Statement of Dr. Philip J. Rasch
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Before the
United States House of Representatives
Committee on Science, Space, and Technology
Subcommittee on Environment
Subcommittee on Energy

November 8, 2017

Major points:

- Research on geoengineering strategies is still in its infancy, but suggests they may represent a promising complement to other responses to climate change. For example, Sunlight Reduction Method (SRM) technologies appear to have the potential to offset, delay, or slow some of the warming driven by greenhouse gas emissions, and thus might help "buy time" for other mitigation and adaptation measures to be put in place.
- However, it isn't yet clear whether geoengineering should be part of solution strategies to address observed and anticipated changes in the climate system—we simply do not yet know enough about the potential benefits or risks that might be associated with large-scale deployment of geoengineering technologies.
- A comprehensive research program—including modeling, laboratory studies, small-scale field experiments, and technology development—is needed to better understand the potential role that geoengineering strategies could take in the broader context of other climate response options. My written testimony contains a number of suggestions for components of such a research program, and examples in areas where progress could be made.
- Even if they are determined to be viable, geoengineering strategies won't be a magic bullet that eliminates the need for emissions reductions or adaptation measures. While geoengineering technologies could be effective at offsetting some of the effects of climate change, they will not compensate for all of them, and may introduce their own problems.
- Similarly, geoengineering will not be a quick fix—sustained investment and work will be required over many years, possibly decades, before we know what, if any, is the right path forward on geoengineering efforts.
- If SRM technologies were chosen as a measure to address greenhouse gas warming, they would need to be used for as long as excess greenhouse gases remain in the atmosphere, requiring long term use to remain effective.
- Marine cloud brightening and stratospheric aerosols are SRM strategies have some common features but they are different in some important ways. Each potential geoengineering strategy has its own potential benefits, risks and costs, and each needs to be carefully evaluated.
- Small-scale field experiments are needed to develop a better process-level understanding of the potential effectiveness of SRM. While the scale of these field experiments would be too small to influence regional or global climate, they would provide opportunities to develop a review and governance strategy to ensure the transparency and safety of such experiments.
- Progress in understanding SRM strategies can also be of great benefit to general climate science. For example, small-scale field studies addressing geoengineering issues could also answer some long-standing, key scientific questions regarding the influence of atmospheric particles on cloud brightness and precipitation.
- I believe it is time for a coherent and goal-oriented geoengineering research program that complements ongoing research in atmospheric processes and Earth System science, and focuses on a defined set of objectives targeting better understanding of the effectiveness and potential risks associated with specific geoengineering technologies.
- It is essential that any geoengineering research program integrate consideration of societal needs, transparency, and governance issues with a program for making progress in the physical and natural sciences. It should also work closely with existing climate science research activities across the federal government, complementing these activities as an addition to these programs.

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Chairman Biggs, Chairman Weber, Ranking Members Bonamici and Veasey, and members of the subcommittees, thank you for the opportunity to provide testimony regarding the status of geoengineering research, also called climate intervention, along with other technical terms used in the research community. I am the Chief Scientist for Climate Science at the Pacific Northwest National Laboratory, a U.S. Department of Energy national laboratory, located in Richland, Washington, where I lead programs on the development of computer models of the Earth's atmosphere, and another project specifically focusing on environmental change in polar regions. My scientific focus is on understanding atmospheric processes and interactions within the broader Earth System science context, and I have been involved in geoengineering research for approximately ten years. This statement was written in collaboration with my colleague, Ben Kravitz, who is also a climate scientist at the Pacific Northwest National Laboratory.

I have authored approximately 20 papers on geoengineering in the last decade, virtually all supported by philanthropic organizations and the National Science Foundation. I was a member of the committee that authored assessments of geoengineering for the National Research Council.[1] I was also a lead author for one of the chapters of the most recent report of the Intergovernmental Panel on Climate Change (the Fifth Assessment Report) covering geoengineering,[2] and a contributing author on two other chapters of that report. Ben Kravitz has published 42 papers on the topic and leads an international collaboration of climate modeling groups. That group, the Geoengineering Model Intercomparison Project (GeoMIP), focuses on assessments of various facets of climate interventions. Both of us have worked on the physical science issues associated with specific geoengineering strategies called marine cloud brightening and stratospheric aerosol geoengineering strategies, which I will discuss later. I would also noe that I testified before this committee in 2010, and it is a pleasure to return again to update you on progress that has been made since then.

In this testimony, I will cover points that I believe are essential for understanding why a research program on geoengineering is needed, and what such a program might look like. The majority of my comments will focus on Sunlight Reduction Methods (SRM), also referred to as Solar Radiation Management. I first provide background on geoengineering and why it is part of the ongoing conversation about climate change, then shift to a discussion of opportunities and next steps. This will include a discussion of the largest uncertainties and open research questions associated with geoengineering, as well as how those uncertainties could be addressed. I will conclude by outlining my thoughts on a comprehensive research program that includes modeling studies, small-scale field experiments, and technology development and engineering feasibility studies as well as consideration of governance and societal issues, and some concluding thoughts for the committee's consideration.

Background: What is Geoengineering?

Americans are becoming increasingly aware of changes in our environment, ranging from dramatic decreases in sea ice in the arctic, to increases in summertime heat waves, droughts, and fires, to damage from hurricanes and other extreme weather events, to increasing ocean acidity. Evidence for historical changes in climate are thoroughly documented in the U.S. National Climate Assessment and the Fifth Assessment of the Intergovernmental Panel on Climate Change. Many of the changes mentioned above are attributable to increases in the atmospheric carbon dioxide concentration.

It will be challenging for societies to dramatically reduce carbon dioxide and other greenhouse gas emissions on a timescale that will limit warming, and even then, the planet is likely to continue to warm, with much of the effect appearing within a century. Due to the slow removal time of carbon dioxide from the atmosphere, it would take millennia for natural processes to re-absorb the excess carbon dioxide that has been introduced even if greenhouse gas emissions associated with human activity were immediately halted.

Geoengineering, or climate intervention, methods have been proposed as a means of addressing some of the impacts due to the changing climate. There are two broad categories of geoengineering: Carbon Dioxide Removal (CDR) and Sunlight Reduction Methods (SRM). SRM has also been referred to as Solar Radiation Management, Albedo Modification, and other names. There are a number of additional terms that have been used to describe these methods, and each has its strengths and limitations, but for the remainder of my testimony I will use "geoengineering" and SRM, or "Sunlight Reduction Methods," for clarity. These methods have been part of the conversation in the scientific community for many years and have great potential, but are as yet untested. Because geoengineering, by definition, requires large-scale interventions to alter the Earth's climate, it is important that any effort to do so proceed systematically and with care. If there is a decision to consider geoengineering, it would be prudent to study, evaluate, and test proposed solutions thoroughly on a smaller scale before consideration of larger scale deployment.

As I am not an expert in Carbon Dioxide Removal, I will not discuss it further. This topic is covered in previous congressional testimony before this committee in the 111th Congress[3] and the 2015 National Academy of Sciences report on Carbon Dioxide Removal.[4]

What are Sunlight Reflection Methods?

Sunlight Reflection Methods (SRM) seek to reflect some of the sun's incoming energy back to space, cooling the planet. These methods have been called "fast, cheap, and imperfect," because they are likely to work rapidly, and cost as little as a few billion dollars per year[5]. However, these methods would likely only offset some of the changes associated with carbon dioxide and greenhouse gas emissions, with the potential for some side effects. The next section of my testimony will briefly summarize some key aspects of SRM approaches.

Although there are many proposed variations of SRM, two have received the most attention. One, called marine cloud brightening, aims to make clouds brighter so they reflect more sunlight. Just as the surface temperature goes down when a cloud passes overhead on a hot summer day, we know some clouds cool the planet. Marine cloud brightening aims to enhance that cooling by introducing sea spray particles below marine clouds that are responsible for much of that cooling. All cloud drops initially form on particles suspended in the atmosphere. By introducing extra particles, more sites would be available for drop formation. The aim would be to create more numerous and smaller cloud drops, which are known to reflect more sunlight and produce rain conditions more slowly, leading to longer-lived clouds.

The other variation of SRM that has received much attention is called stratospheric aerosol geoengineering, which mimics the cooling effects of large volcanic eruptions by placing highly reflective particles (sulfate aerosols) in the upper atmosphere. There have been proposals to evaluate the effectiveness and side effects of non-sulfate particles, but since particles of this type do not occur naturally, their likely effects are not well understood today.

There are many possible objectives of geoengineering, and hypothetical scenarios have investigated this largely through climate model simulations. These include maintaining a constant global temperature, slowing the rate of temperature increase, or offsetting changes in precipitation. One potential downside of SRM technologies is that they would need to be continuously deployed at a scale proportional to the excess carbon dioxide in the atmosphere. In other words, the amount of SRM needed would increase for as long as greenhouse gases continue to accumulate, and would need to be maintained for as long as excess greenhouse gases remain in the atmosphere—which could be many centuries since carbon dioxide has a very long lifetime in the atmosphere. Moreover, if SRM were discontinued abruptly, its cooling effect would disappear abruptly, and the planet then would warm rapidly. This is often called the "termination effect," and the stronger the SRM, the more extreme the potential impacts. Avoiding the problem of the termination effect might involve gradually ramping down the amount of SRM, possibly in concert with Carbon Dioxide Removal methods to draw down carbon dioxide levels in the atmosphere.

It is important to recognize that there are also some effects of climate change that SRM would not be able to modify. For example, the ocean's acidity will continue to increase under higher carbon dioxide concentrations, with implications to ocean biological productivity, including fisheries; SRM would not address this issue.

SRM would not perfectly offset warming effects because it acts differently on the Earth than carbon dioxide. For example, warming from carbon dioxide influences the planet everywhere and at all times, whereas sunlight varies by location and time of day and season. Earlier work[6] on this topic indicates that in spite of these differences, the compensation of SRM works fairly well. However, it has become evident that SRM won't simultaneously and precisely offset temperature and precipitation changes. It also gets harder to do an accurate compensation between the warming from carbon dioxide and the cooling from SRM strategies as the carbon dioxide concentration goes up.[7] Therefore, in my view, geoengineering should only be contemplated in the context of serious emission reductions.

Recent Progress: What have we learned since the last congressional hearing on this topic?

Recent research has expanded the analysis of SRM to other climate features. Those studies indicate that although the compensation is imperfect, SRM could be effective at offsetting some of the negative impacts on many climate features, including temperature,[8] precipitation,[9] extreme weather events,[10] sea ice extent,[11] ocean circulation,[12] and Atlantic hurricane storm surge.[13] SRM does not appear to return all features back to a situation unaffected by excess carbon dioxide, but it is generally much closer to that situation than if nothing were done.

Despite the modeled effectiveness of SRM in offsetting global changes, not all regions are affected equally. For temperature, all regions are cooled, but by different amounts. For other features, like precipitation, SRM would compensate for carbon dioxide-induced changes in some regions and exacerbate changes in others. These effects, which vary from region to region, would become more prominent as the amount of intervention increases.

What are the major next steps in SRM research?

We still do not know enough about the balance of benefits, risks, and tradeoffs of SRM to make well-informed recommendations regarding any possible deployment, where deployment refers to implementation at a scale large enough to affect Earth's climate. Substantial uncertainties remain, and much more work is needed to be able to determine potential benefits, risks and tradeoffs, as well as feasibility. We are also still working to reduce remaining uncertainties in our understanding of broader Earth System processes and interactions to enable better prediction of future climate. If geoengineering is to be considered as a potential response to climate change, progress in reducing those uncertainties is urgent.

There are several critical knowledge gaps that, if researched, would improve the situation. Work is occurring in each of these areas, but most of it is being done outside the U.S., and the little that is being done here is taking place in the context of curiosity-driven research by individuals or small groups. I believe it is possible to make progress more rapidly with a coherent, prioritized research program that includes the following areas (each are discussed in more detail in the following subsections):

- Modeling activities
- Laboratory and field studies
- Advancing climate research
- Technology development and feasibility studies on specific ideas or technologies
- Attention to the importance of governance and transparency
- Improved integration with communities concerned about environmental and human systems

I have identified below some research recommendations based on my experience in this field, where I see some obvious directions that would shed light on some of the key uncertainties. A more thorough, coherent research program would need to be properly scoped, which is something that the 2015 National Academy of Science study on this matter has taken a first step toward, and could be further refined through engagement of the broader research community.

Modeling Activities: Some key modeling uncertainties and low hanging fruit

Computer models are an important tool in expressing scientific knowledge about the Earth System. They can be used to perform calculations over a vast range of processes to provide diagnostics and predictions of a complex system. Models are, by necessity, an approximation of the way those processes operate in the real world. Modeling can happen over a wide range of scales, from process-level to global weather and climate, and for different purposes

Models that focus on "processes" such as particle formation, and coalescence, or drop formation, or even the formation of a cloud updraft, are typically run at very fine scales. The models are needed to understand details critical to a part of the Earth System. These types of models are also needed to better understand and provide predictive capability for SRM studies to understand the behavior of particles that might be introduced to the atmosphere.

For example, the evolution of the sea spray drops used for the marine cloud brightening SRM method will be delivered from a nozzle. Collections of nozzles have been proposed to be used together to produce enough particles to have a significant impact on a cloud. The particles will then undergo rapid evaporation and cooling, and the particles will stick together, forming larger particles. These processes will change the particle sizes, and lifetimes and the air temperature around them. The particle sizes and temperature of the air affect the salt particles ability to disperse beneath the clouds and their ability to form cloud droplets. Similar issues will exist for the particles envisioned for the stratospheric aerosol geoengineering strategy: particle growth and the rate the particles settle out of the upper atmosphere are some of the key sources of uncertainty in determining the effectiveness of SRM using stratospheric sulfate aerosols. As such, we will need similar process models for dealing with stratospheric aerosol geoengineering.

Modeling studies are needed at these very small process scales for marine cloud brightening to better identify the formation, and evolution of the particles from initial injection, until they spread out over a few hundred meters. Similar scale models are needed to study the formation, chemistry and evolution of particles being proposed for high altitude stratospheric aerosol geoengineering although the materials and meteorology are very different.

On a larger scale, models that capture some features of air movement and aerosol-cloud interactions on scales of a few tens of meters to a few kilometers are useful in studying clouds. These models are useful for understanding the feasibility of cloud brightening in different cloud regimes or the appropriate times of days to introduce seeding material**.** Modeling studies are needed to identify whether particle injection should occur at higher altitudes (near the cloud top) or near the surface, as well as the importance of ambient aerosol and meteorological conditions, and impacts of the injection of the cloud field itself, to better identify under what circumstances marine cloud brightening is feasible. Scientists also believe that brightening occurs elsewhere. More work is needed to understand the potential for brightening in other ocean regions, for example to produce cooling in regions that might act to mitigate coral reef bleaching or hurricane initiation.[14]

Similar studies would be useful in characterizing the impact of particles introduced in the stratosphere by stratospheric aerosol geoengineering. These very high resolution models with complex chemistry and aerosol physics would provide information about particle growth and subsequent settling, and changes in small scale circulation features of the middle atmosphere that influence aerosol evolution and mixing near the sources of the stratospheric aerosol injection. In other words, it is important to explore the evolution of the aerosols at intermediate scales that are larger than those discussed in the previous paragraphs, and the larger scales discussed below. There is also the potential for these particles to influence the behavior of ice clouds high in the atmosphere. It will be important to evaluate the impact of changes in the stratosphere such as changed aerosols and stability on the cirrus clouds that occur below the aerosol layer.

On the largest (global) scales, most geoengineering work to date has taken place with coupled Earth system models that cannot treat processes in a highly-detailed manner, but can provide a valuable tool for exploring interactions between components—for example, ocean-atmosphere or human-environment interactions on global scales over many centuries. These global models allow investigation of a crucial component of SRM research, in that the broad climate effects of SRM depend to a large extent on how geoengineering is conducted. For the example of stratospheric aerosol geoengineering, the effects strongly depend upon the latitude (or latitudes) of injection, the altitude, quantity, the time of year, and particle composition.[15]

As such, an important research question is to understand what large scale climatic features can and cannot be changed. Some recent studies have been exploring an adaptive management approach where different characteristics of geoengineering (such as amount of injection) are varied every year. This idea has been demonstrated in climate models for multiple objectives, including global, annual mean temperature[16] as well as large-scale temperature and precipitation changes.[17] There are many opportunities in exploring the space of objectives of SRM, particularly in terms of understanding which uncertainties in SRM can be reduced and which ones can be managed.[18]

Many geoengineering simulations have been performed using simpler forms of global Earth System models. That framework is appropriate for an initial look at questions, but as feasibility studies become more important, it will be increasingly important to use latest generation models. These models would:

- avoid simplifications when they might compromise results;
- strive for very realistic climates;
- include best-of-class treatment of processes that play an important role in the intervention method. The treatment could be guided by the high resolution simulations described above, and the field studies mentioned below; and

- include a broad spectrum of Earth System features, including those involving human and societal interaction.

An example would be high resolution global models that include explicit gas and particle chemistry important to particle formation and evolution, with representations of clouds that are chosen to handle aerosol cloud interactions as accurately as possible. This class of models is very expensive computationally to run, and it will be important to identify the situations where cost is justified. Simulations with current state of the art Earth System models are very expensive, but they will become increasing important to use in geoengineering feasibility studies. It will be important to assure the availability of adequate computer resources to support that class of simulation.

Laboratory and field studies – a vital role

The vast majority of research on geoengineering to date has used computer modeling. Models are useful because they allow a rapid exploration of questions, but there are geoengineering issues that must be resolved through laboratory and field research. There have been a few field studies performed in the past that are relevant to geoengineering,[19] but since the deliberate manipulation of the environment is a sensitive issue and potentially risky, the scientific community has been conscientious and reluctant to approve or conduct such field experiments.

As Keith and colleagues have pointed out,[20] it is useful to consider a range of small-scale field experiments spanning multiple scales, whose purposes range between seeking to understand an atmospheric process (like particle formation, or cloud drop formation) to understanding how the Earth System (weather and climate) would respond if humans imposed an intervention to counter climate change. Process-level experiments typically introduce very small changes to the atmosphere. For example, the smallest experiments being considered by scientists interested in geoengineering involve releases of less than one kilogram of particles that would introduce atmospheric changes that are negligible compared with that of a single flight of a commercial aircraft. Such an experiment could provide data that enable improvements in understanding of specific processes important to geoengineering. In sharp contrast, measuring a climate response to a field experiment on the scale of a continent or larger would require making a change to the Earth System intentionally large enough to induce a measurable change a weather feature, a storm, or a persistent feature of the climate. The smallest field experiments being considered are a factor of 100 billion[21] times smaller in their estimated effect than that of continental scale climate response experiments might be.

One example of a proposed small-scale experiment is SCOPEX,[22] the Stratospheric Controlled Perturbation Experiment, which involves spraying a few kilograms of sulfur into the lower stratosphere and monitoring its subsequent evolution over a few days. Such a study would provide the opportunity to learn about formation of particles, chemical effects, transport, and particle growth, all of which are essential for understanding important mechanisms of geoengineering in the stratosphere and can also contribute to a better understanding of the basic workings of the stratosphere itself. Similarly, the process-level, small-scale field studies proposed by Wood and Ackerman[23] would provide insight into the evolution of the particles important to marine cloud brightening. This would involve measuring sea spray as it is released from nozzles, evaporated, and mixed through the atmospheric surface layer. The particles would eventually be ingested into a cloud, where they could form new cloud droplets, and change the clouds, with the goal of observations and measurements identifying how particles with specific characteristics change cloud brightness, areal extent and lifetime, and the organization of clouds.

A common point of discussion in SRM research is the utility of "measurements of opportunity," which means taking advantage of an existing change in the atmosphere to help with understanding something relevant to geoengineering. For example, some non-explosive volcanic eruptions produce atmosphere-altering gases and particles that reflect sunlight, as do ocean-going freighters that produce emissions trails known as "shiptracks." Field measurements in the vicinity of those effects can provide invaluable information that doesn't require deliberately modifying the atmosphere as an experiment would.

However, these measurements of opportunity are unlikely to be sufficient to characterize the response at a level that is necessary for understanding the impacts of SRM. As discussed in Wood et al,[24] shiptrack and volcanoes are useful in understanding clouds but don't allow for a focused experiment to specifically evaluate the impacts and operational complexities of different geoengineering technologies and approaches in the field. Cloud responses to stratospheric aerosols often vary in the real world because of different weather conditions. This variation can be reduced in a deliberate experiment by selecting for the conditions and locations where the measurement is made. Sources also often differ in measurements of opportunity. Ship emissions are affected by differing schedules, fuels, cargo loads, engine emission controls, and age and condition. Volcano emissions differ from one day to the next due to variations in eruption strength. Variations in wind speed that make waves and sea spray not only produce variations in the small particles that form the usual background aerosol amounts, but also can introduce giant sea salt particles that can produce different an opposing response in clouds. Purposeful small-scale field experiments can circumvent these issues with variability by controlling for particle composition, size, shape, amount, and altitude of injection of the particle sources intended to change the cloud. This would allow for exploration of cloud responses under more controlled conditions, eliminating many of the factors that confuse interpretation of cloud responses to particles. There are similar limitations to the use of volcanic eruptions to understand either the particle-cloud interactions important to stratospheric aerosol geoengineering.

In sharp contrast, large-scale experiments—those deliberately designed to impact the climate—are not likely to proceed absent more serious consideration of deployment issues,[25] which include operational and governance issues. Because research is not yet at the stage where well-informed decisions on SRM can be made, I will not discuss these large experiments further. There are also intermediate scale field studies that would be useful; those studies would have larger impacts than the smallest example I offered. The issues of managing experiments is sensitive, and I talk more about it in a later section.

Geoengineering research can advance other forms of climate research

It is also important to highlight the potential for benefits to basic climate science from some of these proposed experiments. The extra level of control being proposed in small-scale field studies can introduce the opportunity for experimental design much closer that used in a classic physics or chemistry lab. For example, the field studies proposed for marine cloud brightening could help address one of the biggest questions in climate science[26] by providing information on the way particles influence clouds. This issue has been identified as one of the largest sources of uncertainty in our understanding of how the Earth System is changing and will change in the future—that is, how clouds interact with the atmospheric particles known as aerosols. The anticipated outcome is a substantial reduction in the current uncertainty associated with the effect of aerosol on clouds. This is important for understanding factors affecting climate over the past century and should narrow ranges of predicted climate change for the current century. At the same time, these controlled experiments can provide useful new information about the feasibility and risks of proposals that use these techniques for geoengineering.

Technology Development

There are practical engineering concerns that must be pursued if SRM technologies are to work as intended. While I am not an expert in this area, I will briefly discuss its importance as a component of any geoengineering research effort. For example, methods of producing vast amounts of approximately uniform, environmentally benign sea spray particles are needed to better understand the feasibility of marine cloud brightening. Preliminary efforts over years by a group of dedicated retired physicists and engineers have produced a prototype spray nozzle that can create particles of the correct size in large quantities.[27] This technology has never been tested in real-world environments. More work would be needed to scale that technology up to the point that it could produce enough particles to influence a single cloud in support of a marine cloud brightening field study, or an alternative technology would have to be devised.

As another example, it would be very challenging to implement technologies that could carry large amounts (megatons) of material up to the middle stratosphere (approximately 25 kilometers in altitude) and disperse it there.[28] While such a fleet of aircraft is not likely to be built prior to a decision to deploy, near-term planning and design could commence to assess feasibility. Some of these engineering problems are ultimately tractable with enough research, work, and prototyping, and others may prove to be impracticable; more work is needed to understand these issues and help prioritize its efforts. Other examples of technology development include a search types of particles to be used for stratospheric aerosol geoengineering, and exploring their efficacy in reflecting sunlight, on impacts on atmospheric chemistry.

Impacts of geoengineering on environmental and human systems

Most climate modeling studies of the effects of SRM have dealt with physical aspects of climate such as temperature, precipitation, and sea ice. Further work is needed to translate these effects into more societally relevant quantities, such as water security, crop yield, and energy production. Although some research has been done along these lines in terms of agriculture,[29] it has not been tackled systematically. It would be useful to engage those interested in environmental and economic impacts as a component of a research program.

It is important to pay attention to transparency and governance

While I am not an expert in governance issues, I would like to highlight to the committee two examples of field work involving geoengineering that may provide insight into public concern and its impact on geoengineering research.

- In the 1930's, scientists identified the possibility that iron might be a vital nutrient in ocean biology, and that many oceans might be deficient in iron. In the 1980's, people better understood the origin of natural iron sources, and suggested that iron might be added to the ocean surface in effect acting as a fertilizer producing additional biological activity, increasing ocean biota and tying up carbon dioxide that would ultimately settle to the deep ocean bottom. The idea of iron as a fertilizer of ocean biology was interesting scientifically, and also represented a possible geoengineering strategy. These ideas triggered a number of field experiments, which took place with varying levels of scrutiny, review, and governance. The experiments eventually triggered concerns by various communities, and as a result, legislation listing concerns about biological diversity, and dumping of wastes at sea was enacted to prohibit geoengineering experiments.

- In 2011, a planned outdoor experiment that was part of a geoengineering activity called SPICE[30] (the Stratospheric Particle Injection for Climate Engineering project) in England was first delayed, and then cancelled.[31] Concerns about the lack of public engagement, lack of transparency, and ambiguities about who held the patents for technologies that were planned to be used in the study have been listed among the reasons for canceling the study.

My hope is that in the future with more attention to societal issues, transparency and governance, outcomes like those mentioned above will be avoided, and public concerns addressed ahead of time. Next generation programs should think through ways to address and alleviate concerns by the public, governing bodies, and scientists not participating in the research—by tackling these issues up front.

What might a coherent geoengineering research program look like?

Most U.S. research on this topic has been conducted on a "curiosity-driven" basis, often by small groups of scientists and with little overall programmatic structure and very little federal funding. While additional funding is important and would help, there are a number of factors to consider in designing a geoengineering program:

- The curiosity driven model is fine if there is no urgency to getting an answer. In my opinion, there is urgency;
- I recognize there won't be enough funding to do everything, so prioritization is necessary. It should be done deliberately and systematically, and with a broad vision;
- There will also need to be coordination among agencies and activities to move from a modeling activity to a modeling, experiment and validation/testing framework. International cooperation should also be considered.

- Any effort would need to be sustained for a decade or more to enable evaluation of the potential of these methods. A governance structure with a requirement for transparency and public input is critical.

Therefore, if Congress or the Administration decides to invest in these efforts, it would be useful to shift the framework to a coherent research program that identifies the goals of the research, and integrates societal issues and governance issues with a prioritized program for making progress in the physical and natural sciences.

Any geoengineering research program should work closely with existing climate science research activities across the federal government, and should be complementary to and in addition to these programs, as it will require the fundamental advances in Earth System models, measurement science, and interactions provided by these programs. To make rapid progress on key outstanding issues, a geoengineering research program should have a mission-driven focus with a framework for establishing research priorities and overseeing research. Establishing clear mechanisms of research oversight and review are of critical importance, given the broad reaching implications and potential impacts of SRM. Agencies with a mission-driven focus include the Department of Energy, the National Aeronautics and Space Administration, and the National Oceanic and Atmospheric Administration. These agencies excel at mission-driven programs and interagency operations, particularly operations that are sustained over decades. Each has strong, coherent, complementary efforts in Earth System science, including modeling, atmospheric measurements, and technology development, along with substantial computational and laboratory facilities to support such research. There is also a role for complementary curiosity-driven research effort, which the National Science Foundation excels at. It has supported responsive research in the area of geoengineering, to date primarily to individual principal investigators and through support for meetings.

Within this framework, it would be useful to have an advisory body provide recommendations for a program development strategy, as well as a research oversight process to ensure transparency, public engagement, and proper review and oversight with all research activities. If research and development proceeds steadily over the course of several decades, perhaps enough information could be gathered to provide a thorough basis for decision support regarding whether SRM technologies are a viable means of partially and temporarily addressing climate change while other mitigation efforts take place.

Conclusion

Existing research results suggest that geoengineering strategies, while in their infancy, hold great promise. While not without risk, these strategies deserve serious consideration as they could significantly diminish economic and environmental costs as other mitigation and adaptation measures are put into place. As such, a comprehensive research program—including modeling studies, small-scale laboratory and field experiments, and engineering development—is necessary to better understand the potential role that geoengineering strategies could take in the broader context of climate options. It appears to be quite urgent that such a program start now and be sustained for at least a decade to make steady progress in understanding the potential benefits and risks associated with geoengineering approaches. Finally, it will be critical for such research and experiments to operate in transparency and with a rigorous governance and review process.

Thank you for the opportunity to testify today on this important topic. I am happy to answer any questions you may have.

References

Cooper, G., J. Foster, L. Galbraith, S. Jain, A. Neukermans, and B. Ormond. "Preliminary Results for Salt Aerosol Production Intended for Marine Cloud Brightening, Using Effervescent Spray Atomization." *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences* 372, no. 2031 (November 17, 2014): 20140055–20140055. https://doi.org/10.1098/rsta.2014.0055.

Huneeus, Nicolas, Olivier Boucher, Kari Alterskjær, Jason N. S. Cole, Charles L. Curry, Duoying Ji, Andy Jones, et al. "Forcings and Feedbacks in the GeoMIP Ensemble for a Reduction in Solar Irradiance and Increase in Carbon Dioxide." *Journal of Geophysical Research: Atmospheres* 119, no. 9 (May 16, 2014): 2013JD021110. https://doi.org/10.1002/2013JD021110

Keith, D. W., R. Duren, and D. G. MacMartin. "Field Experiments on Solar Geoengineering: Report of a Workshop Exploring a Representative Research Portfolio." *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences* 372, no. 2031 (November 17, 2014): 20140175–20140175. https://doi.org/10.1098/rsta.2014.0175.

Kravitz, Ben, Ken Caldeira, Olivier Boucher, Alan Robock, Philip J. Rasch, Kari Alterskjær, Diana Bou Karam, et al. "Climate Model Response from the Geoengineering Model Intercomparison Project (GeoMIP)." *Journal of Geophysical Research: Atmospheres* 118, no. 15 (2013): 8320–8332. https://doi.org/10.1002/jgrd.50646.

Kravitz, Ben, Piers M. Forster, Andy Jones, Alan Robock, Kari Alterskjær, Olivier Boucher, Annabel K. L. Jenkins, et al. "Sea Spray Geoengineering Experiments in the Geoengineering Model Intercomparison Project (GeoMIP): Experimental Design and Preliminary Results." *Journal of Geophysical Research: Atmospheres* 118, no. 19 (2013): 11,175–11,186. https://doi.org/10.1002/jgrd.50856.

Kravitz, Ben, Douglas G. MacMartin, David T. Leedal, Philip J. Rasch, and Andrew J. Jarvis. "Explicit Feedback and the Management of Uncertainty in Meeting Climate Objectives with Solar Geoengineering." *Environmental Research Letters* 9, no. 4 (April 1, 2014): 44006. https://doi.org/10.1088/1748-9326/9/4/044006.

Kravitz, Ben, Douglas G. MacMartin, Alan Robock, Philip J. Rasch, Katharine L. Ricke, Jason N. S. Cole, Charles L. Curry, et al. "A Multi-Model Assessment of Regional Climate Disparities Caused by Solar Geoengineering." *Environmental Research Letters* 9, no. 7 (July 1, 2014): 74013. https://doi.org/10.1088/1748-9326/9/7/074013.

Kravitz, Ben, Douglas G. MacMartin, Hailong Wang, and Philip J. Rasch. "Geoengineering as a Design Problem." *Earth System Dynamics* 7, no. 2 (May 24, 2016): 469–97. https://doi.org/10.5194/esd-7-469-2016.

Kravitz, Ben, Philip J. Rasch, Piers M. Forster, Timothy Andrews, Jason N. S. Cole, Peter J. Irvine, Duoying Ji, et al. "An Energetic Perspective on Hydrological Cycle Changes in the

Geoengineering Model Intercomparison Project.” *Journal of Geophysical Research: Atmospheres* 118, no. 23 (December 16, 2013): 2013JD020502. https://doi.org/10.1002/2013JD020502.

Latham, J., K. Bower, T. Choularton, H. Coe, P. Connolly, G. Cooper, T. Craft, et al. “Marine Cloud Brightening.” *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences* 370, no. 1974 (August 6, 2012): 4217–62. https://doi.org/10.1098/rsta.2012.0086.

Latham, J., P. Rasch, C.-C. Chen, L. Kettles, A. Gadian, A. Gettelman, H. Morrison, K. Bower, and T. Choularton. “Global Temperature Stabilization via Controlled Albedo Enhancement of Low-Level Maritime Clouds.” *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences* 366, no. 1882 (November 13, 2008): 3969–87. https://doi.org/10.1098/rsta.2008.0137.

Latham, J., P. J. Rasch, and B. Launder. “Climate Engineering: Exploring Nuances and Consequences of Deliberately Altering the Earth’s Energy Budget.” *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences* 372, no. 2031 (November 17, 2014): 20140050–20140050. https://doi.org/10.1098/rsta.2014.0050.

Latham, John, Joan Kleypas, Rachel Hauser, Ben Parkes, and Alan Gadian. “Can Marine Cloud Brightening Reduce Coral Bleaching?” *Atmospheric Science Letters*, June 2013, n/a-n/a. https://doi.org/10.1002/asl2.442.

Latham, John, Ben Parkes, Alan Gadian, and Stephen Salter. “Weakening of Hurricanes via Marine Cloud Brightening (MCB).” *Atmospheric Science Letters* 13, no. 4 (2012): 231–237. https://doi.org/10.1002/asl.402.

Rasch, Philip J, John Latham, and Chih-Chieh (Jack) Chen. “Geoengineering by Cloud Seeding: Influence on Sea Ice and Climate System.” *Environmental Research Letters* 4, no. 4 (October 2009): 45112. https://doi.org/10.1088/1748-9326/4/4/045112.

Salter, S., G. Sortino, and J. Latham. “Sea-Going Hardware for the Cloud Albedo Method of Reversing Global Warming.” *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences* 366, no. 1882 (November 13, 2008): 3989–4006. https://doi.org/10.1098/rsta.2008.0136.

McClellan, Justin, David W. Keith, and Jay Apt. “Cost Analysis of Stratospheric Albedo Modification Delivery Systems.” *Environmental Research Letters* 7, no. 3 (2012): 34019. https://doi.org/10.1088/1748-9326/7/3/034019.

MacMartin, Douglas G., Ben Kravitz, and Philip J. Rasch. “On Solar Geoengineering and Climate Uncertainty: GEOENGINEERING AND UNCERTAINTY.” *Geophysical Research Letters*, 2015, n/a-n/a. https://doi.org/10.1002/2015GL065391.

National Research Council. *Climate Intervention: Carbon Dioxide Removal and Reliable*

Sequestration. Washington, DC: The National Academies Press, 2015. http://www.nap.edu/catalog/18805/climate-intervention-carbon-dioxide-removal-and-reliable-sequestration

National Research Council. *Climate Intervention: Reflecting Sunlight to Cool Earth*. Washington, DC: The National Academies Press, 2015. https://www.nap.edu/catalog/18988/climate-intervention-reflecting-sunlight-to-cool-earth

Rasch, P. J, S. Tilmes, R. P Turco, A. Robock, L. Oman, C.-C. Chen, G. L Stenchikov, and R. R Garcia. "An Overview of Geoengineering of Climate Using Stratospheric Sulphate Aerosols." *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences* 366, no. 1882 (November 13, 2008): 4007–37. https://doi.org/10.1098/rsta.2008.0131.

Rasch, Philip J., Paul J. Crutzen, and Danielle B. Coleman. "Exploring the Geoengineering of Climate Using Stratospheric Sulfate Aerosols: The Role of Particle Size." *Geophysical Research Letters* 35, no. 2 (January 26, 2008). https://doi.org/10.1029/2007GL032179.

Rasch, Philip J, John Latham, and Chih-Chieh (Jack) Chen. "Geoengineering by Cloud Seeding: Influence on Sea Ice and Climate System." *Environmental Research Letters* 4, no. 4 (October 2009): 45112. https://doi.org/10.1088/1748-9326/4/4/045112.

Russell, Lynn M., Armin Sorooshian, John H. Seinfeld, Bruce A. Albrecht, Athanasios Nenes, Lars Ahlm, Yi-Chun Chen, et al. "Eastern Pacific Emitted Aerosol Cloud Experiment." *Bulletin of the American Meteorological Society* 94, no. 5 (May 2013): 709–29.
https://doi.org/10.1175/BAMS-D-12-00015.1.

Russell, Lynn M., Philip J. Rasch, Georgina M. Mace, Robert B. Jackson, John Shepherd, Peter Liss, Margaret Leinen, et al. "Ecosystem Impacts of Geoengineering: A Review for Developing a Science Plan." *AMBIO* 41, no. 4 (March 20, 2012): 350–69. https://doi.org/10.1007/s13280-012-0258-5.

Smith, Steven J., and Philip J. Rasch. "The Long-Term Policy Context for Solar Radiation Management." *Climatic Change*, 2012, 1–11. https://doi.org/10.1007/s10584-012-0577-3.

Solomon, Susan, Gian-Kasper Plattner, Reto Knutti, and Pierre Friedlingstein. "Irreversible Climate Change due to Carbon Dioxide Emissions." *Proceedings of the National Academy of Sciences* 106, no. 6 (February 10, 2009): 1704–9. https://doi.org/10.1073/pnas.0812721106.

Stocker, Thomas F, Dahe Qin, Gian-Kasper Plattner, M Tignor, Simon K Allen, Judith Boschung, Alexander Nauels, Yu Xia, Vincent Bex, and Pauline M Midgley. "Climate Change 2013: The Physical Science Basis," 2013.

Tilmes, Simone, John Fasullo, Jean-Francois Lamarque, Daniel R. Marsh, Michael Mills, Kari Alterskjaer, Helene Muri, et al. "The Hydrological Impact of Geoengineering in the

Geoengineering Model Intercomparison Project (GeoMIP): THE HYDROLOGIC IMPACT OF GEOENGINEERING.” *Journal of Geophysical Research: Atmospheres* 118, no. 19 (October 16, 2013): 11,036-11,058. https://doi.org/10.1002/jgrd.50868.

Tilmes, Simone, Rolando R. Garcia, Douglas E. Kinnison, Andrew Gettelman, and Philip J. Rasch. “Impact of Geoengineered Aerosols on the Troposphere and Stratosphere.” *Journal of Geophysical Research* 114, no. D12 (June 27, 2009). https://doi.org/10.1029/2008JD011420.

Wood, Robert, and Thomas P. Ackerman. “Defining Success and Limits of Field Experiments to Test Geoengineering by Marine Cloud Brightening.” *Climatic Change* 121, no. 3 (December 2013): 459–72.

Wood, Robert, Thomas Ackerman, Philip Rasch, and Kelly Wanser. “Could Geoengineering Research Help Answer One of the Biggest Questions in Climate Science?” *Earth’s Future*, 2017. https://doi.org/10.1002/2017EF000601.

Endnotes:

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[1] NRC, 2014,
[2] IPCC, AR5, 2013
[3] see https://archive.org/details/gov.gpo.fdsys.CHRG-111hhrg53007
[4] see https://www.nap.edu/catalog/18805/climate-intervention-carbon-dioxide-removal-and-reliable-sequestration
[5] Robock et al., 2009 and Sugiyama et al., 2017
[6] Bala (2008)
[7] Irvine et al., 2016
[8] Kravitz et al., 2013
[9] Tilmes et al., 2013
[10] Curry et al., 2014
[11] Moore et al., 2014
[12] Hong et al., 2016
[13] Moore et al., 2015
[14] e.g. Latham et al, 2013
[15] Kravitz, 2013; MacMartin et al., 2013; Tilmes et al., 2017
[16] MacMartin et al., 2014; Kravitz et al., 2014
[17] Kravitz et al., 2016, 2017; MacMartin et al., 2017
[18] MacMartin et al., 2016
[19] Russell et al 2013 used a war-surplus fog generator to introduce particles near the ocean surface and explore the response of clouds.
[20] Keith, D. W., R. Duren, and D. G. MacMartin, 2014
[21] Keith, D. W., R. Duren, and D. G. MacMartin, 2014
[22] Dykema et al., 2014
[23] Wood and Ackerman, 2013
[24] Wood et al 2017
[25] Robock et al., 2010
[26] Wood et al 2017
[27] Cooper et al, 2014; A. Neukermans private communication
[28] McClellan et al., 2012
[29] e.g., Pongratz et al., 2012; Xia et al., 2014
[30] See https://www.nature.com/news/geoengineering-experiment-cancelled-amid-patent-row-1.10645
[31] See https://www.nature.com/news/geoengineering-experiment-cancelled-amid-patent-row-1.10645