# Written Testimony

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I would like to thank the committee for the invitation to provide testimony at this hearing. I am aware that this is the second of three hearings on geoengineering, and that you have already been introduced to many of the concepts behind geoengineering at your previous hearing. A number of important documents were submitted during the previous hearing. I will not submit any more beyond my own testimony during this hearing, but I do refer to a few more scientific papers that I think are relevant (listed in the references at the end). I have attempted to strike a balance between repeating some of the information covered in the last hearing to provide continuity, and new material.

There are two classes of geoengineering (the intentional modification of the Earth's Climate) being discussed in the scientific community and by the congressional committee: 1) Approaches designed to draw down the concentration of Greenhouse Gases, to reduce Global Warming; and 2) "Solar Radiation Management". You asked me to focus on Solar Radiation Management, with particular attention to stratospheric sulfate aerosols, and marine cloud whitening. I will try to respond to the specific questions that you listed in your letter, and will also provide additional information where I think it relevant.

**What is Solar Radiation Management?** Solar Radiation Management refers to the idea that mankind might be able to influence the amount of sunlight reaching the surface of the Earth deliberately. Scientists sometimes use the terms "radiation", "light", "energy" and "heat" in this context interchangeably. So "Solar Radiation Management" really means, "managing the amount of sunlight reaching the Earth's surface". The global temperature of the planet is determined by the Earth system finding a balance between the energy absorbed from sunlight, and the energy leaving the atmosphere as radiant energy (heat) in the infrared part of the electromagnetic spectrum. The idea behind Solar Radiation Management is that if mankind could find a way to make the planet a little more reflective to sunlight, then less would be absorbed by the Earth, and the planet will be slightly cooler than it would otherwise be. **So Solar Radiation Management is designed to cancel some of the warming that we expect from increasing Greenhouse Gas Concentrations.**

**Note that even if Solar Radiation Management succeeds, it will not cancel all the effects of increasing greenhouse gas concentrations**. The increasing acidity of the oceans with its impact on ocean life is a good example of a consequence of increasing CO2 that will not be treated by Solar Radiation Management.

Before jumping in further, I want to get past a few "buzzwords" immediately. From here on I will often replace the term "Solar Radiation Management" with the word "geoengineering". And I will often loosely refer to the "changes in the amount of energy entering or leaving some part of the planet because of some climate factor" as a "forcing". So there is a forcing associated with increasing greenhouse gases, and there is another forcing associated with Solar Radiation Management. The idea is to try to match the forcings so that they kind of cancel.

**Preliminary Remarks on Geoengineering Research Goals and Expected Outcomes**: There are many uncertainties in geoengineering research. Identifying the consequences of geoengineering to the climate of the planet is at least as difficult as identifying the changes to the planet that will occur from increasing greenhouse gases. Just as scientists cannot be certain of all of the consequences of doubling (or more) the concentration of CO2 to the planet, we cannot be certain of the outcome of any particular strategy for geoengineering the planet to counter that warming. What science can do is use the same tools and body of knowledge to indentify likely outcomes from either class of perturbations to the planet.

I am not sure we could ever be certain of the outcome of geoengineering. I think it is important to recognize that geoengineering is a gamble. The decision to try geoengineering in the end will probably be based upon balancing the consequences of a negative outcome from geoengineering against the negative outcome from "not geoengineering".

I believe there are a variety of activities to consider for geoengineering research:

- **Assessment, Integration:** to brainstorm, review suggested strategies, and identify obviously unsuitable suggestions. Only a little work has been done to evaluate proposed strategies for efficacy and costs (e.g. Royal Society report, 2009 and Lenton and Vaughan, 2009).
- **Computer Modeling:** There are a variety of kinds of modeling studies that are relevant to geoengineering.
    - Climate models and Earth system models are needed that provide a global view about interactions between many parts of the climate system over time scales as long a centuries.
    - "Process Models" that include a lot of detail about one specific feature of the Earth system are also needed. These kinds of models might describe how for example cloud drops might form, but they neglect anything that isn't central to that understanding, like what the rainfall was a thousand miles away. They do calculations that are generally far too expensive to be used for a global computer calculation but they are incredibly useful for understanding how a particular process operates. Science frequently uses global models to produce a broad view of geoengineering outcomes, but for those strategies that look promising, increasingly stringent levels of analysis are required to see whether the simple assumptions used in a climate model hold up. Process models are used to understand important details.

  - Other models may also be needed for a broader set of questions (for example the impact of geoengineering on ecosystems or the economy).
- **Lab and Fieldwork:** Lab and fieldwork are critical to assure a thorough understanding of the fundamental physical process important to climate and that computer models are reasonably accurate in representing that process. I think it is critical to distinguish between "small scale field studies" where we might introduce some particles into the atmosphere over such a small scale that they would have negligible climate impact, and "full scale deployment" where we expect to actually have a climate impact. *Field studies might try to induce a deliberate change to some feature of the earth system at a level with a negligible impact on the climate, but the change would allow us to detect a response in a component important to climate*. For example, with Cloud Whitening one might try to modify a cloud, or a group of clouds by introducing a change over a very small area, over and over again for a month, to see whether we really understand how that kind of cloud works, and whether models can reproduce what we see in the real world. With Stratospheric Aerosols one might envision devoting a few aircraft to trying to deliver the material needed to make aerosol particles in the stratosphere, and then look to see whether the right size particles form, and how long they last.
- **Technology Development:** to develop equipment and measurement strategies that might be used for process studies, for exploratory trials, or as prototypes for full deployment. Some work has been done to develop plans for the devices needed for the cloud whitening strategy, and the ships that could deploy the sea salt particles.
- **Deployment Activities**: Obviously, one can envision a gradation of experiments to the climate, ranging from those with no impact, to those having a huge impact. **I am going to reserve the word "deployment" to refer to geoengineering designed to have a big impact on climate. I don't think scientists know enough today about geoengineering, and so I don't think we are ready for "deployment". I am going to avoid much discussion of full deployment scenarios for the rest of my testimony except to tell you what a climate model says might happen, and to acknowledge that when and if we think we understand geoengineering well enough to deploy it we must consider many new issues.** Monitoring, infrastructure, energy consumption, economic modeling, governance, and much else are needed if we reach a stage where deployment is viable.

**Preliminary Remarks on Costs associated with Geoengineering Research.** The costs are determined in large part by the goals of the research, and the outcomes that are to be achieved.

In my opinion before a nation (or the world) ever decided to deploy a full scale geoengineering project to try to compensate for warming by greenhouse gases it would require an enormous activity, equivalent to that presently occurring within the modeling and assessment activities associated with the Intergovernmental Panel on Climate Change (IPCC) activity, or a Manhattan Project, or both. It would involve hundreds or thousands of scientists and engineers and require the involvement of politicians, ethicists, social scientists, and possibly the military. These issues are outside of my area of expertise. Early "back of the envelope" calculations estimated costs of a few billion

dollars per year for full deployment of a stratospheric aerosol strategy (see for example, Crutzen, (2006) or Robock et al (2009b)). These numbers are very rough. I am not sure it is worth refining them much at this time, due to the many uncertainties that need to be resolved by exploratory research.

There are many smaller steps that can be taken to make initial progress on understanding geoengineering at a much lower cost, and at a level that does not require an international consensus, or actually introduce significant changes in the Earth's climate. These steps are worth doing because they allow us to identify obvious deficiencies in geoengineering strategies, and revise or abandon the problematic strategies.

To put my recommendations on future research in context, I want to start by summarizing the research taking place today, and estimating the costs associated with that research.

*The research that has been done so far has been done on a shoestring budget.* I am aware of 3 research groups in the US that have done substantial geoengineering research in the last 5 years (I believe there are now 4 groups). Some of that work was done by postdoctoral researchers or students with fellowships allowing the freedom to work on any topic of their choice. Other work was done because a faculty member or a scientist like myself (in my previous position) had some small amount of flexibility in his or her appointment that allowed them to do research on geoengineering for a small fraction of their time. I believe that there are now two very small research grants sponsored by US government agencies that explicitly support GEOE research totaling about $200,000/year. The "implicit" funding I described might double that contribution. Foundations have also contributed funding for geoengineering that may amount to another $500,000 per year.

*I estimate the total (2009) budget for all geoengineering research within the US is probably $1M/year or less. Perhaps half of that is from private foundations*.

There is a single major European Proposal funded by the EU at $1.5 Million per year to fund geoengineering research, and a number of activities started in the United Kingdom on geoengineering that total perhaps $1.6 Million per year. I believe that Germany is also now considering funding some geoengineering research.

I think the Apollo Program to send a man to the moon took place over about 10 years, and ran about $20 Billion dollars (http://spaceflight.nasa.gov/history/apollo) so that comes to about $2 Billion per year. And those costs are not cast in today's dollars, so it would appear to be more if we adjusted for inflation.

I estimate from the US Climate Change Science Program 2009 budgets (http://www.usgcrp.gov/usgcrp/Library/ocp2009/ocp2009-budget-gen.htm) that the total for climate science in the US is about $1Billion per year.

So the current spending on geoengineering research is tiny compared to these activities. And maybe it should be, that is not for me to decide. I think that is your job in part. But I can tell you that $10, 20, or $50 Million per year would have an enormous effect on the research activity in this area.

Finally, it is worth writing a little bit about costs of field experiments. Although the comprehensive, international and successful VOCALS field research experiment conducted off Chile in 2008 had no geoengineering component to it, the range of techniques and measurement strategies involved were very similar to those required for a limited-area field test of the cloud whitening scheme discussed below. VOCALS cost $20-25 Million.

Now, on to your questions.

**How does stratospheric sulfate aerosol achieve the necessary radiative forcing?**

Mankind has known for many years that the planet cools following a moderately strong volcanic eruption (like Pinatubo). We believe that the planet cools because volcanoes inject a lot of a gas called sulfur dioxide into the layer of the atmosphere called the stratosphere (a stable layer in the atmosphere with its base at about 10km near the poles, and about 18km at the equator). This gas undergoes a series of natural chemical reactions that end up producing a mixture of water and sulfuric acid in small droplets we call sulfate aerosols. *These sulfate aerosols act like small reflectors that scatter sunlight. Some of the sunlight hitting these drops gets scattered down, and some up. The part that goes up never reaches the surface of the Earth and so the Earth gets a bit cooler than it would otherwise*.

The geoengineering idea is to inject a "source" for aerosols into the same region of the atmosphere that volcanoes tend to inject the gas. I use the word "source" to refer to either a gas like sulfur dioxide (or another gas that will eventually react chemically and form sulfate aerosols), or to inject sulfuric acid (or some other particle type) directly. The expectation is that similar particles to those following a volcanic eruption will form from that source, and the earth will undergo a cooling similar to a volcano. The idea is to reduce the amount of energy reaching the surface of the earth to introduce just enough to balance the warming caused by increases in greenhouse gases. If the particles were like those that formed after Pinatubo we think that an amount like one quarter of that injected by Pinatubo per year would balance the warming that we expect from a doubling of CO2 concentrations if it were injected at tropical latitudes. These numbers might change if the aerosols were injected in Polar Regions.

You might also be interested to know that scientists have occasionally considered using other kinds of particles to do geoengineering. But you asked me to focus on sulfate aerosols so I will not discuss other particles further.

**Scale and amount of materials needed.** The amount of material needed depends upon the size of the particles that form. Little particles are better reflectors than big particles,

and big particles also settle out faster than little ones do, so it is desirable to keep them small. Unfortunately, the size of the particles that form is a really complicated process. It depends upon whether particles already reside in the volume where the source is introduced. If particles already exist near the place the source is introduced then the source will tend to collect on the existing particles and make them bigger, rather than making new small particles. One of the main challenges to this geoengineering strategy is finding a way to continue to make small particles. One very recent paper (Heckendorn et al, 2009) suggests that first studies underestimated how quickly big particles will form, and that more of the source will be needed than the first studies assumed (perhaps 5 times as much). *One challenge to this type of geoengineering research is to establish whether it is possible to produce small particles deliberately at the appropriate altitude for long periods of time.*

**Over what time period would deployment need to take place?**

If the geoengineering works as we have seen in climate models [that is, it cooled the planet] there would be very strong hints that the strategy was working within a couple of years of deployment. Scientists would certainly be more comfortable considering averages of 5 to 10 years of temperature data before making very strong statements about temperature changes. It would also take multiple years to sort out all the consequences (good and bad) to precipitation, sea ice, etc. Some of the known negative consequences from this type of geoengineering would be evident quickly (e.g. impact on concentrations of ozone in the stratosphere, changes in the amount of direct sunlight useful for solar power concentrators, and other consequences discussed in Rasch et al, 2008 and Robock 2009). Some effects, like those on ecosystems, might take more years to manifest. I don't think anyone has yet looked at impacts on ecosystems.

**How would we do the deployment?** This geoengineering strategy would require deploying the particle source year after year, for as long as society wanted to produce a cooling. Aerosols introduced in the stratosphere will gradually mix into other layers in the atmosphere as they are blown around by winds or as gravity draws them into lower layers where they are rapidly removed. Aerosols in the stratosphere tend to last about a year before being removed (shorter near the poles where the aerosols get flushed out faster, and longer near the equator). One strategy is to deploy the source near the equator, and allow the particles to spread as a thin layer over the whole globe (this is roughly how things worked for Pinatubo). This would apply a cooling that is relatively uniform over the globe. Model studies usually assume that the source would be introduced steadily near the equator over the course of a year. Another strategy might be to produce the particles only near the poles during the spring, and let them get flushed out over the course of a summer (because they are flushed out faster near the pole). While the aerosols are located above the poles, they would shield the sea ice to keep the poles cooler in summer, and then allow the aerosols to disappear during winter when there is no sunlight at the poles anyway. Robock (2009) has shown that the particles actually spread and produce a cooling beyond the Polar Regions.

**An important issue to note is that will be substantial difficulties in evaluating this geoengineering strategy without full deployment. This makes it difficult to improve our understanding slowly and carefully using field experiments that do not change the Earth's climate***.* The issue is this. We know from volcanic eruptions that stratospheric aerosols reside at these high altitudes for long periods of time (months to a year or so), and over that time, no matter where the aerosols are initially produced, they will spread to cover quite a bit of a hemisphere. We also know stratospheric aerosols develop differently if a source is introduced where aerosols already exist compared to the way they would form if there are only a few aerosols around. A fully implemented geoengineering solution would require that the aerosols cover a very large area of the globe with high concentrations. So it is important that we study the aerosols in an environment where they exist in high concentrations.

But to avoid introducing a large perturbation to the atmosphere with consequences to the Earth's climate during exploratory tests it would be desirable to start by introducing the aerosol over a very small patch of the earth. However if one started with a small patch of aerosol, then it will mix with the rest of the atmosphere and dilute quite rapidly, and we do not expect the aerosol to evolve in the same way when the particles are dilute, as they would if there were a lot of them around. It will also be difficult to monitor their evolution if there aren't many of them around.

So we are caught between rock and a hard place. Too small a field test, and it wont reveal all the subtleties of the way the aerosols will behave at full deployment. A bigger field test to identify the way the aerosols will behave when they are concentrated will have an effect on the planet's climate (like Pinatubo did), albeit for only a year or two. I have not seen a suggestion on how to avoid this issue.

**How long the direct and indirect impacts would persist:** Model simulations, and observations of volcanic eruptions suggest that when the source is terminated, most of the aerosols would disappear in a year or two. Models suggest that the globally averaged temperature would respond by warming rapidly (over a decade or so) to the temperature similar to what would occur if no geoengineering had been done (Robock et al, 2008). The rapid transition to a warmer planet would probably be quite stressful to ecosystems and to society. *There might be other longer timescale responses in the climate system (in Ecosystems (plant and animal life) because it takes many years for plants and animals to recover from a perturbation (think of a forest fire for example). Deep ocean circulations also respond very slowly, so it would take many years to influence them, and many years for them to recover. These effects have not been looked at in climate models and it is another area meriting scientific research.*

**State of Research on geoengineering by stratospheric aerosols** Here is a very brief overview of research has been taking place given the current "shoestring budgets":

1. **Assessment, Integration**: As mentioned above, the papers by Lenton and Vaughan (2008), and the report of the Royal Society (citation) provide some assessments of this strategy compared to others. Those studies are already

somewhat out of date, given the additional information from studies over the last 2 years.

2. **Modeling**: A number of papers have appeared in the scientific literature exploring consequences of geoengineering with stratospheric aerosols using global models. These studies essentially frame the questions by assuming that it is possible to deliver a source gas to the stratosphere, and that gas will produce particles similar to the ones produced after the Mount Pinatubo eruption. Then they proceed to ask questions like "What would be the effect of those aerosols on the Earth System?" using standard climate modeling techniques. The community is beginning to transition from the first "quick and dirty look" (e.g. Robock et al, 2008; Rasch et al, 2008). Each modeling group that explored stratospheric aerosol geoengineering did it a different way. Alan Robock has proposed that modeling groups try to compare their stratospheric aerosol geoengineering studies in a more systematic for the next IPCC assessment. Only one group (Heckendorn) has tried to understand the details of formation and aerosol size evolution, and they used a model framework with a number of very significant simplifications. It would be desirable to remove those simplifications. It is also time to begin assessing the evolution of the source of the aerosol from the time it is delivered from an aircraft until it spreads to a larger volume (like a few hundred km). Rasch et al (2008) revisited research performed during the 1970s and 1980s to estimate the aerosol formation and evolution after the source is released from an aircraft.
3. **Lab and Field Studies**: I am not aware of any efforts to conduct or plan lab or field studies to understand component processes important for this kind of geoengineering.
4. **Technology development**: I am not aware of any efforts to assess or develop technologies for producing the stratospheric aerosols.
5. **Deployment**: There has been one study that tried to assess the cost of just lifting various candidate compounds to the needed altitude using existing technology (Robock et al, 2009). There have been no studies yet published that explore what the optimal source gas or liquid is, how it should be injected into the atmosphere, or how to optimally deliver it. I know that David Keith, who is also testifying here, has thought about this, and he can do a better job briefing you on this activity than I.

**Cost estimates and recommendations for an improved research program for stratospheric Aerosols:**

A few $10s of Million per year funding for research would allow substantial theoretical progress in geoengineering research through modeling, and perhaps some proto-typing of instruments to produce the aerosol source, and specialized instruments for measurement. It might be sufficient for a field program every other year.

**Here is an incomplete list of some of the tasks that should considered in terms of the topics the committee charged me with addressing: 1) Research,**

**2) Deployment, 3) Monitoring 4) Downscaling, cessation and necessary environmental remediation, and 5) Environmental impacts:**

1) **Research**: There are many opportunities for research. Here are a few ideas.
   **Detailed Models**
   a. Systematic assessment of particle formation and growth using size resolved aerosol models. Two different kinds of models would probably be required: 1) A plume model to deal with the evolution of the particles from source release to the point that the plume has grown to maybe 10km in horizontal extent and a few hundred meters in the vertical, 2) a size resolved aerosol model to track the particle evolution from 10km until the aerosol has been removed. Investigator could be tasked with exploring whether one would inject particles or a gas as a source, the strategies for the temporal and spatial scales of injection, and sensitive to the environment that the source is injected (e.g. do the particles developed differently if the air already contains aerosols).

   **Global Models**
   a. Global models indicate a number of positive and negative consequences to the planet from geoengineering. The first "quick and dirty" calculations described above produced different cooling responses, and different precipitation responses in different models. We don't yet know whether the differences are due to model differences, or different assumptions about emissions, particle size, etc. It would be good to systematize studies of geoengineering across multiple models to help in assessing uncertainty about the effect of geoengineering.
   b. We need to make sure that the global models are producing similar pictures of aerosol formation, coalescence and removal to the picture provided by the detailed process models.
   c. Very little work has been done in exploring sensitivity to injection scenarios. For example we don't know whether the geoengineering may have a different impact if we produce the aerosol at a constant rate over a year, or mimic a volcanic injection every other year.
   d. There has been no assessment of the impact of the geoengineering aerosol on homogeneous nucleation of ice clouds
   e. There has been no exploration of how changes in how geoengineering might affect ecosystems (plants and animal health)

2) **Field testing and Deployment**
   a. How do we deliver the source to the region of release? A variety of delivery mechanisms have been proposed, but none have been tested, and no engineering details have ever been developed to the point that costs could be assessed.
   b. Once we have a detailed idea of precisely what source we want, can we produce that source?
   c. Plan an exploratory field experiment to help understand the formation and evolution of the particles for the first few weeks. After injecting the source in the stratosphere do particles form as models suggest? How do we track the plume? What instruments are required to measure the particle properties, the

plume extent, and the reduction in sunlight below the plume. Do the particles coagulate and grow as our models suggest? Do the particles mix and evolve the way our models tell us they will (from source to the first scale, and from the first scale to the globe scale?).

3) **Monitoring:** We don't have much capability of monitoring the details of sulfate aerosol from space any more (we had better capability in the past before the NASA SAGE instrument died). This issue is documented in some of the contributions submitted by Allen Robock in the previous hearing. It would also be good to develop a "standing task force" that was capable of monitoring the detailed evolution of the aerosol plume following a volcanic eruption. This would allow us to gain significant understanding of plume evolution without the need to produce a source for the aerosol.
4) **Downscaling, cessation, environmental remediation**.
    a. The only insight that we have about impacts of the geoengineering by sulfate aerosols come from that gained from the global climate model studies, and seeing the impact of climate changing volcanic eruptions. Both classes of studies suggest that if the source for stratospheric aerosols was turned off, the aerosols go away within a year or two, and the climate returns to a state much like it was before the stratospheric aerosols over a decade or so. The rapid return of temperature to the ungeoengineered state would probably produce significant stresses to society, and ecosystems, but no studies have been done to explore this.
5) **Environmental Impact**: There are a variety of possible environmental consequences, which have been described in the studies by Rasch and Robock submitted at the last hearing. Among them are a) changes in the ratio of direct to diffuse sunlight, with possible impacts on ecosystem, and solar electricity generation; b) changes in precipitation patterns; c) changes in El Nino.

**Which U.S. Agencies might be involved:** I can easily identify expertise and capability in the following agencies:

1) NASA (which has a long history of interest in particles and chemistry at the relevant altitudes through its High Speed Research Program and Atmospheric Effects of Aviation Programs, as well as the capability of remote sensing of particles and their radiative impact from space and the surface),
2) NSF (many university researchers can also contribute to the same parts of the project that are mentioned for NASA).
3) There are individual research groups within DOE and NOAA that could make important contributions to modeling, field campaign and measurement programs.

**How does marine cloud whitening achieve the necessary radiative forcing?**

*The idea behind "Solar Radiation Management" by "cloud whitening" is to make clouds a bit "whiter" (a bit more reflective to sunlight) than they would otherwise be.*

Clouds are enormously important to the climate of the earth. Everyone has experienced the cooling that results on a hot summer afternoon when a cloud goes by overhead and

shades the earth. This occurs because the cloud reflects the sunlight that would otherwise reach the surface and heat up the ground. Clear winter nights will frequently be much colder than a nearby night when the sky is overcast. This is because high clouds "trap" heat that would otherwise escape to space. So it is warmer when high ice clouds are around.

These features of clouds acting to cool or warm the planet are (like the stratospheric aerosols) due to their impact on "radiation" (again loosely identified with "energy", or "light", or "heat"). Low altitude liquid clouds tend to cool the planet more than they warm it. High altitude ice clouds also act to warm the planet, by trapping some of the energy that would otherwise escape to space. Scientists believe the low cloud effect wins out in terms of reflecting or trapping energy, and clouds as a whole tend to cool the planet more than they warm it.

It is easy to find a few places on the planet where we know that mankind makes clouds "whiter" (by which I mean more reflective) because we see evidence for it in satellite pictures. These are the areas where "ship tracks" occur. In these special regions dramatic changes occur in cloud properties near where the ships go. Scientists believe that the clouds are whiter due to the aerosols emitted as pollution by the ships as they burn fuel. The extra aerosols in the clouds change the way the cloud develops, and this makes it whiter, as I describe below.

All clouds are influenced by (both man-made and natural) aerosols. Every cloud drop has an aerosol embedded in it. Cloud drops always form around aerosols. The way that aerosols interact with a cloud is determined by the size and chemical composition of the aerosol, and by the cloud type. To make an extreme simplification of a very complex process, the general idea of geoengineering a cloud goes like this. If one introduces extra aerosol into a region where a cloud is going to form, then when the cloud forms, there will be more cloud drops in it than there would otherwise have been. *The term "seeding" has been introduced to describe the process of introducing extra aerosols into an area.* It ends up that if cloud has more drops in it, then it tends to be whiter than if it had fewer drops. Again, this is a simplification. The whiteness also has to do with the size of each cloud drop, and how it changes the way that the cloud precipitates, but I am trying to keep the discussion short.

It is possible to demonstrate the whitening effect by aerosols for many cloud types over many regions, but the effect is most dramatic in the clouds that form in ship tracks.

The whiteness of a cloud is influenced by many factors. Aerosols are critical but certainly not the only important factor influencing a cloud. One type of cloud (for example mid-latitude storm clouds seen in Washington in January) will respond differently to aerosol changes than another cloud type (for example the marine stratocumulus seen off the coast of California).

The whitening phenomenon is believed to occur in many cloud systems, but the effect may be most important in marine clouds near the Earths surface. Also clouds generally

become more important in reflecting sunlight over oceans because the ocean surface reflects less sunlight than the land or snow even without clouds, so putting a bright cloud over oceans cools the Earth more than if you put the same bright cloud over already bright land or ice.

Scientists have speculated that geoengineering could be performed by whitening many clouds over oceans deliberately, rather than whitening a few of them accidently as we do today with "ship tracks". The idea is to introduce tiny particles made of sea salt into the air near where clouds might form, rather than the pollution particles produced by freighters, and to do it in a lot more places in a controlled and efficient way. Scientists think this seeding might make the clouds whiter, and thus make the planet reflect more sunlight, and become cooler.

Conceptually, the idea is quite simple, but realistically many complications come into play. Clouds are enormously complex features of the atmosphere. While we know a lot about the physics of clouds, we aren't good at representing their effects precisely. One of the most complex and uncertain aspects of clouds is in understanding and predicting how clouds interact with aerosols (the so called "Aerosol Indirect Effect"). This complexity is well described in the Fourth Assessment by the Intergovernmental Panel in Climate Change (AR4, 2007). While we know that there are situations where additional aerosol will make a cloud whiter, we also believe there are situations where putting extra aerosol into a cloud will make little or no difference.

The idea behind cloud whitening as a geoengineering strategy is thoroughly described in a review paper by Latham (2008). Some hints about the complexities associated with changing cloud properties can be found in the papers by Wang et al (2009a, b). Some of the difficulties in treating aerosol cloud interaction are discussed in the paper by Latham et al (2008), and the papers cited there. A very recent review of the reasons why aerosol cloud interactions are so difficult to treat in models can be found in Stevens and Feingold (2009). Some preliminary scoping work has been done to consider how one might design a field experiment to explore changing the reflectivity of a cloud. This is discussed below.

*One very attractive consequence of doing a limited field test of whitening clouds by geoengineering is that it provides an opportunity to get a fundamental handle on the "Aerosol Indirect Effect". Trying to whiten a cloud, or a cloud system, is a fundamental test of our understanding of how a particular cloud type works, and of the ways in which clouds and aerosols interact. Because the Aerosol Indirect Effect is one of the critical and outstanding questions in climate change, doing that kind of field experiment would be of incredible value.*

**Scale and amount of materials needed:** Latham et al (2008) and Salter et al (2008) have estimate that the total amount of aerosol that needs to be pumped into that atmosphere is about 30 $m^3$ per second. They estimate that it might require X ships deployed over a large area (perhaps as much as 30% of the ocean surface) to distribute that sea

**Over what time period would deployment need to take place and how would we do the deployment?** One interesting and important difference between geoengineering using stratospheric aerosols, and geoengineering using cloud whitening is that the very short lifetime of clouds and aerosols near the surface (of a few days or less) means that if one is able to change clouds the changes will be local, and it should be possible to "turn on" and "turn off" the changes in reflectivity of the clouds very quickly (on the time scale of a few days).

There is a lot of variability in clouds, and scientists considering geoengineering by cloud whitening don't expect to change clouds as dramatically as a ship track does. The changes will be subtle and some care will be required to "detect" the change in clouds.

The fact that the response by clouds to the aerosols is immediate and local is good and bad. The positive aspect is that a meaningful experiment can be designed to try to change clouds in a small region for a short time. Since one can restrict the experiment this way it is possible to be very confident that a small test would have no discernable effect on the Earth's climate, but it would be a meaningful test. (I have indicated that this is a difficult for Stratospheric Aerosol Geoengineering). One could imagine trying field experiment at successive locations to see whether it was possible to change particular types of cloud to gain knowledge and experience about cloud, aerosols, and cloud whitening. This means that designing a program to explore the cloud whitening concept and examine the impact on clouds in an incremental fashion is much easier than doing it with stratospheric aerosols.

With either the stratospheric aerosol strategy, or the cloud whitening strategy the goal is to reduce the amount of sunlight reaching the Earth's surface a bit. If the strategy spreads out the shading over a large area (as done with the stratospheric aerosol strategy) then it is not necessary to make much change in sunlight reaching the surface anywhere. If the strategy concentrates the changes over smaller areas (as done with the cloud brightening strategy) then the change in sunlight reaching the surface will be larger at those locations. So geoengineering by cloud whitening is likely to introduce stronger effects locally than would be seen in the stratospheric aerosols.

If it does prove possible to deliberately change the whiteness of a cloud system, then it would be possible to ramp up the activity, increasing the ocean area and the duration of time that the cloud systems are affected to the point that the Earth's climate should be influenced. Obviously larger and larger communities of stakeholders would need to be involved as scope of the project increased.

If changing the cloud forcing was effective and it was ramped up to the point that it is influencing the climate then other issues must be considered. It ends up that the local changes in cooling patterns are likely to set up stronger responses in weather and ocean currents than the broader and weaker patterns seen with the stratospheric aerosols. Also, it is the case that the clouds that are believed to be most easily influenced by the cloud whitening reside in the subtropics, so the reduction in the amount of sunlight

reaching the surface will tend to be strongest in those regions. Since the atmosphere and ocean distribute the heating and cooling through winds and currents the effect will eventually be distributed over the globe, but the difference in the weather or precipitation for example may still be more evident in the cloud whitening than the stratospheric aerosol strategy.

However, there are many processes in the Earth System that would take much longer to respond (with timescales of weeks, months, and years). If society were to "turn on" cloud whitening globally we would probably see noticeable effects on surface temperature within a couple years. We might also see any negative consequences (e.g. changes in some major precipitation systems, if those changes were to occur) within a few years, although it would take a number of years to feel confident in documenting the positive or negative changes in climate (as also seen with stratospheric aerosol geoengineering).

**How long the direct and indirect impacts would persist:** As far as I know, no one has explored the response of the Earth system if geoengineering by sea salt aerosols were terminated in a climate model, and there are no natural analogues like there are with stratospheric aerosols and volcanoes. I expect that after terminating the source for the aerosols, the aerosols perturbations would disappear over a few days. Like the stratospheric aerosols, I would expect after removal of the geoengineering forcing to see a rapid return (on the timescale of a decade or so) to the globally averaged temperature similar to a world experiencing only high concentrations of greenhouse gases. Again, there will probably be longer timescale responses in the Earth System of a more subtle nature (for example some ocean circulations will take years to respond, and there could be long term responses in ecosystems). As with the stratospheric aerosol strategy, these issues should be explored.

**State of Research on geoengineering by cloud whitening.** Here is a very brief overview of recent research with the current "shoestring budgets":

1. **Assessment, Integration**: The report of the Royal Society (2009) provides some assessments of this strategy compared to others.
2. **Modeling**:
   **Global Models.**
   a. A number of papers have appeared in the scientific literature exploring consequences of geoengineering with cloud whitening using global models (Rasch et al 2009; Jones et al 2008). These studies essentially frame the questions by assuming that it is possible to control the number of drops in a cloud system perfectly. Then they proceed to ask questions like "what would the effect be of those cloud changes on the Earth System" using standard climate modeling techniques. The community is beginning to transition from the first "quick and dirty look" to a more thorough exploration of the subtleties of the strategy (e.g. Korhonen et al, 2010) although that study still employed some significant simplifications compared to the state of the art in aerosol and climate modeling.

   b. Each modeling group that has explored cloud whitening geoengineering has assumed different ways of producing cloud changes, and introduced those changes at different longitudes and latitudes, and made different assumptions about greenhouse gas concentrations changes. There have been no attempts yet to systematize these scenarios and explore variations on them.

**Process Models**

   a. There has been some recent work with Large Eddy Simulation studies on ship tracks by Wang (2009)

3. **Lab and Field Studies**: No recent field studies have been done with cloud whitening. In 2008 a field experiment called VOCALS took place to study clouds and cloud aerosols interactions off the coast of Peru and Chile. This field experiment had no geoengineering component to it but the clouds systems in that region are of the type relevant to geoengineering, and the range of techniques and measurement strategies involved were very similar to those required for a limited-area field test of cloud whitening, and it could be used to estimate costs for limited field testing. There have been earlier field studies to measure cloud changes following ship tracks (for example, MAST, the Monterey Ship Track experiment), and I believe another similar study is being planned by B. Albrecht and J. Seinfeld.
4. **Technology Development**: Some exploratory work in developing spray generators to produce the appropriately sized sea salt particles for seeding the clouds has been done in two groups, one led by Armand Neukermans in California, and another led by Dan Hirleman at Purdue.
5. **Deployment:** I don't think we are ready to address this issue
6. **Interactions with other communities**: I don't have the expertise to provide guidance on this issue, but I am interested.

**Cost estimates and recommendations for an improved research program for cloud whitening.**

I see three logical phases to research in exploring cloud whitening. I believe only the first phase should be considered at this time. The others require much more discussion, governance, and involvement by national and international stakeholders and planning.

- Phase 1: Using Models, and extremely limited field experiments where there is no chance of significantly effecting to the climate to determine whether it is actually possible to whiten clouds in a predictable, controlled manner. Are there changes to other cloud properties (for example, cloud precipitation, cloud height, cloud thickness)
- Phase 2: Enlarge the scope of the geoengineering research and consider the consequences if we were to whiten cloud for long enough that it might actually make a difference to local climate. Look at the consequences to the local environment on short time scales (like less than a week). These consequence might matter to people, but they would be small compared to

the kind of ways we already perturb the climate system (like the forest fires in Borneo, a Pinatubo, etc)

- Phase 3: Full scale deployment.

Again, progress would be increased immediately by funding and attention for all of these activities. If the cloud whitening actually proves successful during the smallest scale tests then the deployment issues become important, and a second phase of research and development become necessary.

For the initial exploratory phase, $10 Million per year funding for research would allow substantial theoretical progress in geoengineering research through modeling, and perhaps some proto-typing of instruments to produce the aerosol source, and specialized instruments for measurement.

The 2008 VOCAL field campaign might serve as a reasonable estimate of the cost of a first class one-time field experiment with a focus on aerosol cloud interaction in the right kind of cloud system. That field experiment cost over $20 Million.

Thus, a strong initial effort to study cloud whitening might well be funded at $20-$25 million per year, assuming a field study every 2-3 years.

*Here is an incomplete list of some of the tasks that should be considered in terms of the topics the committee charged me with addressing: 1) Research, 2) Deployment, 3) Monitoring 4) Downscaling, cessation and necessary environmental remediation, and 5) Environmental impacts:*

1) **Theoretical Research and Technology development:**
   **Process Models**
   a. The first studies by Wang (2009) using "Large Eddy Simulation" model for ship track research should be extended to explore the problem from a geoengineering point of view. Investigators could be tasked with exploring how to optimize the injection of the aerosols (how many ships per cloud region, whether it makes a difference if the cloud system has already formed or is expected to form soon, sensitivity to diurnal cycle of boundary layer clouds, sensitivity to levels of background aerosol (pollution levels). This would require simulations over larger domain, longer time frames, different cloud regimes, perhaps with more complex formulations of cloud and aerosol microphysics.
   b. Very high resolution modeling studies should be performed of the evolution of the aerosol particles as they are emitted from the seed generator until they enter a cloud.

   **Global Models**
   a. Make emission scenarios uniform across multiple models
   b. Impact on precipitation
   c. Make sure models are consistent with the picture provided by the detailed models

**Technology Development**

d. We need to develop equipment that is capable of producing the aerosols that will be used to seed the clouds.

2. **Deployment:** The knowledge and technology are not yet at a stage where deployment should be considered. The research program will change completely if research indicates it is possible to whiten clouds in a controllable and reproducible way.
3. **Monitoring:** During the first phase, while trying to establish whether cloud whitening is viable; monitoring should be consider part of the field campaign. The picture will change completely if deployment becomes viable and much more work is required to scope out a monitoring activity.
4. **Downscaling, cessation, environmental remediation.**
   a. During phase 1 there should be no impact on the climate.
   b. If a geoengineering solution were to be deployed, The only guidance we would have on this is research from global climate models. There are no analogues that come to mind in nature for cessation of geoengineering by cloud whitening. My suspicion is that climate models would show a recovery quite similar to that discussed in the section on stratospheric aerosols. This kind of study should be performed.
5. **Environmental Impact:** Because geoengineering has the potential for affecting precipitation patterns, and major circulation features like ENSO and monsoons, there are many ways in which it can have an environmental impact, with consequences to society and ecosystems. This issue will be very important in a "Manhattan" level activity if phase 1 research ever succeeds and deployment is seriously considered.

**Which U.S. Agencies might be involved:** NASA, NSF, DOE and NOAA all have relevant responsibilities and expertise for the Phase 1 activities.

**Closing Remarks:**

Thank you for asking me to testify. I have tried to respond to you questions, and provide some of the answers, although I think that science does not know enough to answer completely.

I would like to leave you with a few take home messages.

1. I recognize that geoengineering is a very controversial and complex subject, and that there are many issues associated with it of concern to scientists and society. It can, for example, be viewed as a distraction, or an excuse to avoid dealing with greenhouse gas emissions. Scientists interested in geoengineering want to be responsible and transparent. We care about doing the science right, and in a responsible way. We believe that our energy system transformation is proceeding too slowly to avoid the risk of dangerous climate change from greenhouse gases, and that there has been little societal response to the scientific consensus that reductions must take place soon to avoid the risk of large and undesirable impacts.

2. Geoengineering should be viewed as a choice of last resort, It is much safer for the planet to reduce greenhouse gas emissions. Geoengineering would be a gamble. Just as there are many uncertainties associated with predicting the kind of changes to our climate from increasing greenhouse gases, there will be similar uncertainties to predicting the changes from geoengineering.
3. Current Climate models indicate that geoengineering would cool the planet and compensate for some, but not all of the consequences of increased greenhouse gases.
4. I don't think scientists know enough today about consequences of geoengineering to climate, and so I don't think we are ready for "deployment". Before anyone should consider full-scale deployment of a geoengineering strategy, lots of basic work (what I call phase 1 research) could be done to lay the groundwork for deployment. The basic work will help in eliminating unsuitable strategies, in identifying important issues to hone in on, to help us revise strategies to make them more suitable for deployment, and in some cases could help in revealing fundamental information critical for understanding climate change (I am thinking about information about the "Aerosol Indirect Effect" when I refer to the issue of critical understanding).
5. Right now, less than $1 million per year is spent on geoengineering research in the US. A viable research activity with a chance of making rapid, solid progress including field studies would probably require $20-40 million per year for either program.
6. I believe that if phase 1 research does come up with a promising strategy for geoengineering, and deployment is seriously considered, that the level of scrutiny and level of funding must increase very sharply to a level similar to that of a "Manhattan Project". Such a project would need to consider many issues beyond the physical sciences.

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