3 Ozone depletion

Stratospheric ozone depletion is the integrated effect of the surface area of the sulfate particles, temperature, and the concentration of ozone depleting chemicals such as chlorine (from CFCs). Since stratospheric chlorine concentrations are expected to decrease over the next few decades, the risk of ozone depletion due to solar radiation management should also decrease.

Strong new evidence suggests that sulfuric acid solutions are principally responsible for the “ozone depletion chemistry” that occurs in the Northern Hemisphere. Crutzen (2006) made extensive use of existing analyses of the effects of the Pinatubo eruption and found, tentatively, that ozone depletion would not be worrisome with regard to the volumes of sulfate aerosols needed for solar radiation management. However, a recent study used satellites to observe enhanced sulfate aerosols’ impact in the stratosphere polar ozone destruction (Tilmes *et al.*, 2003). Results suggest that injecting sulfur species broadly into the stratosphere could diminish stratospheric polar ozone levels in the late winter season. Although the amount of diminution is currently uncertain, extreme Antarctic-style depletion is unlikely in the Northern Hemisphere with the small amount of sulfur supplied in geoengineering trials. Nevertheless, this is an important research issue.

The interactions between temperature, the presence of sulfate aerosols, and the levels of ozone depleting chemicals creates uncertainties about the relationships between stratospheric injections of sulfates and ozone depletion. The appendix describes some of these uncertainties.

1.4 Preservation of non-CO₂ greenhouse gases

Solar radiation management technologies deployed in the stratosphere or in space could diminish the level of ultraviolet radiation striking Earth’s atmosphere. Indeed, some solar radiation management technologies are designed to preferentially diminish the levels of ultraviolet radiation reaching the surface and the troposphere. Such strategies may offer large bonuses in terms of public health and agricultural productivity.

However, ultraviolet radiation accelerates the breakdown of non-CO₂ greenhouse gases in the atmosphere. Per unit of mass, many of these gases are more potent in their contribution to greenhouse warming than is CO₂. Thus a solar radiation management technology that reduces ultraviolet radiation striking the troposphere is likely to extend the atmospheric life of these other gases potentially offsetting some of the cooling affect of the system.

1.5 Ecosystem disruption

Participants also questioned if solar radiation management might change existing eco-systems. For example, the lower ultraviolet radiation levels might enhance plant and animal health, but might also have other consequences. They might favor invasive species or curtail the niches of incumbent ones. Such changes and their economic consequences would be hard to predict. Changes in light level and the change to a more hazy indirect light also have effects on ecosystems, and might change emissions patterns of CO₂ and non-CO₂ greenhouse gases; it is important to understand and quantify these effects.

Furthermore, it should be noted that CO₂-fertilization of plant growth would affect natural ecosystems on land even in the absence of climate change. Govindasamy and Caldeira (2002) simulated some of these effects and found them interpretable, resembling, in different ways, current and CO₂-enhanced ecosystems. Other simulations are needed to improve this understanding. Solar radiation management approaches cannot be expected to mitigate the non-climate effects of greenhouse gases such as ocean acidification. However, solar radiation management schemes would not be expected to worsen these non-climate effects.

2. Political concerns

Workshop participants also discussed political factors that some saw as affecting solar radiation management. Some of these factors related to the interaction between solar radiation management and emission reductions (mitigation). However, other comments focused on the politics, public attitudes, and international political dynamics of solar radiation management itself. However, discussion of the wisdom or a research program in solar radiation management requires balancing many interests and is outside the scope of this report.

Conclusion

Having identified many uncertainties about how solar radiation management could best serve as a climate policy tool and other questions about the possible disadvantages to its use, the workshop participants defined a preliminary research agenda. This agenda was divided into three parts: environmental science, engineering, and policy sciences. This report's appendix summarizes the research questions and approaches suggested in these discussions.

Bibliography

Although the main report did not contain full references for many statements reported, the interested reader should find supporting information with these references, using authors names or publication titles for guidance. Further references relevant to the history and science of solar radiation management are also provided.

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		DAY ONE	Sat, Nov. 18	
Dur.	Time (min)	Description	Speakers & Discussion leaders	
	8:00 30	Breakfast		
	8:30 15	Introduction: Objectives and logistics	Worden, Chatfield, Caldeira, Lowenstein	
	8:45 15	Introduction of participants		
	9:00 20	TALK: Overview of climate energy problem and possible need for geoengineering as an emergency response	Hoffert	
	9:20 20	Discussion	Kheshgi	
	9:40 20	TALK: History of geoengineering proposals	Fleming	
	10:00 15	Discussion	Kheshgi	
	10:15 15	Break		
	10:30 20	TALK: The climate science of intentional modification of Earth's radiative balance	Caldeira	
	10:50 40	Discussion	Rasch	
	11:30 15	Break		
	11:45 20	TALK: Engineering of space environment to modify Earth's radiative balance	Angel	
	12:05 40	Discussion	Worden	
	12:45 60	Lunch		
	13:45 20	TALK: Engineering the atmosphere to modify Earth's radiative balance	Wood	
	14:05 40	Discussion	MacCracken	
	14:45 15	Break		
	15:00 15	TALK: Role of geoengineering in a portfolio of policy options	Wigley	
	15:15 15	Discussion	Hawkins	
	15:30 20	TALK: Social science issues associated with intentional climate modification	Schelling	
	15:50 40	Discussion	Barrett	
	16:30 15	Break		
	16:45 15	TALK: Increasing cloud albedo with sea-salt CCN	Latham/Salter	
	17:00 15	Discussion	Hamill	
	17:15 10	TALK: Consequences of delayed deployment, hazards of failure, and implications of carbon-cycle feedbacks	Matthews	
	17:25 5	Discussion	Tilmes	
	17:30 10	TALK: Use of lunar materials for solar radiation management	Criswell	
	17:40 5	Discussion	Tilmes	
	17:45 10	TALK: Geoengineering the Arctic	Benford	
	17:55 5	Discussion	Tilmes	
	18:00 100	Adjourn / reception		
	19:40	DINNER:		

AGENDA

		DAY TWO	Sun., Nov. 19
Dur.	Time (min)	Description	Speakers & Discussion leaders
	8:00 30	Breakfast	
	8:30 20	TALK: Implications of stratosphere based geoengineering proposals for atmospheric chemistry	Tabazadeh
	8:50 10	TALK: Relevance of simulations of chemical responses to climate change for atmospheric chemistry	Tilmes
	9:00 30	Discussion	Brasseur
	9:30 15	Break	
	9:45 15	TALK: Exploration of geoengineering with stratospheric sulfate aerosols (AGU style 12+3 min)	Rasch
	10:00 15	TALK: Simulation of multiple Pinatubos (AGU style 12+3 min)	Robock
	10:15 15	TALK: First results on a stratospheric sulphate umbrella in the ECHAM5-HAM GCM (AGU style 12+3 min)	Quaas
	10:30 15	TALK: Aerosol-based geoengineering may be more problematic than anticipated (AGU style 12+3 min)	Lacis
	10:45 45	Discussion	Penner
	11:30 15	Break	
	11:45 20	TALK: Prospects for sub-deployment-scale experiments	Keith
	12:05 40	Discussion	Woolf
	12:45 60	Lunch	
	13:45 15	Introduction to breakouts	Lane Caldeira Chatfield
	14:00 90	Breakouts on research questions and approaches: (a) engineering issues (b) chemistry issues (c) climate and ecology issues (d) social science issues	
	15:30 30	Break	
	16:00 30	Reporting of breakout groups	
	16:30 45	DISCUSSION: Research priorities; contrasting designs of possible geoengineering research programs	
	17:15 15	Break	
	17:30 30	Review of main points of meeting / next steps	Lane
	18:00 90	Adjourn/reception	
	19:30	INFORMAL DINNER	

List of Participants and Affiliation

- Angel, Roger** Professor, University of Arizona, Department of Astronomy
- Barrett, Scott** Professor of Environmental Economics & International Political Economy, Johns Hopkins University
- Benford, Gregory** Professor of physics at the University of California, Irvine
- Bergstrom, Robert** Director of Research, Bay Area Environmental Research Institute
- Caldeira, Ken** Department of Global Ecology, Carnegie Institution of Washington
- Chatfield, Robert** Earth Sciences Division, NASA Ames Research Center
- Criswell, David** Director of the University of Houston Institute for Space Systems Operations
- Fladeland, Matthew** Earth Sciences Division, NASA Ames Research Center
- Fleming, James** Professor of Science, Technology and Society at Colby College, Maine
- Hamill, Pat** Professor, Physics Department, San Jose State University
- Hawkins, David** Director of the Climate Center at the Natural Resources Defense Council
- Hipskind, Steve** Chief, Earth Sciences Division, NASA Ames Research Center
- Hoffert, Marty** Professor, Department of Physics, New York University
- Houlton, Benjamin** Post-doctoral Fellow, Carnegie Institution, Department of Global Ecology
- Katzenberger, John** Executive Director, Aspen Global Change Institute
- Keith, David** "University of Calgary, Canada Research Chair in Energy and the Environment Chemical & Petroleum Engineering"
- Kheshgi, Haroon** Corporate Strategic Research. Exxon Mobil Research & Engineering
- Lacis, Andrew** Goddard Institute for Space Studies
- Lane, Lee** Consultant, CRA International
- Langhoff, Stephanie** Chief Scientist, NASA Ames Research Center
- Latham, John** Research Scientist at the University Corporation for Atmospheric Research
- Loewenstein, Max** Earth Sciences Division, NASA Ames Research Center
- Matthews, Damon** Post-doctoral Fellow, Carnegie Institution, Department of Global Ecology
- Penner, Joyce** Professor of Atmospheric Sciences, University of Michigan
- Pomerance, Rafe** Chairman of the Climate Policy Center
- Rasch, Phil** Scientist at National Center for Atmospheric Research
- Robock, Alan** Professor, Department of Environmental Sciences, Rutgers University
- Quaas, Johannes** Scientist, Max Planck Institute for Meteorology
- Salter, Stephen** Engineer, University of Edinburgh
- Schelling, Tom** Professor, University of Maryland School of Public Affairs
- Tabazadeh, Azadeh** Associate Professor, Civil and Environmental Engineering and Atmospheric chemistry at Stanford
- Tilmes, Simone** Research Scientist at the University Corporation for Atmospheric Research
- Wigley, Tom** Senior Scientist, Climate and Global Dynamics Division of the NCAR
- Wood, Lowell** Professor, Physics Department of the University of California LLNL
- Woolf, Nick** Professor of Astronomy, University of Arizona
- Worden, Pete** Center Director, NASA Ames Research Center

Appendix

The workshop included three breakout sessions focused on identifying the key scientific questions that need to be considered to mature the technology and to further understand potential unintended consequences. A main goal of the breakout sessions was to identify a set of researchable questions and model studies. The three breakout sessions included geophysical sciences, engineering, and public policy. This material is placed in the Appendix, not because it is unimportant, but because it is at a higher technical level and thus more relevant to scientists intending to do research in the field. Furthermore, the ideas expressed here represent the preliminary thoughts of a small group of researchers and may not be representative of either their more considered views or the views of a broader and more representative group. Thus, the research issues, questions, and approaches should be interpreted as indicative of the kinds of questions and approaches that a research program might address, with the understanding that a well-thought-out research program may or may not include these specific elements and would almost certainly include elements not considered here.

1. Geophysical Sciences: Climate, Chemistry, and Ecology

This breakout session considered three solar radiation management technologies: (1) the injection of aerosols such as sulfate, soot, dust, and engineered particles into the stratosphere; (2) the modification of low stratiform clouds; and (3) the deflection of solar radiation by a sunshade at the Lagrange (L1) point. These technologies are broken out separately, since the research questions are different for each.

1.1 Stratospheric aerosols

The participants of this breakout session felt that in assessing the effects of aerosols in the stratosphere, it would be useful to define a set of initial calculations to help standardize the outputs from the different General Circulation Models that might be employed in the research.

Inputs: One suggestion for a standard input is to compare the effect of a global shortwave radiation reduction of approximately 1.5 W/m^2 , with a continuous injection of SO_2 (if the model can calculate the aerosol formation) or sulfate aerosol, in either case equivalent to 1 Tg S per year, at the Equator, at a 25 km injection altitude. If it is possible to specify and control the aerosol size, an effective radius of 0.1 microns should be specified.

Standardized runs: Suggested runs to equilibrium included control (yr. 2000), aerosol, $2\times\text{CO}_2$, and aerosol plus $2\times\text{CO}_2$. Alternatively, conduct transient runs with anthropogenic forcing (greenhouse gases and tropospheric aerosols) only, solar radiation management aerosols only, or both. More elaborate runs could consider land use change, volcanic eruptions, and other forcings, but conducting an agreed-on standardized set of runs to sort out differences in the model predictions would be invaluable.

Scientific questions: The scientific questions to address include:

- What is the climate response of aerosol loading, including global average and patterns of temperature, precipitation, insolation, wind, and other climate variables?

- What is the effect of aerosol loading on stratospheric ozone? It is critical that model runs use a standard set of “years,” so that the predicted temperature, Cl, Br, and CO₂ levels correspond. Aerosol loading effects on ozone are expected to be less several decades from now, assuming chlorine levels decrease as expected.
- What effects does aerosol injection have on the biosphere? This depends in a complex way on climate, UV responses, as well as potentially large changes in acid deposition. Are there critical thresholds we need to consider?
- What is the effect on tropospheric pollution as aerosols are both dispersed and removed from the stratosphere?
- Will geoengineering affect the lifetime of other important greenhouse gases by changing tropospheric OH and ozone concentrations or by attenuating UV levels that would slow down their photolysis and subsequent removal?
- If aerosol loading changes the spectral distribution, what are the changes and effects on biology and the carbon cycle?
- What are the effects of sulfuric acid on the probability and properties of ice clouds?
- What are the effects of atomic oxygen, ozone, and UV on the evolution of the aerosol size distribution and how does it effect the lofting of soot?
- What are the relative responses to regional (e.g., Arctic) vs. tropical or other injection sites? How does the height of injection affect the results? Does pulsed vs. continuous injection make a large difference?
- What are the effects of other particles, including engineered particles, and ‘designer mixes’ like carbon black and sulfate or metallics? Proposed materials include resonant materials (jacketed dyes) designed to self-loft. There are questions concerning stability against oxidation, coagulation, and ice/HNO₃ scavenging. Other materials have been suggested such as dielectrics other than sulfates, e.g. diatomaceous earth and oxides such as Na₂O and Fe₂O₃. How does transformation, coagulation/loss and self-lofting affect the results for these materials during their residence in the stratosphere?

1.2 Modification of Low Stratiform Clouds

One of the solar radiation management strategies that was discussed at some length at the workshop was the Latham (1990) and Bower *et al.* (2006) scheme to enhance the oceanic cloud cover, thereby increasing the albedo and reducing heating. This method has the attractive feature that it could be tried on a small scale without significant risk. However, there remain many unanswered questions that should be pursued by both regional and global large eddy simulations. Specific research questions are enumerated below.

Scientific questions:

- How much local radiative cooling would be required for global forcing to counteract the warming? How large a region and what forcing would be required over the oceans?
- Would the local effects be extreme, on the ocean surface temperature, circulation, and ecosystems?
- How would the large local atmospheric response propagate regionally?
- What would be the effect of extra sea-salt on other cloud condensation aerosols (e.g., organics or non-sea-salt sulfate aerosols) within the cloud?
- What would be the effects on cloud dynamics: stratocumulus vs. fair-weather small cumulus clouds?

- What would be the effects on local subsidence velocity and the marine planetary boundary layer structure? How would these perturbations interact with other scales?
- Would a large emission of sea salt have local and regional ecological effects, including on adjacent land areas?
- How extensive are teleconnection effects, such as have been noted with El Niño modification of the radiative and dynamic balance?
- In general, further research is needed to understand the roles of all types of natural and anthropogenic aerosols in modifying cloud albedo, cloud persistence, and the intensity of the hydrologic cycle, both at present and if modified in various locations around the world.

1.3 Deflection of Solar Radiation at the Lagrange L1 Point

The final solar radiation management strategy that was discussed in the breakout session was the deployment of a sun shade at the L1 point. Several research questions for this approach were also identified (see below).

Scientific questions:

- What would be the effects of the proposed -1.8% change of total solar radiation on the climate? Would the proposed shields reduce all wavelengths equally or have a certain spectral distribution?
- If there are large changes in the UV, how would this affect atmospheric chemistry and biology?
- How would the proposed uneven shielding of the Equator and the poles affect climate? A model experiment with this monthly cycle of dimming would be useful.

1.4 Possible experiments that could be carried out in the real world

- Heterogeneous nucleation vs. homogeneous nucleation in the upper troposphere/lower stratosphere.
- Ice observations and experiments in the upper troposphere, now being conducted by NASA, NCAR and a UK consortium.
- One boat or barge emitting salt as an experiment or conducting the experiment from an island. This effort should be part of a study advancing our understanding of climate dynamics and climate sensitivity in the non-engineered case, and important studies should be limited in space and time, minimizing harmful side effects.
- Biological effects of CO_2 and temperature phasing and amplitude decoupled from the normal.
- Historical research: Where have interventions succeeded in the past? Where not?

1.5 Other geoengineering schemes not considered

- Making deserts more reflective
- Modifying ocean albedo
- Reforestation (CO_2 effect, but albedo effect causes warming)
- Ocean fertilization
- Direct absorption of CO_2

2. Engineering considerations

The engineering breakout group acknowledged that the engineering challenges were a strong function of both the geoengineering approach and deployment altitude, which can vary from surface coverings on the ground, to low tropospheric clouds, to aerosols in the stratosphere, to sunshades at L1. The engineering challenges also depend on a number of other factors, such as

- Spectral considerations, such as whether just the UV or the whole solar band was blocked or deflected.
- Spatial consideration, e.g., whether aerosols were deployed in just the Arctic regions or on a world-wide scale.
- Temporal aspects, such as deployment lifetimes and the frequency of any control function.
- Other critical factors such as reversibility, disposal issues, and unforeseen consequences.

The engineering group broke the activities into the categories of design, construction, deployment, station maintenance, and disposal. The following observations were made:

- For vehicles such as sunshades at L1 the chemistry is straightforward, the control problem is manageable, and the optical design work would be affordable. The group questioned whether mass production techniques could give micron size features over millions of square kilometers.
- For low orbit vehicles it was thought that much higher masses would be needed to ensure stability and that there would be high risks of collisions.
- Stratospheric scattering with either vehicles or aerosols share many design features with L1, but the harsh chemical and UV environment poses operational challenges. While initial zonal concentration at say the poles was possible, there were concerns about drift and fallout.
- Research into materials and optical coatings that could produce alternatives to SO₂ was recommended
- It was noted that operation in the troposphere placed heavy demands on biological acceptability with many materials giving rise to safety concerns.
- Participants regarded the Latham proposal to use seawater aerosol to exploit the Twomey effect as likely to be cheap, fast to develop, fast to respond, locally variable, rapidly stoppable, incrementally installable and very like what happens already with breaking waves and spouting whales.
- There should be a user friendly climate model with easily variable inputs for engineering design work.
- The Department of Defense should be encouraged to declassify relevant information.
- Curriculum should be designed to train a generation of geoengineers with emphasis on system engineering.
- We should build an 'atmospheric test tube' with full and instantaneous control of temperature, pressure, light radiation, electro-magnetic field with close, high speed observation and analysis of all variables to help in design work.

3. Public policy research tasks

The policy sciences breakout session briefly examined several aspects of solar radiation

management likely to raise researchable questions. As time was limited the following discussion focuses more on identifying key questions and less on defining specific research projects that might contribute to answers.

3.1 Under what conditions would solar radiation management be acceptable to the public?

The answer could differ depending on whether the issue was posed in terms of R&D or in terms of deployment. At the moment only R&D is relevant. Eventually, however, R&D would be unimportant if deployment were likely to be politically impossible.

As already discussed, the two solar radiation management deployment strategies explicitly proposed at the workshop envision two quite different sets of political circumstances at the initial decision point. The preemptive deployment strategy is likely to face more severe political challenge. In assessing the political acceptability of preemptive deployment, analysts might wish to conduct the following kinds of studies:

- Case studies of past government interventions, especially those that entailed public education, might illuminate the political strategies available to both proponents and opponents.
- Such studies should encompass both domestic and international politics.
- Base line studies of public attitudes and those of the policy elites might also suggest possible strategies. Specifically, 'qualitative' opinion research might illuminate the realism of using solar radiation management research as a bargaining chip.
- The risk education literature may suggest options.

As in the larger workshop participants discussed the relationship between mitigation and solar radiation management. Clearly in the minds of some, these strategies are rivals. To others, they are complements. As a practical matter, if solar radiation management proves technically feasible, some combination of strategies is the likely outcome. In either view, improved understanding of the costs and benefits of each approach would enable better decision making. This suggests several possible lines of analysis including the following:

- Conventional benefit/cost analysis of mitigation needs to account for recent developments. Assessments of the risks of abrupt climate change may be increasing. However, analysis by Montgomery, David and Tuladhar (2006) suggests that because of institutional factors omitted in conventional climate models Chinese and Indian greenhouse gas abatement costs are likely to significantly exceed previous estimates. Benefit/cost analysis of mitigation strategies should be updated to reflect both sets of findings.
- In some future solar radiation management scenarios, decision makers may need to make trade-offs between ozone depletion and climate change. While more scientific research is required for a definitive assessment, economists might suggest some initial comparisons of the potential costs involved in this trade-off.
- Scientific research and economic analysis should better define the CO₂ emission damage functions related to ocean acidification.

3.2 Organizational questions and governance

Part of the question relates to managing the R&D phase of solar radiation management. Part however extends to deployment. The question of how best to organize R&D on solar radiation management surfaced in the workshop discussion.

- One research option is, again, use of case studies. For example, there has been at least one recent case study of the suitability of the model of the Defense Advanced Research Projects Administration as a model for climate and energy related R&D (Van Atta 2006). Other models are possible, and other case studies could reveal their advantages and disadvantages.
- Research on climate issues partly shares the global public good characteristics of mitigation strategies. This fact argues for an international negotiation to share costs and knowledge. Proposals have surfaced for a new international negotiation outside the Kyoto and UNFCCC frameworks. Policy analysis designed to explore how such a negotiation could foster progress on solar radiation management might be worthwhile.
- Which treaties, if any, would constitute possible barriers to solar radiation management? The Montreal Protocol might be one and other examples were mentioned although not entirely convincingly.
- Should there be a global scientific assessment as part of a research agenda? Should it be undertaken within the Intergovernmental Panel on Climate Change, for example, as a special report?

The break out group concluded that some level of follow up was appropriate. Options include a conference, one or more workshops, or an ongoing steering committee.

4. Ozone depletion considerations

As described in the text, potential interaction of sulfate aerosols, stratospheric chlorine and temperature affects of global cooling create uncertainties about solar radiation management's possible impacts on ozone depletion. Some specific comments and observations by workshop participants relating to ozone depletion are noted below. Overall, it was felt that the uncertainties warranted further research in this area.

- Increasing the surface area of sulfate particles in the stratosphere could increase the environment within which ozone depleting chemical reactions occur.
- With colder temperatures, sulfate aerosols become liquid or solid rather than gaseous. This change of state allows processes such as heterogeneous catalysis to contribute to chemical changes (see Drdla, 2007, Tilmes *et al.*, 2006, Tilmes *et al.*, 2007 and Tabazadeh, 2004).
- While the concentration in the stratosphere of ozone depleting chemicals remains significant, policies introduced in the wake of the Montreal Protocol are causing these concentrations to fall. Later in this century, chlorine concentrations are expected to reach levels at which ozone depletion is very unlikely to constitute a serious concern with sulfate-based solar radiation management technologies.
- Sulfate injections affect stratospheric temperatures, which, in turn, affects mid-winter Arctic ozone depletion. The absorption of solar radiation by particles leads to a general warming effect. The expected outcome for a stratosphere with both particles and higher greenhouse gases is for slight cooling (Rasch, 2007). Further research is needed to quantify these effects.
- Polar stratospheric wintertime temperatures also vary more dramatically than do those at the surface. Robock (2000) describes how these stratospheric temperature variations are driven by a complex mechanism involving wintertime weather pat-

terns in the lower atmosphere. Further research is needed to fully understand the temperature effects of high sulfate aerosol loading.

- General ozone levels in the stratosphere will have nearly the same temperature responses as those without aerosol injections, although slightly less cooling of the stratosphere is to be expected (Rasch *et. al.*, 2007).
- Injections of sulfur species just over the Arctic could be substantially gone by December when ozone depletion becomes possible. This protects mostly the summer-time Arctic Ocean region (north of 70 N). Further studies could confirm that intended geoengineering shielding effects would greatly outweigh ozone depletion.
- The Pinatubo aerosol injection produced so much material that the size of the aerosol was substantially larger from a “best-designed” small injection; both climate cooling due to reflection and ozone-depletion effectiveness differ from the geoengineering situation. This suggests overall somewhat less ozone depletion for the small geoengineering injections, but also the need for more study.
- Silica particles can act as a surface allowing condensation of sulfuric or nitric acids at temperatures less extreme than required for sulfuric acid aerosol implicated in seasonal North-Polar ozone destruction. “Inert” particles with an acid/water coating maximize the surface area per unit mass of acid for chemical reactions, which could further accentuate North Polar seasonal ozone destruction. Further studies of particles, especially designer particles, under stratospheric conditions are required.
- Intensive studies of any moderate to large volcanic eruptions affecting the stratosphere and global temperatures are extremely important, both to quantify possible solar radiation management effects and simultaneously to study the mechanisms defining climate sensitivity.

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