GEOENGINEERING: INNOVATION, RESEARCH, AND TECHNOLOGY

JOINT HEARING

BEFORE THE

SUBCOMMITTEE ON ENVIRONMENT &
SUBCOMMITTEE ON ENERGY

COMMITTEE ON SCIENCE, SPACE, AND TECHNOLOGY

HOUSE OF REPRESENTATIVES

ONE HUNDRED FIFTEENTH CONGRESS

FIRST SESSION

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November 8, 2017

GEOENGINEERING: INNOVATION, RESEARCH, AND TECHNOLOGY

Wednesday, November 8, 2017

HOUSE OF REPRESENTATIVES,
SUBCOMMITTEE ON ENVIRONMENT AND
SUBCOMMITTEE ON ENERGY,
COMMITTEE ON SCIENCE, SPACE, AND TECHNOLOGY,
Washington, D.C.

The Subcommittees met, pursuant to call, at 10:11 a.m., in Room 2318 of the Rayburn House Office Building, Hon. Andy Biggs [Chairman of the Subcommittee on Environment] presiding.

LAMAR S. SMITH, Texas
CHAIRMAN

EDDIE BERNICE JOHNSON, Texas
RANKING MEMBER

Congress of the United States
House of Representatives
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Geoengineering: Innovation, Research, and Technology

Wednesday, November 8, 2017
10:00 a.m.
2318 Rayburn House Office Building

Witnesses

Dr. Phil Rasch, Chief Scientist for Climate Science, Laboratory Fellow, Pacific Northwest National Laboratory

Dr. Joseph Majkut, Director of Climate Policy, Niskanen Center

Dr. Douglas MacMartin, Senior Research Associate, Cornell University

Ms. Kelly Wanser, Principal Director, Marine Cloud Brightening Project, Joint Institute for the Study of the Atmosphere and Ocean, University of Washington

U.S. HOUSE OF REPRESENTATIVES
COMMITTEE ON SCIENCE, SPACE, AND TECHNOLOGY

HEARING CHARTER

November 2, 2017

TO: Members, Subcommittee on Environment & Subcommittee on Energy

FROM: Majority Staff, Committee on Science, Space, and Technology

SUBJECT: Joint Environment & Energy Subcommittees Hearing:
"Geoengineering: Innovation, Research, and Technology"

The Subcommittee on Environment and the Subcommittee on Energy of the Committee on Science, Space, and Technology will hold a joint hearing titled *Geoengineering: Innovation, Research, and Technology* on Wednesday, November 8, 2017 at 10:00 a.m. in Room 2318 of the Rayburn House Office Building.

Hearing Purpose:

The purpose of this hearing is to assess the status of geoengineering research in the United States, while also exploring potential technologies and innovation.

Witness List

- **Dr. Phil Rasch**, Chief Scientist for Climate Science, Laboratory Fellow, Pacific Northwest National Laboratory
- **Dr. Joseph Majkut**, Director of Climate Policy, Niskanen Center
- **Dr. Douglas MacMartin**, Senior Research Associate, Cornell University
- **Ms. Kelly Wanser**, Principal Director, Marine Cloud Brightening Project, Joint Institute for the Study of the Atmosphere and Ocean, University of Washington

Staff Contact

For questions related to the hearing, please contact Taylor Jordan or Jimmy Ward of the Majority Staff at 202-225-6371.

Chairman BIGGS. The Committee on Science, Space, and Technology Subcommittee on Environment and Subcommittee on Energy joint hearing on Geoengineering: Innovation, Research and Technology is called to order.

Without objection, the Chair is authorized to declare recesses of the Subcommittee at any time, and I now recognize myself for five minutes for an opening statement.

Good morning, and welcome to the joint Environment Subcommittee and Energy Subcommittee hearing on geoengineering. I thank each of our witnesses for being here today.

Since this is the first time we're discussing the topic of geoengineering this Congress, it is important to explain what geoengineering actually is. In its simplest terms, geoengineering is the concept of using scientific understanding to alter the atmosphere in a way that produces positive outcomes and results. Many of the concepts in this field deal with solar radiation management, or how to influence the effects of the sun on the earth.

But the field is by no means limited to solar research. Geoengineering can also be used to manipulate different levels of gases in the atmosphere, such as carbon dioxide. These avenues of geoengineering research and others are still in the developmental stage, and any or all of them may warrant further exploration.

While there are at least a few programs in our Nation's universities that are looking into these concepts, federal research is still limited. However, if in the future the government wants to actually apply the concepts and findings of geoengineering research, we must fully examine both the potential merits and potential pitfalls of this emergent field.

Since the theories and concepts involved are still so new, we cannot say definitively if geoengineering technology warrants full-scale development or deployment. Quite simply, more basic research is necessary to determine whether it is a viable tool.

Today, we will learn about what research has been conducted on geoengineering and which promising concepts should be explored further. We will hear from government, academia, think tank and industry representatives who have unique perspectives on this topic. They will tell us about the research being done, as well as future concepts and how they could be used responsibly.

We as lawmakers have a responsibility to explore these concepts, learn as much as possible about them, and discuss ideas about how we can be helpful in supporting basic research.

I'd also like to take a moment to clarify any mischaracterizations about this hearing. The purpose of this hearing is to discuss the viability of geoengineering and any early-stage research associated with this approach. The hearing is not a platform to further the debate about climate change. We've had lots of that this session. Instead, its aim is to explore approaches and technologies that have been discussed in the scientific community and to assess the basic research needed to better understand the merits of these ideas. It is my hope that members will respect this focus so that we can have a meaningful discussion about geoengineering.

Again, I want to thank the witnesses for being here today, and I look forward to hearing more about these interesting concepts.

[The prepared statement of Chairman Biggs follows:]

COMMITTEE ON
SCIENCE, SPACE, & TECHNOLOGY
Lamar Smith, Chairman

For Immediate Release
November 8, 2017

Media Contacts: Thea McDonald, Brandon VerVelde
(202) 225-6371

Statement from Chairman Andy Biggs (R-Ariz.)

Geoengineering: Innovation, Research, and Technology

Chairman Biggs: Good morning and welcome to today's joint Environment Subcommittee and Energy Subcommittee hearing on geoengineering. I'd like to thank our witnesses for being here today.

Since this is the first time we are discussing the topic of geoengineering this Congress, it is important to explain what geoengineering actually is.

In simplest terms, geoengineering is the concept of using scientific understanding to alter the atmosphere in a way that produces positive outcomes and results.

Many of the concepts in this field deal with solar radiation management, or how to influence the effects of the sun on the earth. But the field is by no means limited to solar research. Geoengineering can also be used to manipulate different levels of gases in the atmosphere, such as carbon dioxide.

These avenues of geoengineering research and others are still in the developmental stage, and any or all of them may warrant further exploration. While there are at least a few programs in our nation's universities that are looking into these concepts, federal research is still limited.

However, if in the future the government wants to actually apply the concepts and findings of geoengineering research, we must fully examine both the potential merits and potential pitfalls of this emergent field.

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It is my hope that members will respect this focus so that we can have a meaningful discussion.

Again, I want to thank the witnesses for being here today and I look forward to hearing more about these interesting concepts.

###

Chairman BIGGS. With that, I yield back my time and recognize the Ranking Member, Ms. Bonamici for her opening statement.

Ms. BONAMICI. Thank you very much, Mr. Chairman, and thank you for holding this important hearing.

I'm very encouraged that the Science Committee is discussing geoengineering, a field of science and engineering that is still in its infancy and has ample areas for future research, and it's noteworthy for its potential. It's important that we consider it from political, ethical, legal, and environmental perspectives.

Geoengineering is a set of climate interventions that aim to manipulate our climate to either remove greenhouse gases from our atmosphere or reduce the amount of sunlight absorbed by the Earth. Now, some may argue that geoengineering is a way to use technology to bypass important mitigation and adaptation strategies that address the impacts of climate change, but even with geoengineering, our first and primary actions to address climate change must be mitigation and adaptation strategies.

In our communities, climate change is not a partisan issue. Nationwide, there are fishers and farmers and small-business owners, and servicemen and women who are having to change the way they do their jobs because of climate change, and regardless of their political affiliation. The economic, health, and environmental consequences of climate change are well known, and our understanding about how to address the causes of climate change continue to improve.

It's critical that we support scientific research about climate, and that we build on rather than break down decades worth of progress on this issue. I urge the Committee to hold hearings specifically on mitigation and adaption strategies to help communities grapple with this situation.

Geoengineering is an option our country should explore. The state of current geoengineering research makes clear that we are years or perhaps decades away from potential deployment, and the risks of deployment are not well understood, and we're hoping for some answers here today. In fact, a key finding in the U.S. Global Change Research Program's Climate Science Special Report, which was published last Friday, determined that further assessments of the technical feasibilities, costs, risks, co-benefits, and governance challenges of climate intervention or geoengineering strategies, which are as yet unproven at scale, are a necessary step before judgments about the benefits and risks of these approaches can be made with high confidence.

This is because of a lack of technical maturity and understanding of the risks associated with geoengineering. We do not currently have enough evidence to determine whether any of the various proposals for geoengineering can provide long-term solutions to address the impacts of climate change, or that they would not pose any adverse consequences to our environment.

Our climate is changing, and the warming trends observed over the last hundred years are primarily caused by human activities, specifically the emission of greenhouse gases. In fact, this is one of the most prominent findings in the Climate Science Special Report. This report unequivocally lays out the need to reduce carbon dioxide emissions to prevent long-term warming and short-term climate change.

I want to ask the Subcommittee Chairman for unanimous consent to include a letter addressed to him and Chairman Smith into the record. It's been signed by many prominent members of the geoengineering research community, highlighting the urgency of the threat that climate change poses and reemphasizes that geoengineering is not a magic fix to addressing climate change.

Chairman BIGGS. Without objection.

[The information appears in Appendix I]

Ms. BONAMICI. And with that, Mr. Chairman, I'd like to yield the remainder of my time to the gentleman from California, Mr. McNerney.

[The prepared statement of Ms. Bonamici follows:]

OPENING STATEMENT
Ranking Member Suzanne Bonamici (D-OR)
of the Subcommittee on Environment

Committee on Science, Space, and Technology
Subcommittee on Environment
Subcommittee on Energy
"Geoengineering: Innovation, Research, and Technology"
November 8, 2017

I want to thank the Chairman for holding this important hearing today on geoengineering.

I am encouraged that the Science Committee is discussing a field of science and engineering that is still in its infancy and has ample areas for further research. It is noteworthy for its potential, and it's important that we consider it from political, ethical, legal, and environmental perspectives.

Geoengineering is a set of climate interventions that aim to manipulate our climate to either remove greenhouse gases from our atmosphere or reduce the amount of sunlight absorbed by the Earth. Some may argue that geoengineering is a way to use technology to essentially bypass important mitigation and adaptation strategies that address climate change impacts, but even with geoengineering, our first and primary actions to address climate change must be mitigation and adaption strategies.

In our communities, climate change is not a partisan issue. Nationwide, fishers, farmers, small business owners, and our servicemen and women are changing the way they do their jobs because of climate change – and regardless of their political affiliation. The economic, health, and environmental consequences of climate change are well known, and our understanding about how to address the causes of climate change continue to improve.

The time is now. It is critical that we support scientific research about climate, and that we build on rather than break down decades worth of progress on this issue. I encourage this Committee to hold hearings specifically on climate mitigation and adaption strategies to help communities grapple with this dire situation.

Geoengineering is an option our country should look into. The state of current geoengineering research makes clear that we are decades away from potential deployment and the risks of such a deployment are not well understood.

In fact, a key finding in the US Global Change Research Program's Climate Science Special Report, which was published last Friday, determined that "[f]urther assessments of the technical feasibilities, costs, risks, co-benefits, and governance challenges of climate intervention or geoengineering strategies, which are as yet unproven at scale, are a necessary step before judgments about the benefits and risks of these approaches can be made with high confidence."

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Before I close, I would like to ask the Subcommittee Chairman for unanimous consent to include this letter, addressed to him and Chairman Smith, in the record. This letter has been signed by many prominent members of the geoengineering research community. It highlights the urgency of the threat that climate change poses and reemphasizes that geoengineering is not a magic fix to addressing the impacts of climate change.

I would like to yield a minute of my time to the gentleman from California, Mr. McNerney.

Chairman BIGGS. Mr. McNerney, please.

Mr. MCNERNEY. Well, I thank the gentlewoman from Oregon, and I thank the Chairman for calling this hearing.

Climate change is happening, and the effects are accelerating faster than the scientific models predict. The changes we are experiencing today are the results of heating that has taken place over the past decades. Meanwhile, carbon concentration in the atmosphere is continuing to increase. Therefore, additional heating and climate impacts are inevitable even if we were to stop carbon emissions immediately. In other words, we are committed to significant change.

The unknown is how much change we're committed to and how fast it will take place. It's not known if we are committed to truly catastrophic change with the current policies or not. But no matter what, it's absolutely critical to reduce carbon emissions and prepare for the changes that are coming, in other words, mitigate and adopt.

The changes we are committed to may be so strong that we'll need to know what can be done to prevent utter catastrophe. What tools are available? What are the technical feasibilities? What are the costs and what are the risks of the different approaches to avoiding catastrophic change?

That's where this hearing comes in. What are the hypothetical alternatives and how do we best go about determining their feasibility, costs, and impacts?

I will be dropping a bill next week, which members of the panel have already seen, and I need guidance from experts on what changes to the proposed legislation is needed.

Thank you, I yield back.

Chairman BIGGS. Thank you.

I now recognize the Chairman of the entire Committee, Chairman Smith.

Chairman SMITH. Thank you, Mr. Chairman, and I also thank Congressman Weber for letting give my opening statement before him. I have a markup that began in the Judiciary Committee that unfortunately I've got to attend but I hope to be back shortly.

Mr. Chairman, first I want to thank the Chairman of the Environment Subcommittee, you, for having this hearing, and also Representative Weber of Texas, the Chairman of the Energy Subcommittee, for your interest in this subject. I also want to thank the gentleman from California, Mr. McNerney, for his persistent interest in this subject. Every time I've seen him on the House Floor for the last couple of months, he's wanted to have this hearing, so we appreciate his interest as well.

Mr. Chairman, geoengineering's potential is worth exploring. Generally, we know that the technologies associated with geoengineering could have positive effects on the Earth's atmosphere. These innovations could help reduce global temperatures or pull excess greenhouse gases out of the atmosphere.

For instance, one of the most intriguing ideas in this field is solar radiation management. This concept involves finding innovative strategies to reduce the amount of sunlight that reaches and warms the earth. Today, one of our witnesses will expand on this idea with a concept that brightens clouds and reflects sunlight, which is measured in albedo. While this technology is interesting, we have a lot to learn.

Some have questioned the unintended consequences of geoengineering. One concern is that brightening clouds could alter rain patterns, making it rain more in some places or less in others. Such technologies could drastically reduce global temperatures in the future by spraying aerosols into the atmosphere to reflect sunlight. While we are not sure this is plausible, some scientists believe it could achieve substantial environmental benefits at a cheaper cost than regulations.

Regardless of these claims, we still do not know enough about this subject to thoroughly understand the pros and cons of these types of technologies.

As the climate continues to change, geoengineering could become a tool to curb resulting impacts. Instead of forcing unworkable and costly government mandates on the American people, we should look to technology and innovation to lead the way to address climate change.

Geoengineering should be considered when discussing technological advances to protect the environment, and geoengineering should not be ignored before we have an opportunity to discover its potential. This hearing will help Congress do just that.

Mr. Chairman, I thank our witnesses today for testifying on the current state of geoengineering research and for their recommendations about how to advance practicable efforts in this area, and I'll yield back.

[The prepared statement of Chairman Smith follows:]

COMMITTEE ON
SCIENCE, SPACE, & TECHNOLOGY
Lamar Smith, Chairman

For Immediate Release
November 8, 2017

Media Contacts: Thea McDonald, Brandon VerVelde
(202) 225-6371

Statement from Chairman Lamar Smith (R-Texas)

Geoengineering: Innovation, Research, and Technology

Chairman Smith: First, I want to thank you, the Chairman of the Environment Subcommittee, and the Chairman of the Energy Subcommittee, Rep. Weber of Texas, for holding this important hearing, and Rep. McNerney of California for his persistent interest in this subject.

Geoengineering's potential is worth exploring. Generally, we know that the technologies associated with geoengineering could have positive effects on the Earth's atmosphere.

These innovations could help reduce global temperatures or pull excess greenhouse gases out of the atmosphere.

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Instead of forcing unworkable and costly government mandates on the American people, we should look to technology and innovation to lead the way to address climate change.

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And geoengineering should not be ignored before we have an opportunity to discover its potential. This hearing will help Congress do that.

I thank our witnesses today for testifying on the current state of geoengineering research and for their recommendations about how to advance practicable efforts in this area.

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Chairman BIGGS. Thank you, Mr. Chairman.

I now recognize the Chairman of the Energy Subcommittee, Mr. Weber, for an opening statement.

Mr. WEBER. Thank you, Mr. Chairman. Let me add my welcome to today's joint Environment and Energy Subcommittee.

Good morning and welcome to today's Joint Environment and Energy Subcommittee hearing. Today, we are going to hear from a panel of experts on the status of America's research in geoengineering, a field truly in the scientific unknown. Hearings like today's help remind us of the Science Committee's core focus: the basic research that provides the foundation for technology breakthroughs.

Within the DOE lab system, Pacific Northwest National Lab is leading the effort to protect—to explore the potential impact of geoengineering technology. PNNL hosts geoengineering researchers who hope to open the dialog on this groundbreaking technology—Jerry, you'll be glad to hear—and consider what methods could have the most positive impact on the climate. Some proposed ideas at PNNL include placement of mirrors in space, injection of naturally occurring substances into the atmosphere to mimic a volcanic eruption, or brightening the clouds overhead. All of these methods could have a cooling effect on our lower atmosphere.

It's amazing to think that molten lava from volcanic eruptions can actually produce compounds that cool the air. Brightening clouds is equally interesting, but only early-stage evaluation has occurred on the practicality of this approach. As we will hear from one of our witnesses, we have already seen ship tracks that create this brightening effect, where the sunlight is reflected back into the atmosphere. By injecting aerosols composed of seawater particles into low ocean clouds, researchers could shrink the size of water droplets and in turn brighten those clouds.

PNNL's Climate and Earth Systems Science researchers and partnerships have to rely on computer models to understand the potential impact of these very basic geoengineering methods, but as we've heard before in this Committee, models are only as good as the data they use.

I believe that we should consider funding appropriately scaled field-testing to improve the accuracy of geoengineering models. Through the National Labs, the United States already partners with researchers from Canada, China, Denmark, Germany, Japan, and Norway. These scientists used the output from 12 climate models in the Geoengineering Model Intercomparison Project, which seek to understand the possible climate effects of geoengineering.

Geoengineering has the potential to provide us with a whole new understanding and approach to atmospheric research. If we put aside the debates about climate change, we can support innovations in science that can create a better prospect for future generations.

The Federal Government should prioritize this kind of basic research so we can not only understand the science of geoengineering, but hopefully partner with the private sector to develop technology to mitigate changes in climate. When the government supports basic research, everyone has the opportunity to access the fundamental knowledge that can lead to the development of future technologies.

The future's bright for geoengineering, and I want to thank our panel of witnesses for testifying today. I look forward to a productive discussion about the innovation, research and technology of this emerging field of science.

Mr. Chairman, I yield back.

[The prepared statement of Mr. Weber follows:]

COMMITTEE ON
SCIENCE, SPACE, & TECHNOLOGY
Lamar Smith, Chairman

For Immediate Release
November 8, 2017

Media Contacts: Thea McDonald, Brandon VerVelde
(202) 225-6371

Statement from Chairman Randy Weber (R-Texas)

Geoengineering: Innovation, Research, and Technology

Chairman Weber: Good morning and welcome to today's Joint Environment and Energy Subcommittee hearing. Today, we will hear from a panel of experts on the status of America's research in geoengineering, a field truly in the scientific unknown.

Hearings like today's help remind us of the Science Committee's core focus – the basic research that provides the foundation for technology breakthroughs. Within the DOE lab system, Pacific Northwest National Lab (PNNL) is leading the effort to explore the potential impact of geoengineering technology.

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As we will hear from one of our witnesses, we have already seen "ship tracks" that create this brightening effect, where the sunlight is reflected back into the atmosphere. By injecting aerosols composed of seawater particles into low ocean clouds, researchers could shrink the size of water droplets and in turn brighten the clouds.

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The future is bright for geoengineering and I want to thank our panel of witnesses for testifying today. I look forward to a productive discussion about the innovation, research and technology of this emerging field of science.

###

Chairman BIGGS. Thank you, Mr. Weber.

I now recognize the Ranking Member of the Energy Subcommittee, Mr. Veasey, for an opening statement.

Mr. VEASEY. Thank you, Mr. Chairman, and we have an excellent panel of witnesses today and I'm really looking forward to hearing their insights, and thank you very much for being here.

Despite the numerous claims, geoengineering is not the answer to 150 years of polluting our planet at an unsustainable rate, and in order to slow the impact of climate change and eventually reverse its effects, we have to get out priorities straight, and mitigation and adaptation must be part of the top priorities. We must face the global challenge of climate change, and solving this challenge requires every nation to find effective solutions to reduce our emissions and set us on a far more sustainable path.

The scientific community has made clear that climate change will continue to be an issue for the rest of this century and beyond. The long-term nature of this challenge is the reason we need to investigate every possible solution in addition to implementing mitigation and adaptation strategies.

Geoengineering, in particular, is in its very early stages and more research is required to expand our understanding of its risks and potential benefits. During our discussion today, I hope the witnesses can provide us with their recommendations on what types of research the Federal Government should invest in for the benefit of all Americans. These recommendations will help shape our national investments in climate modeling, Earth systems research, laboratory experiments, and potential small-scale field tests in the coming decades.

On that note, I would like to stress to my colleagues the importance of supporting the full spectrum of research at the Department of Energy. In particular, activities within the Office of Science's Biological and Environmental Research program are crucial to expanding our knowledge of Earth systems and climate modeling. Funding this important research can have numerous benefits, including advancing the field we are discussing today.

It is unfortunate that the Trump Administration's budget proposal included a 43 percent cut to BER with major cuts and outright eliminations of key activities within the Earth and Environmental Systems subprogram. These cuts would hurt the emerging field of geoengineering, but more importantly, they would cripple our ability to understand the range of factors driving global temperatures upward. If you are a climate skeptic, then you must support more research to expand our collective understanding. If you cannot support that, then you are choosing to ignore the facts. Frankly, we have no time to ignore the mounting scientific evidence as it relates to climate change. We need productive dialogue if we want to better understand this challenge and embrace the necessary solutions.

In addition to supporting the key research activities that underpin geoengineering, there may also be additional federal investments that Congress should consider in order to have an impact in the near future. Carbon dioxide removal strategies are a generally less-risky form of climate intervention that may prove useful in our efforts to fight the impacts of climate change. These strategies come in the form of bioenergy with carbon capture and sequestration, direct air capture technologies, enhanced geological weathering, and land use management, just to name a few.

The National Academies examined carbon dioxide removal in 2015 and concluded that this area is ripe for further federal research investments. For this reason, I included this critical research in a draft bill that I will be introducing in the coming weeks: the Fossil Energy Research and Development Act. In addition to authorizing key R&D activities for carbon capture, utilization, and sequestration activities, the bill would also instruct DOE to create a research program on carbon dioxide removal. I hope that my of my colleagues on both sides of the aisle will join me as a cosponsor of this legislation. The bill would push the DOE to prioritize the important work of environmental mitigation within the Office of Fossil Energy. The public health and economic benefits are considerably numerous. I hope this bill can be a bipartisan path forward to an area of research at DOE that needs it.

I look forward to working with my colleagues on these issues, and thank you, Mr. Chairman. I yield back the balance of my time.

[The prepared statement of Mr. Veasey follows:]

<u>OPENING STATEMENT</u>
Ranking Member Marc Veasey (D-TX)
of the Subcommittee on Energy

Committee on Science, Space, and Technology
Subcommittee on Environment
Subcommittee on Energy
"Geoengineering: Innovation, Research, and Technology"
November 8, 2017

Thank you, Mr. Chairman. We have an excellent panel of witnesses and I am really looking forward to hearing their insights.

Despite numerous claims, Geoengineering is not the answer to 150 years of polluting our planet at an unsustainable rate. To slow the impact of climate change and eventually reverse its effects, our first priorities must be mitigation and adaptation.

The most pressing global challenge we face is climate change. Solving this challenge requires every nation to find effective solutions to reduce our emissions and set us on a far more sustainable path. The scientific community has made clear that climate change will continue to be an issue for the rest of this century and beyond. The long-term nature of this challenge is the reason we need to investigate every possible solution in addition to implementing mitigation and adaptation strategies. Geoengineering, in particular, is in its very early stages and more research is required to expand our understanding of its risks and potential benefits.

During our discussion today, I hope the witnesses can provide us their recommendations on what types of research the federal government should invest in for the benefit of all Americans. These recommendations will help shape our national investments in climate modeling, Earth systems research, laboratory experiments, and potential small-scale field tests in the coming decades.

On that note, I would like to stress to my colleagues the importance of supporting the full spectrum of research at the Department of Energy. In particular, activities within the Office of Science's Biological and Environmental Research program (BER) are crucial to expanding our knowledge of Earth systems and climate modeling. Funding this important research can have numerous benefits, including advancing the field we are discussing today. It is unfortunate that the Trump Administration's budget proposal included a 43% cut to BER, with major cuts and outright eliminations of key activities within the Earth and Environmental Systems subprogram. These cuts would hurt the emerging field of geoengineering, but more importantly, they would cripple our ability to understand that the range of factors driving global temperatures upward.

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In addition to supporting the key research activities that underpin geoengineering, there may also be additional federal investments that Congress should consider in order to have an impact in the near future. Carbon dioxide removal strategies are a generally less-risky form of climate intervention that may prove useful in our efforts to fight the impacts of climate change. These strategies come in the form of bioenergy with carbon capture and sequestration, direct air capture technologies, enhanced geological weathering, and land use management, to name a few. The National Academies examined carbon dioxide removal in 2015 and concluded that this area is ripe for further federal research investments.

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I look forward to working with my colleagues on these issues. Thank you again, Mr. Chairman and I yield back the balance of my time.

Chairman BIGGS. Thank you, Mr. Veasey.

Let me introduce our witnesses. Our first witness today is Dr. Phil Rasch, Chief Scientist for Climate Science and Laboratory Fellow at Pacific Northwest National Laboratory. Previously, Dr. Rasch served as a Chair of the International Global Atmospheric Chemistry program and was named a Fellow of the American Association for the Advancement of Science. He received a bachelor's degree in atmospheric science and chemistry from the University of Washington and a master's of science in meteorology from Florida State University, and he completed his Ph.D. at the National Center for Atmospheric Research in Boulder, Colorado.

Our second witness is Dr. Joseph Majkut, Director of Climate Policy at Niskanen Center. Previously, Dr. Majkut worked as a Congressional Science Fellow under the American Association for the Advancement of Science and the American Geoscience Institute. Dr. Majkut received degrees from Princeton University, the Delft University of Technology, and Harvey Mudd College.

Our next witness is Dr. Douglas MacMartin, Senior Research Associate at Cornell University. Previously, Dr. MacMartin led the Active Control and Flow Control Research programs at the United Technologies Research Center. He received his bachelor's degree from the University of Toronto and his Ph.D. in aeronautics and astronautics from MIT.

And our last today is Ms. Kelly Wanser, Principal Director at Marine Cloud Brightening Project, Joint Institute for the Study of the Atmosphere and Ocean at the University of Washington. Ms. Wanser is a Member of the National Academies of Sciences. She received her bachelor's degree from Boston College and her master's degree from the University of Oxford.

I now recognize Dr. Rasch for five minutes to present——

Dr. RASCH. Are we ready?

Chairman BIGGS. We're going to keep discussing her for a few minutes. No, I think we're now ready to recognize Dr. Rasch for five minutes to present his testimony. Thank you, Dr. Rasch.

TESTIMONY OF DR. PHIL RASCH,
CHIEF SCIENTIST FOR CLIMATE SCIENCE,
LABORATORY FELLOW,
PACIFIC NORTHWEST NATIONAL LABORATORY

Dr. RASCH. Thank you. Chairmen Biggs and Weber and Smith, Members Bonamici and Veasey and Subcommittee Members, thanks for the opportunity to be here.

I testified before this Committee in 2010 on geoengineering. I'm the Chief Scientist for Climate Science at Pacific Northwest National Labs, where I lead programs studying Earth's atmosphere and environmental change. I've also been involved in geoengineering research. I've authored about 20 papers on geoengineering, supported mainly by philanthropic foundations and the NSF in my previous job. I was also a member of the committee that wrote the National Research Council report on geoengineering, and a lead author on relevant chapters from the Intergovernmental Panel on Climate Change report as well.

Americans have become increasingly aware of changes in our environment ranging from dramatic decreases in sea ice in the arctic to increases in summertime heat waves, droughts, floods, fires, and damage from hurricane and other extreme weather events including increasing ocean acidity that damages fisheries.

Evidence in the National Climate Assessment and elsewhere indicates that the changes are connected to increases in carbon dioxide so a prudent step to reducing impacts is to stop increasing carbon dioxide as quickly as possible.

Two engineering methods attempt to address some of these threats through two very different strategies. I'm not an expert in the carbon dioxide removal strategy you heard about earlier so I won't discuss it further, and I'll sometimes talk about solar radiation management as sunlight reflect methods, a term I prefer.

Sunlight reflection methods try to reflect some of the sun's energy back to space, cooling the planet. Two strategies have received the most attention so I'll focus on those. One method is called marine cloud brightening. You'll all have felt the surface temperature go down when a cloud passes overhead on a hot summer day by reflecting sunlight back to space. This is how clouds cool the planet. We know clouds can be further brightened. One dramatic example occurs when ocean freighters add particles below clouds to change them and form bright ship tracks. Marine cloud brightening attempts to mimic that kind of cooling by introducing sea salt particles below clouds. Stratospheric aerosol geoengineering tries to mimic the cooling effects of large volcanic eruptions by placing extra particles in the upper atmosphere.

Let me just cover a bit of what we know and don't know and then make some recommendations for progress. There's a lot more detail in my written testimony. We know it's still early days for SRM research but there are hints it could help address climate change by offsetting, delaying or slowing warming. Hints are, that help counter other changes as well. We think SRM could buy time for other measures to be put in place. Even if it works, though, we know it won't be a magic bullet. It won't compensate for all problems, and it may have side effects. Stratospheric aerosol geoengineering and marine cloud brightening have some common features but they're different with different risks and impacts to the planet.

If we used geoengineering, it would need to be adjusted to balance the excess carbon in the atmosphere, and we think it would be very risky to balance a lot of carbon dioxide.

We don't yet know whether geoengineering should be a part of the strategies addressing climate change. It'll take at least a decade to sort out the benefits, risks, and tradeoffs associated with these different technologies.

So what should we do? I think it's time for a coherent and goal-oriented geoengineering research program that complements ongoing research in Earth systems science but focuses on a defined set of objectives targeting better understanding of the effectiveness and potential risks associated with specific geoengineering techniques. That program should include modeling, lab studies, small-scale field studies, and technology development in addition to addressing societal needs for transparency in governance.

Small-scale field studies are needed. These studies should be far too small to affect climate but they'll help us understand the processes important to the SRM strategies, and also help answer crucial questions for climate science. I discuss one example in my written testimony. I believe it's urgent to have a review on governance strategy for this program to help with public understanding and engagement and to improve safety.

Thanks, and I'm happy to take questions.

[The prepared statement of Dr. Rasch follows:]

Statement of Dr. Philip J. Rasch
Chief Scientist, Climate Science
Laboratory Fellow
Pacific Northwest National Laboratory

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.

Statement of Dr. Philip J. Rasch
Chief Scientist, Climate Science
Laboratory Fellow
Pacific Northwest National Laboratory

Before the
United States House of Representatives
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Subcommittee on Environment
Subcommittee on Energy

November 8, 2017

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.

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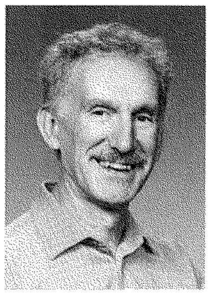
Phil Rasch Biography



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Dr. Philip Rasch serves as the Chief Scientist for Climate Science at the Pacific Northwest National Laboratory (PNNL), a Department of Energy Office of Science research laboratory. In his advisory role, he provides leadership and direction to PNNL's Atmospheric Sciences and Global Change Division. Dr. Rasch provides oversight to more than 90 researchers who lead and contribute to programs within a number of government agencies and industry. These programs focus on climate, aerosol and cloud physics; global and regional scale modeling; integrated assessment of global change; and complex regional meteorology and chemistry.

Dr. Rasch is internationally known for his work in general circulation, atmospheric chemistry, and climate modeling. He is particularly interested in the role of aerosols and clouds in the atmosphere, and has worked on the processes that describe these components of the atmosphere, the computational details that are needed to describe them in computer models, and on their impact on climate. He has authored over 180 scientific papers and is a Fellow of the American Geophysical Union and the American Association for the Advancement of Science.

Rasch is a co-chair of Atmospheric Model component of the DOE's Energy Exascale Earth System Model, and is also on the council for that Project. He has served as co-chair of the Atmospheric Model Working Group activity of the Community Earth System Modeling Project, serving on its steering committee, and was a leader of the development team for the fifth version of the NCAR Community Atmosphere Model. Dr. Rasch has been a chair of the International Global Atmospheric Chemistry Program, and served in various editorial positions journals and on advisory panels for NSF, DOE, NASA and the AMS. He was a lead author for the chapter on Clouds and Aerosols for the Fifth Assessment of the Intergovernmental Panel on Climate Change, and a contributing author on other chapters and reports. He was also a lead author on the National Research Council special report on Geoengineering (2015).

Chairman BIGGS. Thank you, Dr. Rasch.

Now I'll recognize Dr. Majkut for five minutes to present his testimony.

TESTIMONY OF DR. JOSEPH MAJKUT, DIRECTOR OF CLIMATE POLICY, NISKANEN CENTER

Dr. MAJKUT. Thank you, Chairmen Biggs and Weber, and Ranking Member Bonamici, and Members of the Committee. I'm grateful for the invitation to join you today.

My name is Joseph Majkut, and I'm the Director of Climate Policy at the Niskanen Center here in Washington, D.C., where my work focuses on research in climate energy issues, and my personal area of expertise is climate science.

There is no practical scientific doubt that human activity is contributing to climate change nor that continuing emissions will lead to more warming. There is, however, a great deal of uncertainty about the extent of future warming and its environmental and economic consequences. Given that uncertainty, we should think about this as a risk management problem. There may be no perfect solution but in general we should seek ways to reduce greenhouse gas emissions, minimize societal vulnerability, and otherwise limit the potential costs of a warming planet.

Geoengineering may be one such tool to address those potential costs. Further research judiciously done will help us answer that question. With that in mind, I would like to emphasize three points from my written testimony.

The first is that there is a great deal of uncertainty about whether or not geoengineering would work in practice. By changing the reflectivity of the high atmosphere or brightening clouds, we might be able to offset some degree of global warming quickly and reduce its attendant effects but the risk of unintended consequences might be large.

We do know that once we start cooling the planet by artificial means, stopping will be followed by rapid warming as long as CO_2 levels remain high. We also know that a geoengineered world could not simultaneously hold temperatures, rainfall and weather patterns static, meaning that there will be tradeoffs should engineering ever be used to partially or completely offset global warming.

The second is the developing a better scientific understanding of those potential tradeoffs justifies ongoing and future research. Whether or not each of us is concerned about the risks of climate change or repulsed by the very idea of geoengineering, changes to the Earth's climate will inevitably force future generations to confront such choices. This research will be affordable and need not supplant other efforts to understand the nature of climate change. Such research will occur in supercomputing facilities, at the lab bench, and also in small-scale field experiments.

I'll add that I hope it will also be approached via the social sciences as judgments of whether geoengineering is good or practical are not consigned to questions of chemistry or physics. Both the 2015 report from the National Research Council and the most recent update of the U.S. Global Change Research Program's strategic plan highlight the importance of this research and complementary observational and theoretical work in climate science, especially since other countries or private actors might start intervention experiments of their own.

Lastly, Congress should consider what regulatory governing structure will maximize innovation and scientific progress while protecting the public and environment from ill-informed experiments or premature deployment of these technologies. Under the 1971 Weather Modification Act, experiments intent on altering the weather or planetary albedo are already regulated, and those regulations currently require that researchers report their activities to NOAA before and after working in the field.

For today, that is enough. No one to our knowledge is set on large experiments in the near future. However, regulatory governance should grow as experiments grow larger, and it is not clear at present how such regulations might look.

Our research at the Niskanen Center indicates that small-scale experiments should be subject to little more than reporting requirements and existing environmental protections because their climatological effect will be vanishingly small. However, Congress may want to consider if intermediate scale experiments should be subject to prior approval of an agency, and if large-scale experiments subject to the express permission of Congress itself. How we define small, medium and large is a question that will require further thought and should involve the input of the scientific community and civil society. A well-defined and stable regulatory structure will publicly clarify research progress and intent, and that intent should be to clarify the questions of how geoengineering might work and what the costs and benefits of doing it may be. That information could be used by future policymakers to avert trillions of dollars in losses.

If the worst-case scenarios of global warming come to pass, these technologies could be used to help people, savings lives and economies from the most severe effects of climate change. Even if emissions reductions happen quickly, future generations may still find limited geoengineering of use. Managing the risks of climate change is not easy but it will be an ever-present task in the 21st century and beyond. Research into these technologies is an important part of that task as are adapting to warming and reducing emissions. A sturdy whip and a well-plotted course are no substitute for a close watch on the waters ahead nor lifeboats if we need them.

Thank you for the opportunity to speak to you, and I look forward to your questions.

[The prepared statement of Dr. Majkut follows:]

STATEMENT OF JOSEPH MAJKUT
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CONCERNING GEOENGINEERING RESEARCH
NOVEMBER 8, 2017

Good morning Chairmen Biggs and Weber, and Ranking Members Bonamici and Veasey, and members of the Committee. I am grateful for the invitation to join you today and the opportunity to share my perspective on geoengineering research.

My name is Joseph Majkut. I am the director of climate policy at the Niskanen Center, located here in Washington, D.C., where my work focuses on climate and energy policy and matters of climate science.[1]

While there is little practical scientific doubt that human activities are behind most of the recently-observed warming of the Earth—with more to come over this century[2]—there is a great deal of uncertainty about the environmental and economic consequences of warming.[3] As such, society should respond to climate change as a risk management problem and seek ways to reduce greenhouse gas (GHG) emissions, minimize societal vulnerability, and otherwise limit the potential costs of a warming planet.

Geoengineering technologies are one prospective means of addressing these challenges. As a class, they would allow people to intervene in the earth system at a large enough scale to deliberately alter the climate. In the near future, these technologies could be deployed to reduce or prevent warming from human (or natural) causes.

Before contemplating such a deployment, a lot more research should be done into the science, engineering, ethics, and politics of intentionally moderating the climate. Without such research, it would be imprudent to deploy these technologies, or even assume their viability.

In my testimony, I would like to emphasize three main points:

1. Climate geoengineering technologies, particularly Solar Radiation Management (SRM), could be used to prevent some degree of global warming and its attendant effects over short timescales, but there are major scientific questions about the trade-offs associated with using them;
2. The potential benefits of addressing those outstanding questions justifies federal research funding; and
3. Given the nature of these technologies, Congress should consider establishing a regulatory governance structure to maximize innovation and scientific progress while protecting the public and environment from ill-informed experiments or premature deployment.

[1] My writings can be viewed at https://niskanencenter.org/blog/policies/climate/.
[2] For a description, see https://www.climateunplugged.com/articles/the-climate-future/.
[3] For a description, see https://www.climateunplugged.com/articles/understanding-climate-risk/.

Solar Radiation Management Technologies

Generally described as climate geoengineering, technological interventions to reduce the human influence on climate fall into two categories: Carbon dioxide (CO2) capture and SRM, mentioned previously.

Carbon dioxide capture, or negative emissions, describes technologies that would artificially remove CO2 from the atmosphere and thereby limit the warming and chemical effects of excess CO2. These are interesting technologies for research that are already aligned with much of what is done at the Department of Energy (DOE) and other agencies.

SRM describes interventions that would decrease the amount of solar radiation that reaches the surface of the Earth by increasing the planet's reflectivity, or albedo. While there are technical nuances and regionally varying details, the amount of cooling we could expect to see is roughly proportional to the decrease in radiation. These technologies could therefore be tuned to partially or fully offset the warming effects of increased CO2 with an large enough intervention, while very small experiments would have no globally detectable signal.

Two different approaches for SRM are the most thoroughly studied.

The first is stratospheric aerosol injection (SAI), whereby small particles are dispersed in a high part of the atmosphere to create a reflective veil around the Earth. This occurs naturally when very large volcano eruptions shoot sulfates into the stratosphere, where they remain suspended for a year or two, cooling the climate. We witnessed this natural process in 1991/1992, after the eruption of Mt. Pinatubo and we very well may see it again soon, as Mt. Agung in Indonesia is on a level 3 (of 4) eruption watch.[4]

Because SAI is similar to the same natural phenomena observed during volcanic eruptions, we are confident in SAI's ability to cool the planet. However, researchers are not sure if human-driven SAI would have the same temperature effects or if it would induce deleterious side effects. Increased levels of stratospheric aerosols can potentially increase acid rain, deplete stratospheric ozone, dramatically warm the stratosphere, and effect regional temperatures and precipitation. Research will be necessary to better understand the uncertainty and reduce the risks around SAI technologies.

The second method is Marine Cloud Brightening (MCB), which attempts to cool the Earth by brightening the clouds over the ocean, instead of increasing stratospheric albedo. The theoretical basis for MCB lies in the Twomey effect, where the smaller and more numerous a cloud's particles, the brighter it will be.[5] By this theory, spraying thousands of gallons worth of 10 nm-sized particles of saltwater would make existing clouds wider, brighter, and more persistent. Only special kinds of clouds would be affected by MCB, and they tend to occur in specific areas, like the sea off the California coast. This limited

[4] For recent reports on global volcanism, see https://volcano.si.edu/showreport.cfm?doi=GVP.WVAR20171025-264020.

[5] S. Twomey, Pollution and the planetary albedo, In Atmospheric Environment (1967), Volume 8, Issue 12, 1974, Pages 1251-1256.

deployment area means we don't know if MCB would have a very large cooling effect, or a very small one.

In 2015, the National Academies of Sciences published a two-part report that provides a comprehensive discussion of the state of the science in geoengineering research including SAI and MCB and their comparative qualities.[6]

It is important to note that while there is much we still don't understand about SRM technologies, we are sure about some concepts.

SRM introduces a new way to manage climate risk, but it will not directly counteract greenhouse-driven warming. According to modeling studies and basic meteorological theory, a geoengineered world could not replicate the preindustrial one or simultaneously hold regional climates, rainfall patterns, and global temperatures static. Thus, any significant deployment of SRM would involve regional and local tradeoffs whose political, economic, and ecological effects we cannot now predict.[7]

If used for offsetting some of the net warming effect of CO_2, SRM deployment will require constant maintenance. Carbon dioxide resides in the atmosphere for centuries to millennia; clouds last a week and aerosols a couple of years. So if SRM was deployed to reduce warming, there would be a relatively sudden warming should the SRM program cease. Thus once humanity starts down the path of slowing or offsetting warming, it will be difficult to walk back while excess CO_2 remains in the atmosphere.

Not all of the considerations that will govern decisions to use or refrain from using SRM technologies are scientific. However, numerous scientific and engineering gaps prevent an informed understanding of the costs and benefits or potential unintended consequences. Reducing uncertainties and better characterizing those risks presents the scientific enterprise with the opportunity to add value for future policymakers.

Research Support Justified

Even if GHG emissions reductions proceed rapidly, temperatures will continue to increase over the next few decades, and likely surpass the 1.5C and 2C targets laid out in international agreements. As temperatures increase, the effects of climate change will become more obvious, widespread, and harmful.[8] As climate impacts worsen, policymakers will face increased pressure to consider fast

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[6] National Research Council. 2015. *Climate Intervention: Reflecting Sunlight to Cool Earth*. Washington, DC: The National Academies Press. https://doi.org/10.17226/18988.

[7] Corner and Pidgeon 2010. Geoengineering the Climate: The Social and Ethical Implications. Environment: Science and Policy for Sustainable Development. 52. 24-37.

[8] For a comprehensive discussion of how climate impacts will progress through different levels of warming, see Oppenheimer, M., et al., 2014: Emergent risks and key vulnerabilities. In: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. https://www.ipcc.ch/pdf/assessment-report/ar5/wg2/WGIIAR5-Chap19_FINAL.pdf.

responses like SRM. However, without a clear understanding of the trade-offs associated with SRM deployment, future actors will be limited in their ability to judge the merits of deployment.

Better characterizing standing uncertainties as inputs to a risk management strategy is valuable for informed policymaking. The potential scale of climate risks and the costs associated with transitioning to a low-carbon economy mean that the potential value of SRM could register in the trillions of dollars.[9] That value may be accounted as reduced climate damages or a less-costly transition to low-carbon energy. Even reducing the uncertainty in the costs and benefits of deploying SRM could be of great value.[10] Given current limitations on our knowledge, learning that SRM is either acceptably risky or totally unacceptable would be valuable.

Within the scientific community, there is a growing sense that pursuing research to resolve the scientific questions surrounding geoengineering is worthwhile. Many organizations, like the Bipartisan Policy Center (BPC),[11] the Royal Society,[12] the National Research Council,[13] and the Governmental Accountability Office (GAO),[14] express some need to better understand the risks of solar geoengineering through research.

In the 2017 update of its strategic plan, the United States Global Change Research Program (USGCRP) acknowledged that geoengineering research is on the horizon and the federal research enterprise could meaningfully inform research activities and governance.[15] That plan noted that:

> [w]hile climate intervention cannot substitute for reducing greenhouse gas emissions and adapting to the changes in climate that occur, some types of deliberative climate intervention may someday be one of a portfolio of tools used in managing climate change. The need to understand the possibilities, limitations, and potential side effects of climate intervention becomes all the more apparent with the recognition that other countries or the private sector may decide to conduct intervention experiments independently from the U.S. Government.

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[9] Arino, Y., et al. 2016. *Estimating option values of solar radiation management assuming that climate sensitivity is uncertain*, Proc. Natl. Acad. Sci. U. S. A. http://www.pnas.org/content/113/21/5886.full.pdf.
[10]Moreno-Cruz and Keith. 2012. *Climate policy under uncertainty: a case for solar geoengineering.* Climatic Change. https://link.springer.com/article/10.1007/s10584-012-0487-4.
[11] Task Force on Climate Remediation Research. Long, J. (Chair) 2011.
https://bipartisanpolicy.org/library/task-force-climate-remediation-research/
[12] The Royal Society. 2009. *Geoengineering the climate: science, governance and uncertainty.*
https://royalsociety.org/~/media/Royal_Society_Content/policy/publications/2009/8693.pdf.
[13] NRC. 2015. *Climate Intervention.*
[14] United States Government Accountability Office. 2010. *Climate Change: A Coordinated Strategy Could Focus Federal Geoengineering Research and Inform Governance Efforts*
http://www.gao.gov/new.items/d10903.pdf.
[15] United States Global Change Research Program. 2017. *National Global Change Research Plan 2012–2021: A Triennial Update.* Washington, DC, USA
https://downloads.globalchange.gov/strategic-plan/2016/usgcrp-strategic-plan-2016.pdf.

Questions may arise over whether this type of research is more valuable than other types of climate studies, advanced energy research, or even research in other scientific disciplines. Especially in a time of increased budgetary pressures, Congress faces tough choices about how to allocate public funds.

Research into geoengineering technologies, at least initially, should not be overly costly or supplant other initiatives. Some of the work you can image scientists pursuing will be beneficial to other questions in climate science and to general intellectual inquiry, while some work will likely benefit mainly geoengineering considerations. Both are valuable.

Further, to anyone contemplating deployment of SRM as a risk management tool, an appreciation of how complementary technologies can measure and understand the climate system and atmospheric compensation should be a top priority. That means better observations, modeling tools, and a strong community of climate scientists and interdisciplinary experts. These things are valuable for climate research generally and broader societal decisionmaking, and would be necessary in any world of judicious climate engineering. You can't engineer what you don't measure or understand.

Should Congress decide that funding geoengineering research is desirable, then research dollars should be directed to multiple agencies, such as the National Science Foundation, National Oceanic and Atmospheric Administration, Department of Energy and other participants in USGCRP. At such an early stage of research, we would benefit from have more perspectives looking at this issue.

Governance

Much of the research that can and will be done on geoengineering will be done in supercomputing centers and in controlled experiments at the workbench. But as this science progresses, researchers will need to move into the field to perform experiments in real world conditions. In the near-term, we shouldn't expect to see manipulation of the climate at large scales, but instead small field experiments to evaluate equipment and make measurable, but trivial, changes to the environment.[16] Though small in net effect, proposed experiments aimed at understanding the chemical and physical processes will provide valuable foundational data.[17]

Such experiments, and the researchers who will carry them out, will benefit from clear and fair regulatory guidance. Any regulatory framework should aim to maximize innovation and scientific progress, while protecting the public and environment from premature or ill-informed experiments.

Present-day Governance

It is important to note that Congress has already given limited authority to regulate experiments intent on altering the weather, including changing planetary albedo. At this point, those regulations are limited to reporting requirements.

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[16] Andy Parker, 2014. Governing Solar Geoengineering Research as it Leaves the Laboratory, Royal Society, 2014.
[17] Introductions to conceptual process experiments can be found in the NRC's 2015 report, "Climate Intervention" table 4.1, list items 1 and 3.

In the 1971 National Weather Modification Act, Congress defined the term "weather modification" to mean, "any activity performed with the intention of producing artificial changes in the composition, behavior, or dynamics of the atmosphere".[18] Section 2 of the 1971 Act provided that, "No person may engage, or attempt to engage, in any weather modification activity in the United States unless he submits to the Secretary such reports with respect thereto . . . as the Secretary [of Commerce] may by rule prescribe."

And as far as NOAA is concerned, "any" means "any", and specifically includes SRM. Rules finalized in 1976 provide that "The following, when conducted as weather modification activities, shall be subject to reporting:

> (1) Seeding or dispersing of any substance into clouds or fog, to alter drop size distribution, produce ice crystals or coagulation of droplets, alter the development of hail or lightning, or influence in any way the natural development cycle of clouds or their environment;
>
> ...
>
> *(3) Modifying the solar radiation exchange of the earth or clouds, through the release of gases, dusts, liquids, or aerosols into the atmosphere;*[19]

Thus by regulation, anyone intent on engaging in field experimental perturbations of planetary albedo are already required, by law, to submit *ex ante* and *ex post* reports documenting the extent of their activities.

Section 5 of the 1971 Act provides, "Any person who knowingly and willfully violates section 2 of this Act, or any rule issued thereunder, shall upon conviction be fined not more than $10,000." Note the word "conviction"; this is a criminal offense.

Future Governance

As prospective research moves beyond model and bench studies, it will be important to establish a clear regulatory framework for field tests and *in situ* experimentation that goes beyond reporting. Regulatory governance should grow as experiments grow larger.[20] Congress should consider a 3-tier structure for this purpose.

First, there should be a *de minimis* threshold, below which would be experiments—far too small to measurably affect the earth's surface—that should require no federal permission and only be subject to reporting requirements similar to those in effect today. By maintaining a permissive regulatory

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[18] P.L. 92-205, https://www.gpo.gov/fdsys/pkg/STATUTE-85/pdf/STATUTE-85-Pg735.pdf.
[19] 15 C.F.R. 908.3(a).
[20] NRC Report, Chapter 4 and references therein.

environment for researchers doing process-level experiments, we would allow a maximum degree of innovation and scientific progress.

Since these *de minimis* experiments would be too small to affect the earth's surface more than many common activities, these experiments—should the government choose to fund them—should be categorically exempted from the National Environmental Policy Act (NEPA).

Second, Congress should consider what degree of climatological effect, duration, or regional impacts could define a maximum threshold for experimental work. Experiments should not cross this cap without Congressional permission. Such a decision would occur once we have developed a better understanding of the scale of impacts, costs and benefits of larger scale research, and the societal and international response to this type of research.

Third, any proposed experiments above *de minimis* but below the cap, should require agency permission and regulatory approval *ex ante*. Congress should instruct the agency to permit such experiments based on a careful weighing of their risks and benefits and coherence with scientific priorities.

If the required permit triggers NEPA, then it should remain applicable to these agency decisions. In cases where the permitted activity does not rise to the level of requiring NEPA analysis, the agency should still be required to provide public notice of permit applications and the opportunity to comment on them.

In order to allow both the *de minimis* and agency-permitted experiments to proceed without undue burden, Congress should consider preempting state or local laws requiring permission to conduct such experiments. At the same time, Congress should make it very clear that all other laws—state and federal, civil and criminal—apply to the experiment and the person(s) conducting it.

Lastly, in order to ensure public and international confidence in the limited and regulated nature of any such experiments, Congress should ensure that failure to abide by the agency's regulations would be subject to significant civil and administrative penalties, and that violation of the hard cap would also be subject to criminal penalties.

Congress might also consider whether to extend that criminal liability not only to such experiments originating within or over the United States, but also conducted outside of our borders that result in an impact on the United States commensurate with a domestic experiment over the hard cap. Such considerations would need the input of the diplomatic and international community.

Congress could either set the level of the *de minimis* threshold and the hard cap itself, or delegate that responsibility to agency rulemaking done in consultation with the scientific community.[21] To inform such

[21] There have been some suggestions for thresholds of radiative effect that would separate lightly regulated and off-limits experiments to which governments and science agencies could agree. For example: Parson and Keith, *End the Deadlock on Governance of Geoengineering Research*, Science 2013. http://science.sciencemag.org/content/339/6125/1278.

deliberation, Congress may want to request a study from the National Academy of Sciences or a blue ribbon commission to provide a set of recommendations on future governance of geoengineering research.

Conclusion

The case for further scientific inquiry into geoengineering is compelling. It is an idea that could help many people or it could be impossibly hazardous and politically unacceptable. We don't presently know. Giving the scientific community the charge of answering what questions it can seems prudent.

In the near term, this research—even small scale field experiments—probably doesn't need additional regulatory constraint in the United States. But while not immediately necessary for funding to flow or experiments to occur out-of-doors, it would be better for some regulatory structure to be in place earlier rather than later. The framework presented above is one proposal in that direction. The considerations of how to regulate such experiments to protect the public, without impeding scientific progress or creating political storms, will require negotiation and thought.

I would like to thank the Committee for the opportunity to testify on this matter, and look forward to your questions.

BIOGRAPHY OF JOSEPH MAJKUT

Dr. Joseph Majkut is director of climate policy at the Niskanen Center. He is an expert on climate science, the global carbon cycle, and risk and uncertainty analysis for decision-making. Before joining the Niskanen Center, he worked on climate change policy in Congress as a congressional science fellow, supported by the American Association for the Advancement of Science and the American Geoscience Institute. He holds degrees from Princeton University, the Delft University of Technology, and Harvey Mudd College.

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Chairman BIGGS. Thank you, Dr. Majkut, and I apologize for mispronouncing your name earlier. I apologize.

I now recognize Dr. MacMartin for five minutes to present his testimony.

TESTIMONY OF DR. DOUGLAS MACMARTIN, SENIOR RESEARCH ASSOCIATE, CORNELL UNIVERSITY

Dr. MACMARTIN. Thank you. So I want to start by thanking the Committee Members for the opportunity to testify today. So I'm Douglas MacMartin at Cornell University with a background in both engineering and climate science, and I've been working on geoengineering for about the last ten years, and I think one of the striking things about this panel is actually how broad our agreement is likely to be on almost all of the issues.

So the reason we're all here of course is that as was reaffirmed last week by the U.S. National Climate Assessment, we know that the Earth's climate is changing as a direct result of human emissions of greenhouse gases, and we know that the United States is already experiencing some impacts as a result. While these impacts may be manageable today, they will continue to grow so long as we continue to emit greenhouse gases, and so the less we emit, the lower the risk, and nothing we say here today about geoengineering changes the fact that we must reduce our greenhouse gas emissions and that this effort remains the most important component of a strategy to respond to climate change.

That said, geoengineering approaches could become a valuable additional component of an integrated strategy to manage climate impacts. So carbon dioxide removal can effectively produce negative emissions, but we need research there on scalability, costs, and local impacts, and I'll focus primarily on the sunlight reflection, or solar geoengineering side, so ideas like adding aerosols to the stratosphere or making marine boundary layer clouds more reflective, and I'd say from the limited modeling research that we've done to date, it's plausible that a limited amount of solar geoengineering, used in addition to cutting emissions could reduce some of the impacts of climate change but there's still considerable uncertainty into the side effects and risks, and that will require focused, goal-oriented research. That could take decades, at least a decade, maybe more, which is why it's important to start it soon.

So it's important to stress at the outset that solar geoengineering cannot be a substitute for cutting emissions for several reasons. This conclusion has been reached by every assessment of this technology including by the National Academies in 2015, so first it does not compensate all of the impacts of climate change so ocean acidification would continue unchecked.

Second, if we keep adding greenhouse gases to the atmosphere, we'd have to continually increase the amount of geoengineering we were doing, so keep adding more and more aerosols to the stratosphere every year just to keep temperatures in balance, and that would lead to increased side effects and risks.

And third, because of the long lifetime of carbon dioxide in the atmosphere, if we relied only on solar geoengineering, that would lead to a practically indefinite commitment to future generations to either continue deploying it or accept the consequences of high CO_2.

However, as long as it's considered as a supplement to cutting emissions, then it might reduce some climate damages and so it would be valuable to conduct the needed research. A coherent prioritized research effort needs to be driven by the end goal of supporting informed decisions regarding these approaches, and research would need to be integrated into the overall U.S. climate science research effort and should include explicit attention to research governance.

The next step is probably to clearly articulate research needs and how to address them. This might benefit, for example, from an expert body like the National Academies. For stratospheric aerosol injection, we know that it works at least for a degree or two of cooling. It works in the sense of cooling the planet simply by analogy with what happens after large volcanic eruptions, and the observations made after eruptions have helped calibrate our climate models. Near-term research here is likely to continue to be primarily model-based, and once we better understand the uncertainties we need to address, it's likely we would need some outdoor experiments to resolve key uncertainties, but I should emphasize that these would always be at a very small scale. Marine cloud brightening would also benefit from small-scale, controlled experiments, which would also help inform critical uncertainties in climate change science. All of this research will build on continued investments in climate modeling, in high-performance computing, and in our ability to collect observations about the Earth system.

So in summary, I and I think many of my colleagues in the research community believe that even with our best efforts at mitigation, the risks of future climate change are sufficiently concerning that we may need to consider all of the options at our disposal. I conclude that it's essential to conduct focused, goal-oriented research to support informed decisions but reiterate that this needs to be in addition to the work of reducing our emissions of greenhouse gases and not a substitute.

Thank you, and I look forward to all of your questions.

[The prepared statement of Dr. MacMartin follows:]

Statement to the Committee on Science, Space and Technology
of the United States House of Representatives

Hearing on
Geoengineering: Innovation, Research, and Technology

November 8, 2017

Douglas G. MacMartin
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Major points:

- The context for considering geoengineering is the fact that human emissions of greenhouse gases are warming the Earth's climate and creating risks for the United States and other nations.
- Because of the long lifetime of CO_2 in the atmosphere, the more we put in, the larger the impacts will be. Reducing greenhouse gas emissions remains the most important component of a strategy to respond to climate change.
- Geoengineering, including carbon dioxide removal (CDR) and sunlight reflection methods (SRM), could be an additional and valuable part of an integrated strategy for managing climate change. CDR is the only way to achieve negative emissions, while SRM can act quickly to cool the climate.
- Sunlight reflection cannot be a *substitute* for cutting emissions for several reasons:
    - Counteracting rising greenhouse gas concentrations would require continually increasing the amount of geoengineering, leading to increased side effects and rapid warming if deployment were ever interrupted.
    - A significant fraction of the CO_2 we add to the atmosphere remains for more than 1000 years, requiring a practically indefinite commitment for future generations to either maintain SRM or accept the consequences of higher CO_2.
    - SRM cannot compensate all impacts of climate change, e.g., it cannot reverse the ocean acidification caused by increased atmospheric CO_2 concentrations.
- Based on research to date, it is *plausible* that a *limited* amount of SRM, *in addition* to cutting emissions, could reduce some of the impacts of climate change. There is considerable uncertainty about the viability, impacts and risks; research to reduce this uncertainty could take decades.
- A coherent, prioritized geoengineering research effort would be valuable, to support informed decisions regarding these approaches (including possibly abandoning the idea), and would need to include natural sciences, social sciences, and explicit attention to research governance. Such a program would need to be integrated into the overall US climate science research effort.
- Near-term research for stratospheric aerosol injection should be primarily model-based, to characterize model uncertainty and understand the potential to improve outcomes. Marine cloud brightening would benefit from limited field experiments, which would also inform critical uncertainties in climate change science. The first step is to better define research needs.
- Conducted at sufficient scale, carbon dioxide removal would direct address the mechanism of climate change. Research is needed to find approaches that are sufficiently scalable, cost-effective, and without significant local impacts.

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Hearing on
Geoengineering: Innovation, Research, and Technology

November 8, 2017

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Contents

1. Introduction and context

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 in the United States. I hold research appointments in both the Department of Mechanical and Aerospace Engineering at Cornell University and the Computing + Mathematical Sciences Department at the California Institute of Technology. My research lies at the intersection between engineering and climate science, and geoengineering has been my primary research focus for the last ten years.

There are three areas I will briefly address. The first is the role that geoengineering might be able to play in managing climate change. Second, I will make a few comments regarding the current status of research that are relevant for considering the path forward. And third, I will discuss future research needs.

Geoengineering, or climate engineering, refers to two broad categories of technologies. First, carbon-dioxide removal (CDR)[1], including technologies such as burning bio-energy and capturing and storing the carbon underground (BECCS), or direct air capture (DAC) of CO_2, which would reduce atmospheric CO_2 concentrations and directly address the cause of climate change. Second, sunlight reflection methods (SRM), also known as solar geoengineering or albedo modification[2], would involve either adding aerosols to the stratosphere or brightening marine boundary layer clouds, these would cool the climate by reflecting a small portion of sunlight back to space. I will address both but focus on the latter, both because it is the more novel and potentially disruptive of the two, and because I am more knowledgeable about SRM. Both topics were recently addressed by the US National Academies[1,2].

The context for considering these ideas is the fact that human emissions of heat-trapping greenhouse gases (GHG), principally CO_2, are altering Earth's climate, as reiterated in the recent US Fourth National Climate Assessment (2017)[3], which notes that in addition to warming, "Thousands of studies conducted by researchers around the world have documented changes in surface, atmospheric, and oceanic temperatures; melting glaciers; diminishing snow cover; shrinking sea ice; rising sea levels; ocean acidification; and increasing atmospheric water vapor". CO_2 has a long lifetime in the atmosphere, with a significant fraction remaining even after 1000 years[4]; as a result the planet will still be warmer in 1000 years due to the CO_2 we add today[5]. The more CO_2 we add, the greater the warming. It is thus not possible to limit climate change without ultimately reducing net carbon emissions to zero; reducing emissions must therefore be a central element of any meaningful climate change strategy.

The United States is already experiencing impacts of a warmer world, from increased tidal flooding in the Atlantic and Gulf states, increases in heavy rainfall, increased heatwaves, increased large forest fires, and reduced snowpack that affects water resources (see the US National Climate Assessment, 2017 for further details). Additionally, unusually strong hurricanes have likely been amplified by higher than normal sea surface temperatures that are a result of climate change. These impacts are a result of roughly 1.8°F (1°C) of warming. However, without any policy to reduce emissions of greenhouse gases, the warming could reach 9°F (5°C) or more by the end of century, leading to far more extreme impacts and greater risk of crossing irreversible "tipping point" thresholds in the climate system such as triggering significant sea level rise from the Antarctic and Greenland ice sheets. Flooding, heat waves, and forest fires will be greatly exacerbated relative to today, while the risk of chronic long-duration drought is expected to rise. Sea level rise under such a scenario is expected to be at least 1-4 feet by the end of the century, while a rise of as much as 8 feet cannot be ruled out[3].

To avoid these impacts from "business as usual", almost every nation has voluntarily chosen nation-specific targets for reducing their individual greenhouse gas emissions; taken together these commitments have been estimated[6] to lead to end-of-century warming near 3°C. This is far lower than the 5°C that could occur without any agreement to act[3], but still substantially higher than the 1.5 – 2°C level of warming deemed "safe" by the international community[7,8].

Geoengineering technologies may be able to reduce climate impacts in two ways. First, CDR is the only way to achieve net-negative emissions, ultimately reducing the atmospheric CO_2 concentrations and reducing the long-term impacts that our emissions are imposing on future generations. Second, because it acts quickly to cool the planet, SRM could limit the amount of climate damage that would otherwise result from higher atmospheric CO_2 concentrations.

An overall strategy for reducing climate change risks may involve four elements:

- Accept higher levels of warming; some impacts may be reduced through adaptation, e.g., by building sea-walls or relocating some urban areas.
- Increase the speed at which new technologies are adopted to reduce emissions, by earlier adoption of renewable energy, earlier transitions to electric vehicles, etc.
- Large-scale deployment of CDR approaches; to be a relevant component of a strategy the rate of removal needs to be at a sustained level of at least several billions of tons of CO_2 every year.
- Limited use of solar geoengineering approaches.

Neither of the last two options exist today. We do not know whether it will be possible to develop CDR approaches that can be scaled up to the necessary levels at reasonable cost, and without having substantial local impacts such as loss of food production. We do not know whether the risks of solar geoengineering would outweigh the benefits even in a limited deployment scenario. Research into geoengineering could thus add to the portfolio of options available for managing climate change.

Figure 1 (from MacMartin et al 2017[9], adapted from Long and Shepherd 2014[10]) illustrates how these elements might be integrated into an overall strategy to manage climate change: (i) anthropogenic emissions of greenhouse gases are eventually brought to zero, (ii) excess atmospheric concentrations are reduced through CO_2 removal, and (iii) solar geoengineering might be used to limit climate impacts in the interim. Note that while SRM could reduce the global mean temperature, it will not reduce ocean acidification and resulting impacts on ocean ecosystems, and it will also have other effects on the climate system. However, unlike mitigation, solar geoengineering would affect the climate quickly, and thus could provide a unique additional tool for managing climate change.

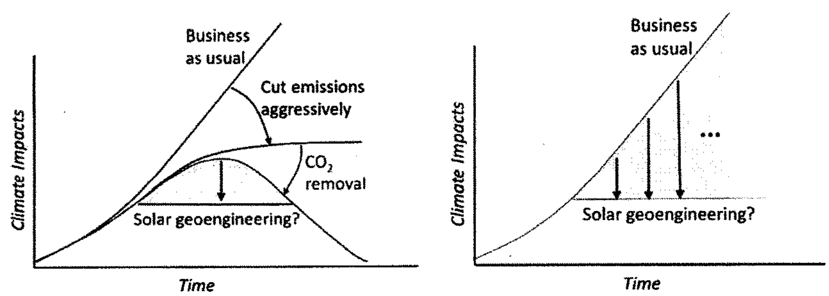

Figure 1. (left) Reducing greenhouse gas emissions, combined with future large-scale atmospheric CO_2 removal, may lead to long-term climate stabilization with some overshoot of desired temperature targets. There is a plausible role for temporary and limited SRM (solar geoengineering) as part of an overall strategy to reduce climate risks during the overshoot period. (right) SRM instead of mitigation would require large and increasing forcing, sustained for millennia, and is thus not realistic. This graph represents climate impacts conceptually, not quantitatively

SRM cannot be an alternative to reducing greenhouse gas emissions. This is a conclusion that has been reached by every assessment that has been conducted of these technologies, including by the US National Academies in 2015. If emissions are not reduced then atmospheric greenhouse gas concentrations continue to grow as illustrated in Figure 1, requiring continuous increases in the amount of reflecting stratospheric aerosols or the amount of cloud brightening to maintain a stable temperature. This is not a viable solution for at least four reasons. First, undesired side-effects of geoengineering (e.g., stratospheric ozone depletion) would increase with the amount used. Second, increased atmospheric CO_2 also results in ocean acidification that would not be counteracted by SRM. Third, because of the long lifetime of CO_2 in the atmosphere, geoengineering would need to be maintained for a practically indefinite time period, imposing a commitment on future generations to either maintain the deployment or accept the consequences of high CO_2; if the deployment were ever terminated there would be a sudden rapid warming[11] that could have impacts worse than if SRM were never initiated. Finally, while we are confident that several degrees of cooling could be achieved, it is not clear how much cooling might be possible[12], and it would be risky to assume that sufficient cooling could be obtained to offset the warming from un-mitigated CO_2 emissions.

Reducing emissions of greenhouse gases is the most urgent and essential response to climate change. However, while every reduction in emissions leads to lower climate impacts and risks, a rapid reduction in emissions will still result in a world that may be substantially warmer than today with correspondingly larger impacts from climate change. While solar geoengineering is not a substitute for cutting emissions, climate modeling research suggests that it is plausible that a limited deployment, in addition to mitigation and CO_2 removal, would reduce many climate risks. However, the current state of knowledge is insufficient to assess whether the risks of deploying geoengineering outweigh the risks of not deploying it. Developing the required knowledge demands a strategic *goal-oriented* research program. This knowledge base could take decades to develop, as some research will require small-scale outdoor experimentation. Meanwhile climate change impacts will continue to grow in severity. The worst-case outcome is that we find ourselves in a climate crisis in 20 years and face the need to make decisions without knowledge; needing to decide whether to deploy SRM without knowing enough to ensure that it will do what we want it to do, safely. In order to support informed decisions, strategic research needs to be initiated soon and conducted with some degree of urgency.

The next section briefly summarizes the status of geoengineering research, highlighting some recent results. Building on current status, Section 3 then addresses research needs.

2. Status of Geoengineering Research

2.1 Carbon dioxide removal

Various approaches have been suggested for deliberately removing CO_2 from the atmosphere; see for example the 2015 National Academies Report[1]. In the near-term, CDR is equivalent in outcome to cutting emissions, but likely at higher cost. In the long-term CDR allows net-negative emissions that would compensate for our current positive emissions; this effectively makes future generations pay for reducing our current emissions. Current human emissions of CO_2 are of order 40 billion tons per year; to make a useful contribution to the problem, CDR would need to be undertaken at least at a fraction of that scale, 10-20 billion tons per year or more. Not all of the ideas that have been suggested are capable of being scaled up sufficiently. While there are no direct climate risks from removing CO_2 from the atmosphere, anything conducted at the massive scale required could have other negative impacts.

The capacity for large-scale CDR later in the century will not materialize without near-term investments to learn whether and how solutions can be scaled up at reasonable cost.

Possible approaches include:

- Bio-energy with carbon capture and storage (BECCS). This involves growing biofuels, burning them in a power plant, capturing the CO_2 before it is released to the atmosphere, and storing it underground. Because the plants absorb CO_2 as they grow, this would both create energy and sequester CO_2, and is likely to be technically possible. However, implementing this on a sufficient scale to be useful would create competition for land use with food crops if terrestrial biofuels were used; using oceanic biofuels might also be possible.
- Direct air capture involves using chemical means to extract CO_2 directly from the atmosphere, and then sequester the CO_2 underground. This is certainly technically possible, and scalable, but there is currently high uncertainty on what the costs are likely to be.
- Enhanced mineral weathering accelerates natural CO_2 removal processes that would otherwise occur on geological timescales.
- Planting trees would reduce atmospheric CO_2 as the trees grow. This is limited by land availability, and while it could contribute, is not sufficient to address the scale of CO_2 removal required.
- Soil management, including biochar: there is significant carbon stored in soils today, and better land management might increase this amount. Estimates suggest that like afforestation it has the potential to contribute but is unlikely to be able to address the full scale of the problem
- Ocean iron fertilization could increase marine phytoplankton, increasing CO_2 uptake through photosynthesis, some unknown fraction of which may ultimately be sequestered in the deep ocean by settling of biological detritus. At scale this approach would have significant implications for ocean ecosystems.

2.2 Sunlight reflection methods

Methods for reflecting some incoming solar radiation could rapidly cool the Earth; for recent reviews see MacMartin et al (2017)[9], or the 2015 US National Academies report[2]. Two principle approaches have been suggested:

- Stratospheric aerosol injection, or SAI. Large volcanic eruptions can introduce significant amounts of sulfate aerosols (an aerosol is a small liquid or solid particle) into the upper atmosphere, where the residence time can be 1-2 years; this results in temporary cooling of the planet by reflecting some sunlight back to space. By analogy, mimicking this natural process by deliberately adding sulfate aerosols to the stratosphere is certain to cool the planet, although it will have other effects on the climate system as well. This is nearly certain to be technically feasible (e.g. by designing suitable aircraft; none currently exist). The direct cost of delivering material to the stratosphere is not likely to be an important factor in deployment decisions.
- Marine cloud brightening (MCB) involves injecting sea-salt aerosols into low clouds in appropriate regions of the ocean; with more cloud-condensation nuclei, the clouds are expected to be "brighter" and reflect more sunlight. A similar phenomenon is observed with ship tracks; the pollution from ship smokestacks results in a cloud that can persist for days. Cloud-aerosol interactions are highly uncertain, and so the feasibility of this approach is less certain.

Other approaches have also been suggested. Cirrus clouds result in a net warming of the planet, and thus deliberately thinning cirrus cloud cover has been suggested as a way of providing some cooling; the viability of this approach is highly uncertain.

To date, research on sunlight reflection methods has relied on climate modeling. References 13 and 14 illustrate the capability of state of the art climate models to capture observed stratospheric aerosol concentrations after the Mt. Pinatubo eruption in 1991, as well as the recovery of the ozone hole. Consistency between model simulations and the observations made during and after an eruption builds confidence that the models can reasonably represent the relevant processes. There are, however, differences between continuously injecting aerosols for geoengineering and impulsively injecting them through an eruption, which leads to some uncertainty in model predictions that will be discussed in more detail below; there are similar uncertainties in model simulations for marine cloud brightening.

Deploying SRM would not simply reverse the heating caused by greenhouse gases, it would also change climate patterns. While a reduction in sunlight would cool the planet everywhere, the cooling would not have the same spatial or seasonal pattern as the greenhouse gas warming. The warming caused by increased greenhouse gases also influences precipitation (both rain and snowfall), while the cooling from SRM would not simply reverse these effects. Thus if CO_2 increases relative to today, and the resulting warming is then offset by a reduction in sunlight, the resulting climate will not be the same as the current climate. However, the resulting climate will be much more similar to the current climate than either would be to the high-CO_2 world without SRM (see MacMartin et al 2017[9], which compares both regional temperature and precipitation projections). Recent research with climate models suggests this may be true for many features of climate change: not only are annual mean temperature and precipitation closer to current conditions with some SRM than without, but that is also the case for high temperature extremes, soil moisture, ocean circulation patterns, Arctic sea ice, and hurricane strength, for example.

One recent development in SRM research worth highlighting comes from exploring how the resulting climate impacts depend on choices that can be made[15], such as the latitude at which to inject aerosols into the stratosphere, or where to deliberately brighten marine clouds. Combining aerosol injection at multiple different latitudes allows the climate response to be at least partially tailored[16], possibly improving outcomes[17]. While sulfate aerosols have often been assumed in simulations, different aerosols could also be chosen that have less stratospheric heating and associated impact on dynamics[18,19] or that might reverse the sign of the effect on ozone[20]. The extent to which SRM can be designed to better manage climate outcomes is as yet unknown, and thus how well it could compensate for the climate effects of increased atmospheric greenhouse gases is still uncertain. This is a promising avenue of research, and one reason why it is premature to assess climate impacts from any current simulations.

There is also significant research in geoengineering beyond the physical climate science described above. This includes evaluations of the ethics of climate intervention, social science to better understand how different publics might respond to the idea[21], and research aimed at building necessary governance.

As noted earlier, progress made to date with climate models suggests that it is at least plausible that a limited deployment (where the amount of cooling provided is no more than 1-2°C) used in addition to, rather than instead of, cutting greenhouse gas emissions would reduce many climate impacts. However, relatively limited research has been conducted to date, and significantly more research would be required to support informed decisions.

3. Research Needs for Sunlight Reflection Methods

3.1 Questions

The goal of research into geoengineering is to support future decisions regarding this technology, i.e., what role, if any, SRM might play in addressing climate change. There are three overlapping sets of questions that will need to be addressed to support an informed decision:

1. What outcomes are and are not achievable through SRM? For example, different choices (such as the latitude of aerosol injection) will lead to different impacts; understanding the trade-offs is needed to define responsible options.
2. What are the impacts of different options for deployment? How would SRM affect the broad list of concerns regarding climate change? What additional concerns are associated with the specific approach (either SAI or MCB)?
3. What is our confidence in predicting outcomes? What uncertainties are there and how do these affect impacts; what is the range of plausible outcomes? What is the justification for our confidence? What research would be needed to further reduce uncertainty?

Research can be framed around these overarching questions. It is reasonable to expect that much of the research between now and any decision regarding deployment will ultimately revolve around how to reduce or manage uncertainty, but a thorough analysis of future research needs does not yet exist.

3.2 Uncertainty

While some progress has been made over the last decade in understanding how SRM might affect the climate system, there is still significant uncertainty[22] about how SRM would affect the climate. First, as noted earlier, there is some uncertainty in small-scale processes directly related to how SRM reflects sunlight, discussed in the next paragraph. Second, there are uncertainties about how the climate system responds to a reduction in sunlight as compared with a change in greenhouse gases, and how these affect the things society might care about, from the probabilities of heat waves or drought to ecosystem health or agricultural yields (which are influenced by a combination of CO_2 concentrations, temperatures, and precipitation), to how effective SRM would be at reducing the risks of sea level rise.

For stratospheric aerosols, process uncertainties in the upper atmosphere include aerosol microphysics (if we release sulfur dioxide, how large are the resulting aerosol droplets), stratospheric chemistry (e.g., what is the impact on ozone), and the impact on cirrus clouds. Stratospheric aerosols also heat the stratosphere and affect stratospheric dynamics and water vapor concentrations; these processes are also uncertain. Validation with existing observations after volcanic eruptions is not sufficient to constrain all of the parameters, as noted earlier. Marine-cloud brightening (MCB) involves injecting sea-salt aerosols into marine boundary layer clouds in order to increase cloud reflectivity. However cloud-aerosol interactions are one of the largest areas of uncertainty in climate change science, and it is thus unclear over what fraction of the ocean MCB might be effective. In addition, while stratospheric aerosols may be relatively uniformly distributed around the world, the regions in which clouds would be brighter would be more localized, potentially creating more regional variation in the climate effects.

3.3 Near-term research needs

Reducing uncertainty to acceptable levels will ultimately require a series of additional dedicated observations and (small scale) perturbative field experiments, each designed to reduce specific uncertainties.

However, for stratospheric aerosol geoengineering, we do not yet know which uncertainties are most important to reduce; that is, how sensitive are the outcomes we care about to uncertainty in some specific physical process? State of the art climate models are now capable of simultaneously capturing aerosol microphysics, interactions with stratospheric chemistry, and coupling with stratospheric dynamics in a fully coupled model[14], but there has not yet been a careful analysis to assess either how uncertain any one of these processes might be, nor how uncertainties in any of the above processes flow down into uncertainty in the outcomes that we care about. As a result, one of the important near-term goals would be to better characterize how much uncertainty there is and how it affects outcomes, in order to better define and prioritize a longer-term and larger-scale research effort in this area. A more thorough exploration of the design space – what can geoengineering do and what can it not do – can also be conducted using existing climate models. Thus for stratospheric aerosol geoengineering, near-term research is likely to be almost exclusively model-based.

This is not necessarily the case for marine cloud brightening, where small scale controlled experiments could inform the relevant cloud-aerosol interactions[23]; indeed, conducting these process experiments would also reduce important uncertainties in climate science[24].

3.4 Longer-term research

An example of a possible future field experiment would be a stratospheric balloon experiment to verify chemical reaction rates[25,26]. This experiment cannot be conducted indoors because of the difficulty in replicating all of the important features of the stratospheric environment in a laboratory setting. A small amount of material would be released, and then instrumentation would sample the ensuing plume to measure the chemistry; the information would then be used to better constrain uncertain parameters in a climate model. The direct environmental impact of such a test would be too negligible to detect. Nonetheless, any outdoor experiment raises some legitimate concerns with the public regarding the intent of research, and thus some level of governance is appropriate.

While future experiments may be somewhat larger in scale than this balloon experiment ALL of the experiments that might ever be conducted on SRM over the coming decades will be relatively small scale in the sense that they will be designed not to have any detectable climate impact. The reason for this is that experiments will be designed to understand specific process uncertainties in models, and not to measure the climate response to geoengineering. An experiment to measure the regional climate response to geoengineering would require such substantial forcing levels[27] so that no such test would ever occur without society first having made an explicit decision to deploy. This both means that there will always be some uncertainty in the regional climate projections prior to deployment, but also that there will be a bright line between research activities and anything resembling deployment.

It is clear that no deployment should take place without adequate research. Since research will take considerably longer than it would take to develop the technical capacity for deployment, it would be inappropriate to develop any deployment capability today or soon.

3.5 Research governance

Research into geoengineering, and SRM in particular, raises important questions for society beyond typical scientific research. While model-based research does not need any unusual governance beyond normal scientific peer review, it would be appropriate to consider governance needs for any geoengineering research that involves outdoor experiments. This echoes the National Academies report[2], which recommended "the initiation of a serious deliberative process to examine: (a) what types of research governance, beyond those that already exist, may be needed for albedo modification research, and (b) the types of research that would require such governance," and that any new governance structure emanating from this deliberation should be transparent and broadly representative; similar observations have been made for high-level principles proposed for responsible geoengineering research[28].

3.6 The path forward

Given this context on research needs, it is appropriate to consider what a path forward might look like.

While I have given some observations on the type of research that is likely needed, a first step would be to conduct a more comprehensive assessment of research needs; this would benefit from involving an expert panel. In addition it would be valuable to put in place appropriate research governance in preparation for the expectation of likely future small-scale outdoor experimentation. Particularly for stratospheric aerosol geoengineering, additional model-based research would be valuable; in part this is needed because without this research it would be impossible to appropriately prioritize any larger research effort. Any research conducted in this space will need to be in coordination with existing climate science research, and will need to build on existing infrastructure for climate observations and US computing resources.

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Biography for Douglas MacMartin

Douglas MacMartin is a Senior Research Associate and Senior Lecturer in the Sibley School of Mechanical and Aerospace Engineering at Cornell University, and also a Visiting Scientist in the Department of Computing and Mathematical Sciences at the California Institute of Technology. Prior to his appointment at Cornell, he was a Research Professor at Caltech. From 1994 to 2000 he worked for United Technologies Research Center where he led the Active Control research activities. He holds a Ph.D. in Aeronautics and Astronautics from the Massachusetts Institute of Technology (1992), and a B.A.Sc. from the University of Toronto in Engineering Science (1987). He is a member of the American Geophysical Union and an Associate Fellow of the American Institute for Aeronautics and Astronautics.

While his original training is as an aerospace engineer, he has been working as a climate scientist since roughly 2002, and has been researching geoengineering since 2006. He has 61 peer-reviewed publications including 24 in geoengineering and another 10 in climate science (the rest in more traditional engineering fields), as well as 73 conference papers, 2 book chapters, and 5 patents. In 2017 he was co-chair of the first Gordon Research Conference on Climate Engineering, and he will be a chair (with Trude Storelvmo) of the second conference in 2020. He is also on the Board of Advisors for the Forum for Climate Engineering Assessment at American University, an informal international advisor for the climate engineering program at Beijing Normal University, and was a member of the Advisory Group for the second international Climate Engineering Conference (CEC17) in Berlin.

The combination of an engineering background and climate science gives him a unique perspective in the field of geoengineering, and he has published on dynamics, the use of feedback to manage uncertainty, treating geoengineering as a design problem, and uncertainty in geoengineering, among other contributions.

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Chairman BIGGS. Thank you, Doctor.
I now recognize Ms. Wanser for five minutes for her testimony.

TESTIMONY OF MS. KELLY WANSER, PRINCIPAL DIRECTOR, MARINE CLOUD BRIGHTENING PROJECT, JOINT INSTITUTE FOR THE STUDY OF THE ATMOSPHERE AND OCEAN, UNIVERSITY OF WASHINGTON

Ms. WANSER. Thank you. I should have some slides.

Thank you, Members of the Committee. It's an honor to be here, and I commend you for taking up this challenging topic. My name is Kelly Wanser. I spent 20 years as an executive and entrepreneur in the technology industry focused on understanding and securing large, complex systems. Ten years ago, I became interested in how we might apply technology to risks in the Earth system and helped form a collaboration that became the marine cloud brightening project. I'm now its Program Director. Prior to that, I served as an advisor to the laser inertial fusion energy program at Lawrence Livermore National Laboratory and as senior advisor to ocean conservancy, looking at ocean climate risk.

I'm here today because increased heat in the atmosphere poses risks to our way of life and critical parts of nature we rely on. We may require options for directly reducing heat in the Earth system. There is a need and an opportunity for innovation, and there are important steps we can take in developing a research program.

Small particles—aerosols—and the way they interact with clouds to reflect sunlight are one of the primary ways that nature keeps our planet cool. The most promising approaches to rapidly reducing heat in the climate involve adding particles to the atmosphere to slightly increase this reflective effect.

One approach to reducing heat, marine cloud brightening—next slide—would use sea-salt mist sprayed from ships to brighten clouds over the ocean. Next slide.

[Slide]

Applied to a fraction of all marine clouds, it might offset 2 degrees of warming globally, and the way the particles brighten clouds and cool the system is a gap in our ability to forecast weather and climate, and in this way research in marine cloud brightening may be of strategic importance to emergency preparedness, national defense, and many industries.

Today, we lack technical capabilities and scientific knowledge for marine cloud brightening or any proposed approach to rapidly reducing heat in the Earth system. Next slide.

[Slide]

Delivering aerosols with the right properties at sufficient scale is a hard engineering problem and takes time. Next slide.

[Slide]

Once we have technology, next steps are to build a system to enable small-scale field experiments to determine whether these ideas are feasible and basic processes to input to models. There is a well-defined research plan that starts with land-based testing, moves to single ship studies, and finally to misting one region of clouds to determine brightening effects. This research plan will take years.

Satellite—next slide.

[Slide]

Satellite, aerial and surface observations are critical and we will want to support our current infrastructure as well as leverage disruptive new technologies and remote sensing from innovative companies like Saildrone, Spire Aerospace, and others. The work will also require significant advances in modeling and data analysis and increased computing capacities to support assessment and prediction of effects. It will take a decade of core technology development and basic science to determine if any options are feasible and another decade to scale capabilities for readiness. Work must commence soon to produce knowledge and options within a time frame relevant to climate risks. With changes occurring around the world, it is likely and may be inevitable that others will develop capabilities. With a potential to produce geographically variable climate outcomes, the United States has a security interest in understanding and controlling them.

Taken alone, capabilities for reducing heat in the atmosphere are not a solution. They should ultimately be considered as part of a portfolio within a management framework that includes emissions reduction, greenhouse gas removal, land and ocean management, industrial practices, economic incentives, and adaptation. Given the magnitude and urgency of the problem and our current lack of knowledge and capabilities, defining a research agenda and developing funding pathways for research may be critical. A National Academies study to help define a research agenda and establish a governance framework for research activities may be a valuable initial step. Next slide.

[Slide]

This type of work is not unprecedented. In 1934, the U.S. government undertook the largest effort to address an environment problem in our Nation's history: planting 220 million trees through the center of the Midwest to address the great storm of the Dust Bowl. Now may be the time to research the possibility of shelter belts in the sky.

[The prepared statement of Ms. Wanser follows:]

Kelly Wanser
Written Testimony for the House Science, Space and Technology Committee hearing of Geoengineering

Nov 8, 2017

Solar Geoengineering to Reduce Warming in the Earth System: The imperative for research

Insuring against catastrophic climate risks

Increased heat in the atmosphere is changing the earth system, with impacts that pose grave risks to communities, infrastructure, political systems and the ecosystems that sustain life. Larger more frequent wildfires are destroying communities in many parts of the west. Overwhelming storms are devastating our coastal communities, and extreme heat is threatening our heartland. Rapid and unpredictable changes threaten our way of life and critical parts of nature we rely on.

Efforts to reduce greenhouse gases may not be sufficient to address these risks, and adaptation measures may be insufficient for the scale and breadth of potential impacts. We may need options for reducing heat in the earth system to maintain stability and prevent catastrophic outcomes, allowing time to address underlying causes and transform our industries and practices.

The only known means of reducing warming in a timespan of years-to-decades is to increase the reflection of sunlight away from earth. – Ken Caldeira, Carnegie Institution for Science

The most promising approaches to reflecting sunlight ("solar climate intervention") involve dispersing particles in the atmosphere to slightly increase its reflectivity: into the stratosphere, "stratospheric aerosol injection" or into low-lying ocean clouds, "marine cloud brightening". Both approaches are based on phenomena observed in the earth system, and have been recommended by the National Academy of Sciences and US Global Change Research Program as priorities for research. [1]

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[1] *National Academy of Sciences 2015:* *Climate Intervention: Reflecting Sunlight to Cool Earth*

Kelly Wanser – written testimony (cont.)

The imperative for research

Today, we lack technical capabilities and scientific knowledge for any proposed approach to rapidly reducing heat in the earth system. It will likely take a decade of technology development, system modeling and process-level experimental research to determine if any options are feasible, and to understand them well enough to inform policy decisions. It may take another decade to scale any capabilities for deployment readiness. Work must commence soon to produce knowledge and options within a timeframe relevant to earth system risks (e.g. 10-20 years).

With damaging changes occurring around the world, it is likely, and may be inevitable, that others develop capabilities. With the potential to produce geographically variable climate outcomes, the U.S. has a security interest in understanding and controlling them.

The nature of the required research

Proposed interventions in the earth system require mission-driven interdisciplinary R&D efforts across multiple fields within geosciences, engineering, computing and operations, aligned with policy, social sciences and public engagement efforts. Even at small scales (by earth standards), technology challenges are substantial, and field research takes time.

A broad solar climate intervention research program should encompass major interdisciplinary efforts for each of the two recommended approaches, stratospheric aerosol injection and marine cloud brightening, and seed programs to explore other promising ideas.

Warming risks are a time-bound problem, and a research program should seek to provide a set of possible technology options, with understanding of their benefits and risks, within a timeframe relevant to decision making. For example, a 10-year program might be designed to deliver core technology and scientific understanding of viable options for reducing heat the atmosphere for policy-makers to assess possible development of capabilities for deployment.

Marine Cloud Brightening – dual purpose research with a well-defined pathway

Kelly Wanser – written testimony (cont.)

Marine cloud brightening is a promising entry point for solar climate research. It offers the potential for studying solutions ranging from local (coral reefs) to regional (dampening hurricanes) to global (warming), and research serves a dual purpose in accelerating understanding of the most significant uncertainty in understanding weather and climate– the effects of particles on clouds. Using natural materials (sea-salt) with short lived (2-3 days), localized effects, small-scale marine cloud brightening experiments can be highly controlled, and performed under existing regulatory and jurisdictional frameworks.

Early marine cloud brightening research is modeled on established designs for observations or other types of aerosol emissions into low-lying ocean clouds: ship-track studies and larger observational studies of pollution emissions such as the VOCALS study of industrial emissions emanating from Chile and ORACLES study of biomass emissions from Namibia. Marine cloud brightening searchers have published their experimental proposals, and engineering methods, and have only lacked funding and governance pathways to proceed.

Innovation is required; and presents an opportunity

Moving forward with research will help surface technical barriers and small-scale dynamics that are critical to assumptions about any forward possibilities, their costs, risks and policy dynamics. We need to know what particles we can generate, how they will behave, and what we can measure to input to models and forecasts of effects and risks.

Delivering aerosols with the right properties at sufficient scale is a hard engineering problem, and requires new technology for aerosol generation and innovative approaches to delivery. The first program to develop lab-scale technology, the marine cloud brightening project, took six years of work by a team of distinguished aerosol engineers and physicists to develop a nozzle to generate 80 nanometer particles at 1 trillion particles per second as required. Other materials proposed for aerosols in the stratosphere, such as calcium carbonate, may present a significantly harder engineering problem.

Kelly Wanser – written testimony (cont.)

Along with aerosol generation and delivery, measurement and detection is critical, and presents an opportunity to leverage disruptive new technologies for remote sensing. Ocean surface vehicles have the potential to make ocean surface, subsurface and lower atmosphere observations orders of magnitude less expensive than they are today, and support coverage of remote regions of the world, currently unobserved. Likewise, aerial unmanned vehicles carrying a new generation of miniaturized instruments and energy capabilities may replace airplanes for aerial atmospheric observations. And, a new generation of satellites may carry LIDAR and other sensitive instruments for detecting tiny particles from space. Companies like Saildrone, Spire Aerospace, Spaceflight and others may be partners in these efforts, working in tandem with existing platforms and programs.

To ensure effectiveness and manage risks, we will need to substantially improve our ability to understand and forecast weather and climate. We will need to use an array of approaches, from advanced data analysis via machine learning to advances in models and simulations. This will require increased computing capacity. Climate research is the largest consumer of computing resources on earth (only astrophysics has greater requirements). We will need to invest in the next generation of super-computing – exascale – and accelerate the adoption of cloud computing for dramatic increases in support for all types of data and analysis. Quantum and exascale computing start-ups, next-generation networking and chip companies and established players like IBM, Amazon Web Services, Google and others are potential partners in this innovation.

The current state of research

Today, the funding for research in the field is less than $10M globally, concentrated in computer modeling and policy research. There are no significant experimental or technology R&D programs in the United States or any other country. In 2017, China announced a $3m/year research program, currently comprised of modeling efforts. In recent international meetings in Berlin and Kenya, representatives from developing countries expressed interest in research on any solutions that might mitigate effects they are already experiencing, while communicating their lack of capabilities for doing so.

Kelly Wanser – written testimony (cont.)

The U.S. has the largest infrastructure for climate research in the world, encompassing observational platforms, computing, models, data and expertise. Solar climate engineering research efforts can build from these capabilities, but require new programs and resources for technology development, field trials, enhanced observation methods, and improved climate modeling.

Two major universities currently have programs in solar climate intervention: Harvard University, focused on stratospheric aerosols, and University of Washington, focused on marine cloud brightening and broader management of the atmosphere. These and other universities are likely to be important partners in any Federal research program.

The proposed path forward

Any capabilities for reducing heat in the atmosphere should ultimately be considered as part of a portfolio within an earth systems management framework that includes green-house gas removal, emissions reduction, land and ocean management, industrial practices, economic incentives, adaptation, and other activities with significant impact on the earth system.

Governance and regulatory efforts are needed that encourage and facilitate low-impact field research, while developing approaches for managing large-scale interventions. Oversight will help promote transparency, robust science and public engagement, and should be rapidly established.

Recognizing the importance of a carefully considered research agenda, a thoughtful and transparent approach to defining any program, such as a National Research Council study, may be a valuable initial step. This could be undertaken rapidly, in tandem with any smaller-scale grant programs and in advance of any larger national research program. With a clearly-defined research agenda, a similar process can be used establish a governance framework.

The solar geoengineering research community currently is currently comprised of a relatively small number of academic experts, concentrated in modeling, physics and social sciences. A process to define a program should expand the community to include engineering and systems,

Kelly Wanser – written testimony (cont.)

economics and risk and other disciplines, and include expertise in the management of long-term interdisciplinary science and innovation programs.

Initially, a grant-making program might be established to fund basic technology, science and modeling work in advance of a full program. To extend beyond modeling, such a program may require $5-10m a year to enable early technology development and field work to inform models.

Solar geoengineering research is mission-driven and interdisciplinary, with basic science, applied science and national security characteristics. A full federal research program should be housed in an agency capable of all of these missions. With partnering roles for multiple agencies, universities, and private sector partners, a national laboratory structure may provide a useful point of integration for a larger, multi-faceted federal program.

Given the magnitude and urgency of the problem, and our current lack of knowledge and capabilities, defining a research agenda and developing funding pathways for research, may be important and beneficial investments for the country, of profound benefit to our communities and constituents.

Kelly Wanser

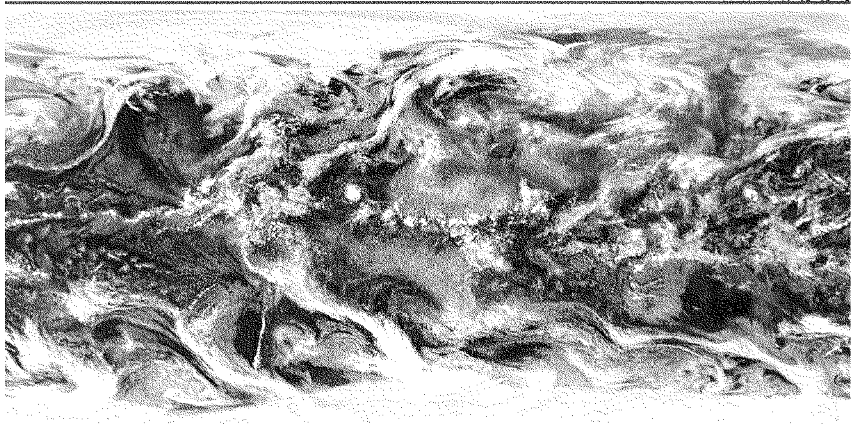
Technology executive and strategist focused on data and systems technologies for IT infrastructure, climate and energy.

Kelly Wanser is Principal Director of the Marine Cloud Brightening Project responsible for program management, strategy and engagement with public, private sector and academic partners. She is member of the National Academy of Sciences President's Circle and advisor to Climate and Ocean Studies Board efforts. She previously served as Senior Advisor to Ocean Conservancy on accelerating innovation to assess climate-ocean impacts and Senior Advisor to Lawrence Livermore National Laboratories on industry strategy for fusion energy.

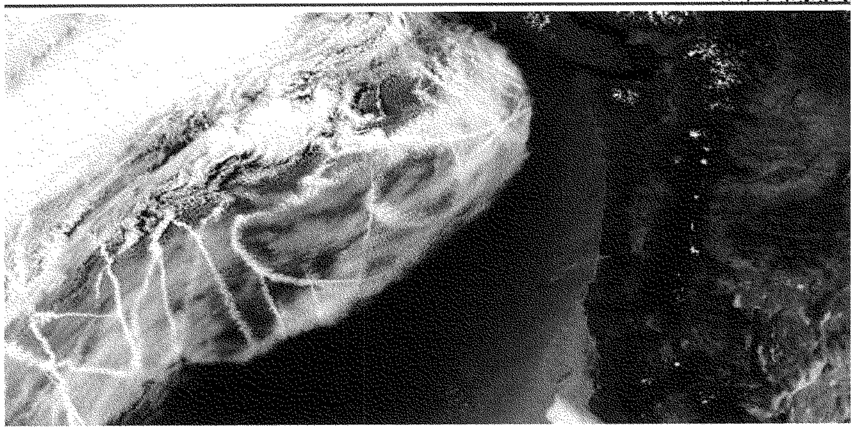
Ms. Wanser began her engagement with solar geoengineering in 2008, under the guidance of distinguished climate scientist Ken Caldeira, when she initiated the collaboration that became the marine cloud brightening research effort. She subsequently coined the term "marine cloud brightening".

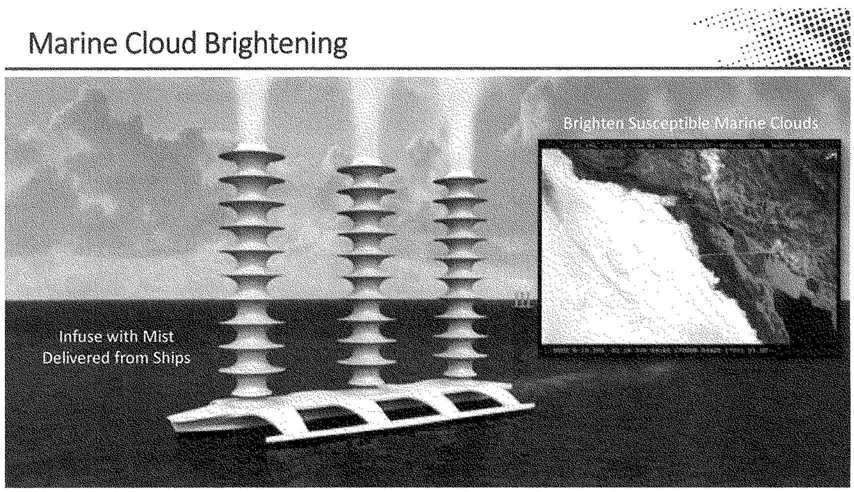
A technologist, executive and entrepreneur, she previously founded companies in IT infrastructure, analytics and security, including ColdSpark, eCert and Luminus Networks. She is the author of over 20 patents related to electronic messaging, security and network analytics. Earlier in her career, she was a strategy consultant for European firm Arkwright, and held positions in outcomes research and web-based disease management for GlaxoWellcome. She is a graduate of Boston College and Oxford University with degrees in Economics and Philsophy, and spent two years as a volunteer lecturer at St. John's College, Belize.

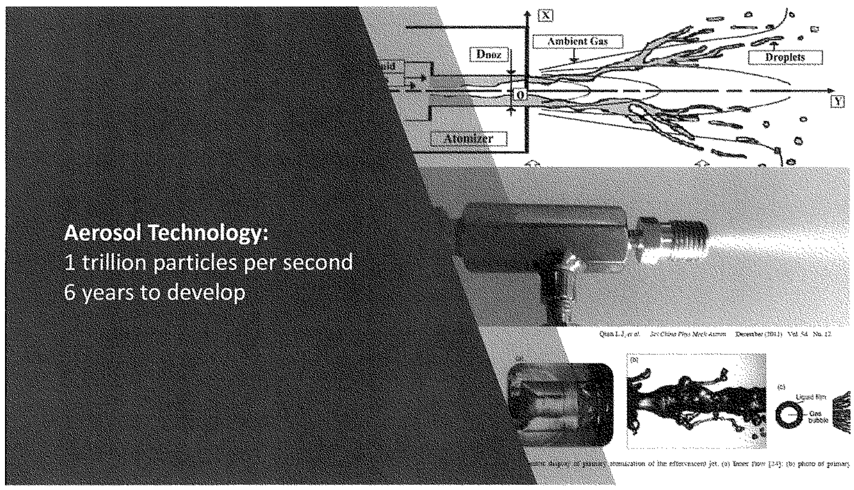
Aerosol cooling



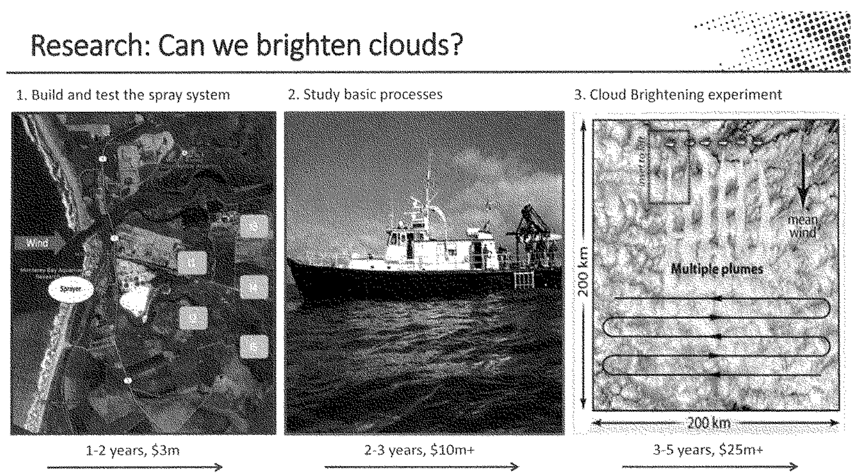
Cloud-aerosol effects




Marine Cloud Brightening
Brighten Susceptible Marine Clouds
Infuse with Mist
Delivered from Ships



Aerosol Technology:
1 trillion particles per second
6 years to develop
Ambient Gas
Droplets
Atomizer


Research: Can we brighten clouds?
1. Build and test the spray system
Wind
Sprayer
2. Study basic processes
3. Cloud Brightening experiment
mean wind
Multiple plumes
200 km
200 km
1-2 years, $3m
2-3 years, $10m+
3-5 years, $25m+


Innovation: What technologies do we need?
1
Particle generation and delivery
Develop ways to generate and deliver right-size particles
2
Surface and air observations
Measure the behavior and effects of cooling particles from Earth
3
Satellite observations
Measure the behavior and effects of cooling particles from space
4
Analytics and models
Advances in all methods of understanding the system and predicting its state
5
Computing
Expanded and advanced computing for data processing and simulation

Great Plains Shelter Belts.

Potential benefits.

Chairman BIGGS. Thank you. I think each of the witnesses for your very interesting testimony. I recognize myself now for five minutes for questions.

Dr. Rasch, I understand that most of the federal research on the topic of geoengineering has been conducted at our federal labs. Can you elaborate on how much funding is currently slated for this type of research?

Dr. RASCH. To my knowledge, the current funding is restricted essentially to a few university professors through the National Science Foundation. The rest of it is being occasionally supported from various agencies to stay engaged in activities like the research reports which you've heard about but most of the other work that's being done is being done through supportive philanthropic organizations or for free on weekends and evenings by scientists who are interested in these things. It probably is bounded by less than a million dollars a year. It could be a few hundred thousand dollars a year of supported research directly for geoengineering. That's to my knowledge. I don't really know.

Chairman BIGGS. Any other panelists want to weigh in on that question? Dr. MacMartin?

Dr. MACMARTIN. The National Center for Atmospheric Research has been providing computer time, which is supported by the NSF, but that's basically—Phil's answer is correct.

Chairman BIGGS. And so I would guess that—and I don't want to presume anything but it sounds like you would agree that the topic has not been adequately pursued in the recent phase?

Dr. RASCH. Right. My reaction is that it's very easy to identify the fact that a very small amount of effort has been put into this area and that progress could be made much more rapidly with a relatively small amount of funding.

Chairman BIGGS. It leads me to ask why has geoengineering not received the same kind of funding as maybe some other types of research over the last 8 to ten years. Dr. Rasch?

Dr. RASCH. Well, I think there's a recognition by all that it's quite a controversial subject of real concern to citizens of the United States and to other scientists as well, and there is some reluctance to take the first step is my sense. That's my best answer.

Chairman BIGGS. Dr. Majkut, or actually anyone on the panel, outside of the Federal Government, is—and you mentioned some of the philanthropic supporters of geoengineering research. What's the postsecondary education or university level of research in this area? Ms. Wanser?

Ms. WANSER. So the overall philanthropic funding in this area is, I would characterize it as maybe in the range of $1 to $2 million a year, mostly allocated towards one program, the stratospheric aerosol program at Harvard. For the most part my experience in the philanthropic community is that this subject matter is not yet acceptable for funding, so traditional sources of environmental and climate research funding in the philanthropic community are not yet funding in this area.

Chairman BIGGS. And Dr. Majkut, how about universities?

Dr. MAJKUT. Well, we know there's a few research programs around the country, Harvard University, Washington, other individual scholars. Whether or not this particular item falls under a research priority for a particular university I don't think is a question that's easy for me to answer. There are individual academics who put their energy into it, as Phil says, but it's not a very large field as you go to these scientific meetings where geoengineering is discussed. You see that there's a relatively small number of people working on these issues.

Chairman BIGGS. Are other countries working on geoengineering research, Dr. MacMartin?

Dr. MACMARTIN. So I think the largest program in the world is probably the one at Beijing Normal University in China but that's relatively new and unclear exactly where they're going with that, but in Europe there's some small efforts as well but not substantially larger than what's in the United States.

Chairman BIGGS. So thinking of it in terms of global competition, it doesn't sound like we're falling behind global competitors, it's just that we're not advancing as rapidly as perhaps many or some would like. Is that fair to say?

Dr. MACMARTIN. Not yet but that may change depending on China's future——

Chairman BIGGS. Dr. Rasch?

Dr. RASCH. It was just—I might beg to differ a little bit with Dr. MacMartin that my sense is that over the last five years or so, a variety of European countries have identified explicitly some funding for geoengineering research that amounts to a few million dollars a year perhaps for—at that level, which is substantially larger than the amounts that I could identify in the United States.

Chairman BIGGS. Well, again, thank all of you for being here, and my time is expired, and I recognize the Ranking Member of the Environment Subcommittee, Ms. Bonamici.

Ms. BONAMICI. Thank you, Mr. Chairman.

Just to follow up on the Chairman's questions about work being done internationally, were any of you at the conference in Berlin? Yes? So in terms—I know the Chairman mentioned global competition but we also need to I think have a conversation with the concerns, and Dr. Rasch, you recognize, as our constituents do, there's some controversy and we need some ethical discussions and boundaries, and Dr. Majkut, you mentioned that there's a statute in the United States that research needs to be reported and there needs to be some framework. So how much work is being done internationally on collaborating on some of these questions of what are the frameworks and what are the ethical considerations and how much is regulated in terms of—climate doesn't know political boundaries so, you know, somebody in the United States has to comply with this law but what about internationally? Who's leading that discussion?

Dr. MAJKUT. So there are several newer organizations that are looking at the international aspects of this research and also, you know, geoengineering more broadly as something that might be used to prevent climate risk not represented here today. I think those discussions are beginning to occur but it's—you know, they're consigned to issues that are related to but not just scientific, right, so the moral and ethical frameworks in which we look at these questions. Those conversations are beginning. It's still early stage.

Ms. BONAMICI. And how does the United States compare with other—you mentioned China, Russia, other countries that are maybe working on this in terms of having some sort of regulatory framework or guidance and ethical considerations.

Dr. MAJKUT. I couldn't say about the foreign countries, sorry, but the United States, I think, you know, as I testified, has a framework in place for any research that's going to take place in the next few years, and because of the strength of our scientific community and the National Academy of Sciences, I expect that we will remain at the front of figuring how we can go about this research judiciously.

Ms. BONAMICI. And Dr. MacMartin, we've heard today a few times that geoengineering is not going to be the magic bullet or a fix, it's not a substitute for mitigation and adaptation, and you said that geoengineering could be part of the strategy. So could you please talk about the range of activities that would be included in mitigation and adaptation, and what mitigation work is still required to prevent the most catastrophic consequences of climate change and what role might geoengineering play in that in terms of priorities?

Dr. MACMARTIN. So I think it is clearly that we eventually have to get to zero emissions or net zero emissions of carbon dioxide principally. Basically when we hit zero is when we stop making the problem worse, and the question really is how fast that happens because we can't do that overnight. That would have serious economic consequences if we tried to do that instantly. And so the question in some sense is, how do you balance the needs of our—how do you balance the needs of our grandchildren to have a safe environment and to have a decent economy. So the best efforts at mitigation are still probably going to result in some serious climate damage. You can imagine using carbon dioxide removal in the long term to pull the CO_2 levels back down and in the interim potentially thinking of solar geoengineering as a way to keep the temperatures from getting too bad so that you don't do things like lose parts of Antarctic ice sheets while you're waiting for the CO_2 removal to bring us back down.

Ms. BONAMICI. Does anybody else want to add to that, the question of—we know there's a lot of interest in exploring geoengineering but what are the mitigation and adaptation activities that perhaps need to have priority?

Dr. MAJKUT. Well, we know that, or our sense is that mitigation and adaptation are both beneficial today. The question of geoengineering is if it will be beneficial in the future. They're very different by nature. Reducing emissions permanently reduces the net impact of humans on the climate. Potentially introducing these technologies at some later date will do that temporarily but their nature is very different.

Ms. BONAMICI. Dr. Rasch?

Dr. RASCH. If I can follow up, it's just to affirm what Doug MacMartin said, which is essentially I think many of us view the sunlight reflection methods as being an interim solution which allows—provides some breathing space while the mitigation and adaptation measures take place, and I think we all believe that they should occur as rapidly as possible. Lots of us are hoping that the carbon dioxide removal methodologies will be economically viable and provide a mechanism for drawing some of the CO_2 out of the atmosphere, so that's a very important strategy to consider.

Ms. BONAMICI. Thank you. My time is expired. Thank you, Mr. Chairman.

Chairman BIGGS. Thank you.

The Chair recognizes Mr. Weber, the Chairman of the Energy Subcommittee, from Texas.

Mr. WEBER. Thank you, Mr. Chairman. I appreciate it.

Dr. Rasch, in your testimony you said you'd been kind of looking at this field for about ten years and you published 20 papers, or maybe it was in your comments before your testimony as I read through it, and you also cited another gentleman that had published 42 papers, and what was his name?

Dr. RASCH. Ben Kravitz——

Mr. WEBER. Okay, and——

Dr. RASCH. —another colleague here at PNNL working with me.

Mr. WEBER. And how long has he been in the field?

Dr. RASCH. Probably ten years as well. He started as a Ph.D. student working for a very eminent professor who chose to support him to work in this area based on his work on volcanic eruptions because this is a related—the impacts of volcanoes are related to the ones we're exploring today.

Mr. WEBER. Right. So the theory and concept of geoengineering is not new in the scientific community. Would you say it's just kind of taken off in the last 10 years?

Dr. RASCH. Well, it's interesting. You can go back to the 1960s and find conversations that have been occurring about geoengineering. It certainly started to receive a huge amount of attention following a paper that was published by a Nobel Prize-winning chemistry named Paul Crutzen in 2006, so it's about ten years old. In fact, that scientist and that paper was what brought me into the field and it might have been some of the other people on this committee.

Mr. WEBER. And is Paul Crutzen—what country is he from?

Dr. RASCH. He has spent the last 30 years or so in Germany. He did have a position at my former institute, the National Center for Atmospheric Research, in Colorado, and he's originally from Holland.

Mr. WEBER. Okay, not that you know much about him.

Dr. RASCH. I didn't quite know how to answer that.

Mr. WEBER. Well, we only have five minutes so—so he published the paper, and you got interested. Is he still active in this field?

Dr. RASCH. He is engaging. He's in his late 80s and ill so he's not as heavily involved but he does actually endorse the importance of doing research in this area to this day.

Mr. WEBER. Okay. So as we've heard today, research has been moving kind of slowly, and of course, you just described the last ten years, I guess. So how do you get that idea out there to make more people interested in it? In your opinion, what steps could be taken to increase the participation of researchers while encouraging experiments in geoengineering? What needs to be done?

Dr. RASCH. Well, I'm a strong advocate for this coherent research program that involves a set of five elements, which I've listed in my written testimony.

Mr. WEBER. Okay.

Dr. RASCH. And which I'd be happy to discuss.

Mr. WEBER. Okay. So much of what we know today is based on computer climate modeling. So how would small-scale field experiments improve those models, and can you describe a small-scale experiment?

Dr. RASCH. Sure. You saw some examples of some of the elements of a small-scale experiment on the slides Ms. Wanser showed, and——

Mr. WEBER. Did you all collaborate on those?

Dr. RASCH. We have been working together.

Mr. WEBER. Good.

Dr. RASCH. I'm part of that marine cloud brightening team that's located at the University of Washington, where I also have an appointment.

So it would involve seeing whether we could—let's talk about marine cloud brightening for a moment. It would—that one we know it is possible to make clouds more reflective but it only happens in certain circumstances, and we're very—it's very difficult to be precise about the circumstances that it can occur in. So what we would like to be able to do—first off, there are many variables that take place which could help to explain that. The weather situations and clouds could be part of it. We see these clouds form in the wake of freighters which have different technologies on board. They use different kinds of fuel. They use different emission——

Mr. WEBER. That's kind of fascinating because those emissions that come from those freighters is producing a heat content, perhaps carrying CO_2 obviously with it, and so you're saying that in and of itself produces droplets that intermingle with the clouds?

Dr. RASCH. It's actually the particles that come out. If the emission controls on those ships were perfect, then they probably wouldn't be producing these ship tracks. What happen is that every cloud drop wants to form on a particle, all cloud drops in the atmosphere, and these ships release some particles, and when they do, those particles act to allow more clouds—more drops to form in certain clouds.

Mr. WEBER. So you can duplicate that process?

Dr. RASCH. That's part of it, so what we would like to see is if we can do it in precisely the circumstances because I was saying, as ships—one ship is different from another, and it's very difficult to be precise about exactly what the conditions were that allows the brightening to occur, and we would like to be more precise about those things?

Mr. WEBER. Okay. My time is expired, Mr. Chairman. Thank you.

Chairman BIGGS. Thank you.

The Chair recognizes the Ranking Member on the Energy Subcommittee, Mr. Veasey from Texas.

Mr. VEASEY. Thank you, Mr. Chairman.

In addition—and this is for all the witnesses to answer. In addition to the solar radiation management, one alternative climate intervention strategy that the National Academies examined recently is carbon dioxide removal. What is the potential of carbon dioxide removal to play a significant role in our efforts to mitigate the effects of climate change?

Dr. MACMARTIN. So there's a number of ideas that have been suggested including bioenergy with carbon capture and sequestration, so basically you grow crops, you burn them in a power plant, you suck the CO_2 out of the flue gas and store it underground, and the problem with ideas like that is that the scale that you need to do them on to make a dent in climate change is something of order the scale that we're currently emitting CO_2 at, which as a species is about 40 gigatons per year, and so unless you're talking about pulling, you know, 5, 10, 15, 20 gigatons per year out of the atmosphere, it's a pretty small dent. And the problem basically is that things like the bioenergy with carbon capture and storage would compete with land use that we use for food crops, and then there's another set of ideas to directly capture it from the atmosphere, directly capture CO_2 from the atmosphere. That is almost certain to be technically feasible but right now probably too expensive, and it's almost certain to be cheaper to not put it in the first place than to take it out after you've put it in. And then there's a variety of other ideas that are probably less well understood. So the bottom line is, all of the things need either—we need something that is scalable, cost-effective, and does not have substantial local impacts, and right now we don't have any ideas that satisfy all three of those, which is why we would need more research in that, and if we don't start now, it's not going to happen.

Ms. WANSER. I would add to that list genetically engineered organisms and plants that might more efficiently capture carbon in the way that nature does but in an accelerated fashion. Some of the new capabilities with genetic modification, the CRISPR technologies, may be relevant for investment in this area.

I would also say that carbon removal capabilities at scale, many of them carry serious ecological consequences that also need to be evaluated as we look at them.

Mr. VEASEY. Another controversial area in the Congress, the GMOs.

Some of the riskier strategies for carbon dioxide removal include ocean iron fertilization and the large-scale enhanced weathering. What are the drawbacks to these strategies in an environmental and public-health context?

Dr. MAJKUT. Well, those technologies, you know, could prospectively capture quite a bit of carbon dioxide from the atmosphere and retain it in places where it would be durable either the sea or in rocks. The issue, as Doug says, is to do this in a way that's going to significantly affect how much excess CO_2 is in the atmosphere. It's going to take a lot of land or a lot of ocean, and the ecological effects of either of those things is not quite known.

Mr. VEASEY. Also, I wanted to talk with you briefly about funding levels. You know, I'm very concerned, as a lot of people are, about federal R&D programs under this Administration. We saw in the budget proposal earlier this year, the Trump Administration supports very large cuts to research agencies. For example, the proposal included major cuts to climate modeling and Earth systems sciences at the DOE. Will these funding cuts hurt or help us better understand the field of geoengineering?

Ms. WANSER. So I think it's important to acknowledge that if we're interested in engineering the climate system that our capabilities or observing, analyzing and interpreting the information about the climate system are essential. So all of the platforms and capabilities and talent that we have are not only areas that we want to preserve but if we're interested in active intervention in the Earth system, we would want to advance and enhance those capabilities.

Dr. MACMARTIN. I would just second that. We need the same climate models. We need a lot of the same observational capacity, and we use the exact same high-performance computing.

Mr. VEASEY. Thank you very much, Mr. Chairman. I yield back my time.

Chairman BIGGS. Thank you.

The Chair recognizes the gentleman from Florida, Mr. Posey.

Mr. POSEY. Thank you, Mr. Chairman. Thank you for calling this very interesting hearing, and thank the witnesses for their informative testimony.

Do you believe—this is for anyone on the panel, for all on the panel—there's a risk that in starting to build geoengineering capabilities, we could lose control of them, and how do you think it would compare to the risk of bioengineering and nanotechnologies?

Dr. RASCH. I'm willing to take a stab at it. I think scientists are all concerned about the possibility of this—us losing control of it and adopting it but I personally feel that it works better to operate from a position of knowledge about it rather than the absence of that knowledge, and I think the cat's kind of out of the bag at this point in the game that the technology is possible. So I would prefer to be spun up on what it's——

Mr. POSEY. Okay. Ms. Wanser, you had your hand up next.

Ms. WANSER. Well, solar climate engineering technologies actually have a high barrier to entry, so they're relatively expensive to engineer and relatively expensive to measure, and they scale linearly, so you evolve solar climate engineering technologies with a number of disbursals you have. They're very easy to see and detect. Whereas nanotechnology and bioengineering techniques have very low barriers to entry. They now—you can now buy a kit to engineer organisms with CRISPR for less than $200, and you could release them into the wild. So the challenge with things like bio engineering is that they are low barriers to entry and self-replicating. So in some senses, solar climate engineering actually is less challenging from a governance perspective provided we have a framework in place.

I disagree a little bit with Dr. Majkut that we already have one. I think it's part of what we would want to define in conjunction with the research program. But I think some of the challenges here are a bit more straightforward than they are in some of these other fields.

Mr. POSEY. Anyone else care to comment?

Dr. MACMARTIN. Yeah, I just wanted to add, if we did put aerosols into the stratosphere at any point, the lifetime in the stratosphere is about a year or two, and so whatever we put up there is just going to come back down. That also means that if you want to maintain it, you have to constantly be putting more in. So there's less risk of it running away when you're actually deploying it than there would be for, say, a biotechnology-type intervention.

Mr. POSEY. Any hard evidence on the effect that subsurface activity has on the atmosphere? I mean, we know what ended the last Ice Age. It was an asteroid strike which basically created the Gulf of Mexico and darkened out the Earth for many, many years and allowed it to freeze over. There are some conditions that exist here now that have the potential to recreate that catastrophe. Some of the research I've seen at Yellowstone, the big volcano in the Azores that they say will cause 100-foot-high tsunami, you know, but your thoughts on how that may affect us?

Dr. MAJKUT. Well, relevant to these questions, there's a volcano, Mount Agung, which is on currently a level 3 eruption watch, so we may have a natural experiment coming up should it erupt and inject sulfates into the atmosphere. Then we would see a repeat of what previous volcanoes have done and probably some cooling influence, and thankfully the scientific community I believe is ready and standing by to observe that and understand the processes as best they can. That's certainly true.

Dr. RASCH. If I might follow up——

Mr. POSEY. Dr. Rasch?

Dr. RASCH. —it's to say just that the scientific community is very interested in a rapid response team for watching over these volcanic eruptions but they are sort of assembling it as we speak, and it's not maybe quite as far along, as Joe mentioned.

Mr. POSEY. One last question. What have other countries done so far in this realm?

Dr. RASCH. The rapid response team is part—is an international effort. There's certainly a very large and interested part of American U.S. scientists participating but that is an international activity.

Mr. POSEY. Okay. Thank you, Mr. Chairman. My time's expired.

Chairman BIGGS. Thank you.

I recognize the gentleman from California, Mr. McNerney.

Mr. MCNERNEY. I thank the Chairman and I thank the witnesses.

You have seen the legislation I am about to introduce. Do any of you have comments about that legislation, whether you think it's useful or should be improved or anything like that? Anyone care to answer that question?

Dr. RASCH. I've had only a chance to look at it very briefly and would be delighted to provide some more comments offline.

Mr. MCNERNEY. Thank you.

Dr. MAJKUT. I have the same idea.

Mr. MCNERNEY. Thank you.

Dr. MACMARTIN. So I haven't read through it in complete detail but I think in general I'm very supportive of having the National Academies involved in trying to understand exactly—basically lay out the roadmap for research in this area as well as looking at the governance side of things.

Mr. MCNERNEY. Thank you.

Ms. WANSER. As I mentioned in my remarks, I'm very supportive of the notion of a National Academies study process to help define a research agenda. The community to date in geoengineering has been very small and centered in modelers with some physicists and some ethicists and policy researchers. So I believe that that process could help expand the array of disciplines that we need to look at this area and also help to build consensus about what a research program should look like.

Mr. MCNERNEY. Well, following up with that on a governance framework, what sort of scope of organizations and individuals should be involved in the development of a governance framework?

Dr. MAJKUT. I think we should be looking at sort of all the concerned parties, right? So the scientific community plays a vital role. I think civil society should play some role as well, and I think Congress should take into consideration the idea that you might want to have a say in how these things get governed, and then going forward, we can also look at managing these types of things with international partners as well.

Mr. MCNERNEY. Ms. Wanser, you mentioned that it would take about 20 years for the technology to be deployable. Would having a research governance mechanism speed up that timeline in your opinion?

Ms. WANSER. At the moment, one of the barriers to technology development and field research is the lack of either a government framework or social license for the work. So I think it would reduce risk for people who would fund the research and people who would enter the field to have an appropriate governance framework to allow it to proceed. So yes.

Mr. MCNERNEY. Very good.

Do any of you know if there have been field tests on geoengineering that have been carried out by other countries?

Dr. RASCH. I'm not aware of any.

Dr. MACMARTIN. There's been—there was a brief attempt in the U.K. to do an experiment that was just on a tethered hose so it was just developing hardware that didn't actually take place, and there was an attempt in Russia a number of years ago to try to do something that was a bit of a stunt but it wasn't really scientifically accurate.

Mr. MCNERNEY. Do Russia and China have limitations on what their scientists are able to do in terms of geoengineering?

Dr. MACMARTIN. So the program in China right now is purely based on climate modeling and much more focused on what the impacts of deploying solar geoengineering would be. I do know from conversations with them that they're asking questions about whether their next phase of their research should involve some experimental work but they have not yet made any decisions about that.

Mr. MCNERNEY. So we don't need to be worried about them doing large-scale deployments?

Dr. MACMARTIN. I don't think we need to be worried about anybody doing large-scale deployments because if you want to do scientific research, the research questions are all about process uncertainties, you know, trying to understand chemical reaction rates in the stratosphere and things like that, and they don't require large tests to do those things.

Mr. MCNERNEY. So then what are some of the key ethical questions that we should be considering in moving forward with this field of work?

Dr. MACMARTIN. I think my personal answer to that would simply be that a lot of people are very concerned about the slippery slope and whether an effort in research is eventually going to lead to deployment, and I think a lot of people are very concerned about the research effort in geoengineering detracting from efforts in mitigation, and so in some sense the issues with ethics and governance are primarily wrapped up in involving the public participation and where we want to be going as a society in the future.

Mr. MCNERNEY. Mr. Chairman, I want another five minutes. I yield back.

Chairman BIGGS. Thank you, and the Chair recognizes the gentleman from Texas, Mr. Babin.

Mr. BABIN. Thank you, Mr. Chairman. Extremely interesting topics, and I appreciate you convening this hearing and your witnesses being here.

You've already alluded to it a little bit about the safety and environmental risks of this research being proposed, and we just talked about Russia and some of the other countries and maybe deploying fully things of this nature, and you mentioned a slippery slope, Dr. MacMartin, and what do you mean exactly by slippery slope? Is this something that you mess around with Mother Nature and it may turn into something that's even worse than you're trying to fix?

Dr. MACMARTIN. I was actually referring to the societal process, the concern that if we start doing research, that eventually that's going to lead to deployment, and people might think wait, wait, we haven't actually decided on deployment yet.

Mr. BABIN. Right.

Dr. MACMARTIN. So that's a concern that people have expressed.

Mr. BABIN. Okay. But is that a concern with any of you folks that are involved in this, that we could unleash something irreversible if you continue to do this cloud brightening or the stratospheric procedure? Is that a possibility?

Dr. RASCH. I think at the level that we're talking about doing things right now, as I think Joe mentioned, the changes to the planet are vanishingly small. It would be hard for you to notice, to even detect it if you didn't know it was happening. So it's really tiny compared to, for example, the impact that flying an aircraft from Washington, D.C., to Seattle would have on the planet. So they're small today. If one wants to get to the point of considering having a climate-altering effect, then the impacts get much more important to worry about, and we have to be more careful when things get ramped up to that time.

Mr. BABIN. Right.

Dr. RASCH. As Kelly mentioned, I think it would take 20 years to decide on whether we have a good enough understanding to decide that it might be useful to do this or not, if we're going all out on it.

Mr. BABIN. All right. Thank you.

Anybody else want to add to that?

Dr. MAJKUT. Yeah, I think I would just reiterate that a lot of the sort of smaller-scale field experiments that scientists are presently proposing to do are going to be unnoticeable to the untrained eye. You need a really fancy experimental setup and cool instruments to even detect that it's going on, right? Questions of, you know, does this research affect sort of other societal questions about how we address climate change are real but I think it's—you know, it's a bit of speculation to say whether that'll cut one way or another. We should go about this judiciously and carefully and slowly and with an open and transparent process. I think that's probably the best approach.

Dr. MACMARTIN. I agree.

Mr. BABIN. Okay. Yes, ma'am?

Ms. WANSER. I think one of the things that may be helpful from a governance process or an oversight process is a definition of what we mean by research-scale or small-scale experiments and then lots of transparency with regard to that so that where it's not easy for people to understand what the limits of these things are. We have some very bright, shiny lines between what we do for research and the kinds of things that would have greater impacts.

Mr. BABIN. Okay. And while you're at the mic, you discussed the need for research framework earlier in this field, and could you explain what your whole-systems approach to geoengineering research would be?

Ms. WANSER. Well, probably not terribly briefly, but I think there's—it's what sometimes referred to as a transdisciplinary field, so we think about certainly the climate research part of it. We have a technology innovation component. We need to think how systems would interact together and how different actions taken on the Earth system would interact like policies that we make that change the forcings in the climate too. So part of a research program is to bring people who are not currently present into the discussion starting with aerosol engineers and other types of engineers who would be needed to think about how these things would actually work, looking at the innovations in observations measurement and computing. So today the experiment that I showed you about marine cloud brightening, they do observations like that now of pollutants, and when they go out and take those measurements, they bring them back. They take months to analyze the data. If we're acting on the Earth system actively, we're going to want information much faster and we're going to need to improve our systems to do that.

So when we think about the whole system, we have to think forward a little bit about what we'd be looking at in terms of the feedback to the perturbations that we make and how we need to understand them. Does that help?

Mr. BABIN. Yes. Yes, it does. Thank you very much, and my time is expired, Mr. Chairman. Thank you.

Chairman BIGGS. Thank you. The Chair recognizes the gentleman from New York, Mr. Tonko.

Mr. TONKO. Thank you, Mr. Chair, and thank you to our impressive panel of witnesses for joining us today.

As the only New Yorker on the Committee, I would like to take a moment to give special thanks to Dr. Douglas MacMartin from Cornell University. We thank you for your time and your expertise, and we thank Cornell for the contributions it makes.

The recently released 4th National Climate Assessment Climate Science Special Report represents the scientific collaboration of some 13 United States federal agencies with sign-off from the White House. That report found with high confidence a likely human contribution of well over 90 percent of the observed change between 1951 and 2010 in the global climate. Furthermore, the report found with very high confidence that the magnitude of climate change beyond the next few decades will depend primarily on the amount of greenhouse gases emitted globally and on the remaining uncertainty in the sensitivity of Earth's climate to those emissions.

We know the harms caused by climate change are grave and that they are growing. They have already done harm to human health, to water quality and availability, sea-level rise, and they have worsened natural disasters. For this and countless other reasons, failure to address climate change will result in significant economic harm to our country and her people.

Given the conclusions of these impartial scientists and the widely accepted consensus that climate change is real and primarily driven by human activity, I urge all members of this Committee to move forward with this White House-approved consensus in mind.

Geoengineering absolutely should be a part of the discussion of solutions, but with that said, we can't lose sight of the fact that significant reductions in GHG emissions are indeed necessary.

So for all of our witnesses, you have emphasized that numerous gaps remain in the scientific understanding of geoengineering technologies. Can each of you just briefly describe these gaps in the scientific understanding of geoengineering strategies?

Dr. RASCH. Yeah, I'll mention one or two because I could go on for the whole five minutes. So——

Mr. TONKO. One or two will do.

Dr. RASCH. Okay. So we at the moment don't—the situation of using geoengineering differs from either the marine cloud brightening or volcanoes because we would intend to put particles into the atmosphere continuously rather than they would just occur episodically, and we don't know how the existing particles will respond to the—to putting in these kind of particles for long periods of time. Models tell us that it will be different from the way it would work for a volcano, let's say, so that would be one example of something which we don't know but we need more information.

Mr. TONKO. Okay. Thank you.

Doctor?

Dr. MAJKUT. One particular aspect of this that really fascinates me is questions of when you have these sort of compensating mechanisms of warming at the surface and cooling in other parts—either concentrated parts of the atmosphere or high up in the atmosphere, what are going to be the effects on other conditions that we care about, not just temperature, right? So biology, the oceans. I think a lot of these downstream issues need to be investigated much further.

Mr. TONKO. Thank you.

And Dr. MacMartin?

Dr. MACMARTIN. So I would second both of those and just reiterate that we know a fair amount of stratospheric aerosols just from observing volcanic eruptions, but it is different from a large volcanic eruption. We don't actually have any observations of geoengineering obviously and so we sort of have to figure out as we go how do we go collect that knowledge about what the processes in the stratosphere are going to be.

Mr. TONKO. Okay. Thank you.

Ms. WANSER. Well, we don't yet have any technology for producing aerosols of the type and at the scale that we're talking about for this, and until we know what the limits of those technologies are, what we're inputting to our models is very much guesswork, and we also don't know how to measure and detect in real time.

Mr. TONKO. So then what would the next steps be to address these gaps? Any recommendations to the Committee?

Dr. MACMARTIN. So I think one step is clearly to actually just start by saying if we want to support informed decisions in 10, 15, 20 years to be very careful that writing down what all the uncertainties are and propagating those through the climate models, so if there's something uncertain about stratospheric aerosol microphysics or chemistry, how important is that in terms of influencing our decisions and therefore what experiments would we need to do to help resolve those uncertainties. That's the type of research that I think we need to be focused on.

Mr. TONKO. Anyone else?

Dr. RASCH. Yeah. I mean, I will just say that there are—I think one of the things that is missing so far is that the research that's been done today is primarily curiosity driven and people have picked at various elements of the geoengineering unknowns, but I think we need to do it in a much more systematic way to try and move pretty quickly towards getting an idea about what are the tradeoffs involved in this work.

Mr. TONKO. Okay. With that, I yield back, Mr. Chair.

Chairman BIGGS. Thank you.

The Chair recognizes the gentleman from Illinois, Mr. Foster.

Mr. FOSTER. Thank you, Mr. Chair, and thank you for holding this hearing. It really shows a level of engagement on this issue that I think is overdue and very welcome.

Are there any sort of zero-order either cost estimates or estimates for the amount of aerosols that you'd need, for example, to reverse a 2-degree warming or a calculation of, you know, if you have a gigaton of coal, how many gigatons or tons of aerosols you have to put into the atmosphere? Are there any rough estimates based on volcanoes and similar that people have done?

Dr. MACMARTIN. So I'll give you a rough estimate that 1 degree of—1 degree Celsius of cooling, so 1.8 Fahrenheit is, say, 10 megatons of sulfur dioxide into the upper atmosphere, and in terms of cost, there's estimates of costs that are in the billions of dollars, but quite frankly, I don't think that the direct economic costs of bringing material to the stratosphere, those probably are not the reasons why we would—how we would evaluate this. It's far more a question of what the risks and the side effects are.

Mr. FOSTER. Right. Okay. So it wouldn't be the direct costs of actually even carrying this out. They all would be dwarfed by, you know, the trillion-dollar scale effects of, you know——

Dr. MACMARTIN. Yeah, and the direct costs of doing it is probably more observational capacity of satellites and things to monitor things.

Mr. FOSTER. Which brings me to the issue of international governance because, you know, Congress can pass all the laws we want and if, you know, China decides that it wants to preserve its islands it just built in the South China Sea or, you know, Bangladesh or Micronesia decides that they're going to be underwater in short order, you know, their interests are not necessarily aligned with ours, or if you do this and you see it's going to redistribute rainfall globally, you know, or reverse the Gulf stream or stop the Gulf stream. You know, there are worries like that that are out there. And so it seems like you need an international mechanism for someone who will say no, you cannot do that. And you know, we're in a tough situation right now because we have an Administration that's done things like reject the Paris agreement. And so I was wondering if there are serious, maybe outside this country, serious discussions of how we're going to regulate this internationally.

Dr. MACMARTIN. Discussions are beginning but, you know, as we kind of see here today, this is a new topic for conversation, particularly for a lot of policymakers. So they're sort of at their early stages. I highlight in my testimony some ideas. I'd be happy to follow up with you about them in more detail about how we can accomplish some of these questions here and sort of build a national governance model that could influence how things work internationally. I think that would be a good thing to talk about. But yeah, we're still at very early stages in terms of international issues.

Mr. FOSTER. It also seems to me that the level of controversy having to do with CO_2 removal strategies is much lower than albedo modification, particularly atmospheric. Is that a fair reading of sort of your—the attitudes you see toward this, that the objections of CO_2 removal are simply going to cost a lot more than averting the emissions in the first place.

Dr. MACMARTIN. So in terms of direct climate impacts, then there's basically no climate impacts from pulling CO_2 out. It just—that solves the root of the problem. But I think one of the reasons there hasn't been any pushback is perhaps people don't quite get what the local impacts might be. So if you need to displace land area the size of India for food crops for bioenergy, I think that would actually have some serious consequences. So I think yes, people are less concerned about CDR but maybe they should be a little bit more concerned than they are.

Mr. FOSTER. That would be a very technology-specific thing.

Dr. MACMARTIN. Very, very specific to the technology.

Mr. FOSTER. And so now, when you got these sort of natural experiments from volcanoes going off, how frequent are volcanoes that actually provide you relevant data and get enough aerosols up in the stratosphere that you actually get a useful volcano? Do they happen once a decade, once a century, or once every few years?

Dr. RASCH. Probably less frequently than once a decade and more frequently than once a century they come alive.

Mr. FOSTER. All right.

Dr. RASCH. They do have smaller-scale volcanoes. One went off in Iceland a few years ago that was useful for understanding some aspects of, for example, the way clouds could be brightened by addition of extra particles in the atmosphere. But the really big eruptions like Pinatubo or Agung, those are——

Mr. FOSTER. Those are rare. I remember after that volcano happened, I called up Nathan Myhrvold, who you're probably well aware is one of the, you know, people of means interested in paying for this, and he indicated that it simply didn't put enough into the high stratosphere to be useful.

Dr. RASCH. For the stratospheric aerosol analog.

Mr. FOSTER. Right. But now, if you look at the historic record of——

Chairman BIGGS. The gentleman's time is expired.

Mr. FOSTER. Excuse me. I yield back.

Chairman BIGGS. Thank you, Mr. Foster. I appreciate that.

The Chair recognizes the gentleman from Indiana, Mr. Banks.

Mr. BANKS. Thank you, Mr. Chairman. It's a very interesting discussion today. Thank you for being here.

I believe like probably most of my colleagues do that it's imperative that we deal with the reality of a $20 trillion national debt. Even though that debt is driven by mandatory spending programs, our constituents at home expect us to find savings wherever possible. We've seen in my home State of Indiana the innovative utilization of public-private partnerships to overcome this dilemma. One example I'd like to point to is the Indiana Biosciences Research Institute. The Institute is a public-private partnership between universities and research institutions, industry and the State of Indiana. The Institute fosters collaboration between these entities in life sciences research and support the commercialization of their research. One big advantage, in my view, of an arrangement like this is that the participation of industry ensures that research will be directed toward endeavors that are commercially viable and produce a positive return on investment.

So with that, I'd like to hear the panel's perspective on the potential for public-private partnerships to advance research in this area. Dr. Rasch, if you could respond to that first, we'd appreciate it.

Dr. RASCH. Well, I know that my laboratory is quite interested in these public-private partnerships. I have to admit I'm not an expert in the area and can't tell you about the potential for this particular application.

Mr. BANKS. Okay. And next to you?

Dr. MAJKUT. I would also have to demur. I think public-private partnerships are useful in many contexts but it's hard for me to state strongly one way or another on this issue.

Mr. BANKS. Ms. Wanser, I see you raising your hand.

Ms. WANSER. So I see tremendous opportunity for public-private partnerships and the disruptive innovation that's happening in remote sensing and in computing. So for the types of capabilities that we need to monitor and interpret what we would do in geoengineering, there are particular opportunities to work with those companies to do things in a way that's potentially an order or two orders of magnitude less expensive than we do it now in satellite observations, in ocean observations, the opportunity to have much more comprehensive Earth coverage and a much more granular level, and at the same time I think that are big opportunities for partnerships in the computing space for the adoption of cloud computing for some of the workloads that we do in this area that could be done on the public cloud in a cheaper and more agile way and opportunities to explore exoscale computing for the kinds of things we haven't solved yet in terms of understanding the Earth system more rapidly.

Mr. BANKS. So you agree that public-private partnerships are fruitful, but do you believe that the environment exists to further public-private partnerships as it stands today?

Ms. WANSER. My experience leads me to believe—to be hopeful, yes.

Mr. BANKS. Thank you. I yield back.

Chairman BIGGS. Thank you. I thank each of the witnesses for being here today and a very interesting Committee hearing, and appreciate the members and their questions.

The record will remain open for two weeks for additional written comments and written questions from members.

And this hearing is adjourned.

[Whereupon, at 11:44 a.m., the Subcommittees were adjourned.]

Appendix I

Additional Material for the Record

STATEMENT SUBMITTED BY FULL COMMITTEE RANKING MEMBER EDDIE BERNICE JOHNSON

OPENING STATEMENT
Ranking Member Eddie Bernice Johnson (D-TX)

Committee on Science, Space, and Technology
Subcommittee on Environment
Subcommittee on Energy
"Geoengineering: Innovation, Research, and Technology"
November 8, 2017

Thank you Mr. Chairman. Last week, the U.S. Global Change Research Program released the Fourth National Climate Assessment – an authoritative assessment of the science of climate change. Among other troubling observations, the Assessment states that, "the magnitude of climate change beyond the next few decades will depend primarily on the amount of greenhouse gases (especially carbon dioxide) emitted globally…continued growth in [carbon dioxide] emissions over this century and beyond would lead to an atmospheric concentration not experienced in tens of to hundreds of millions of years. There is broad consensus that the further and the faster the Earth system is pushed towards warming, the greater the risk of unanticipated changes and impacts, some of which are potentially large and irreversible."

These findings are a stark reminder of what we must now overcome to avoid potentially severe impacts on the lives of future generations. Make no mistake, this challenge only becomes harder to overcome the longer we wait to act, and we will have fewer and fewer options at our disposal to address the growing consequences of climate change. I am encouraged that we are holding this hearing today to discuss the research necessary to evaluate geoengineering as one potential method in our toolbox to address the impacts of climate change. It is important that we advance technologies and processes that may help alleviate the burden of populating an ever-modernizing globe, but we should do so in a manner that is responsible to the long-term health of the environment and the public.

As these innovative technologies develop, they must not be viewed as an excuse to pollute our atmosphere at greater rates, nor should we ignore the necessity to mitigate climate impacts. Nor should we cease exploring methods to achieve reductions to carbon emissions. As we explore potential methods of addressing this issue in our skies, we must not forget that reducing and eliminating carbon emissions starts here on the ground.

I look forward to listening to the testimony today, and am appreciative that as a nation we are exploring efforts to support research in this area. We must continue to make the necessary investments in these kinds of potential innovations, while continuing to focus our efforts on reducing carbon emissions. Thank you and I yield back.

LETTER SUBMITTED BY SUBCOMMITTEE ON ENVIRONMENT
RANKING MEMBER SUZANNE BONAMICI

November 8, 2017

TO: **The Honorable Lamar Smith**
Chairman, House of Representatives Committee on Science, Space and Technology
2409 Rayburn House Office Building
Washington, DC 20515

The Honorable Andy Biggs
Chairman, House of Representatives Subcommittee on Environment
1626 Longworth House Office Building
Washington, DC 20515

The Honorable Randy Weber
Chairman, House of Representatives Subcommittee on Energy
1708 Longworth House Office Building
Washington, DC 20515

CC: **The Honorable Eddie Bernice Johnson**
The Honorable Suzanne Bonamici
The Honorable Marc Veasey

Dear Chairman Smith, Chairman Biggs and Chairman Weber,

A hearing on geoengineering co-convened by the House SS&T Subcommittees on Energy and Environment is scheduled for November 8, 2017.

Anthropogenic climate change is a problem requiring swift and effective response, including by the U.S. government. The primary and essential elements of such an effective response are measures to sharply cut emissions of greenhouse gases, and measures to adapt to unavoidable climate changes.

Geoengineering is not a silver bullet, and treating it as one could greatly increase already severe climate change risks. We agree with the conclusions of the 2015 U.S. National Research Council reports (NRC 2015: 192) on Climate Intervention which, while recommending careful and accountable research, emphasize "there is no substitute for dramatic reductions in CO2 emissions to mitigate the negative consequences of climate change at the lowest probability of risk to humanity."

While further research could help address questions about the proposed technologies' efficacy, risks, and cost-effectiveness, we already know that geoengineering, including solar radiation management and carbon dioxide removal approaches, can at best be a supplement to reducing sources of greenhouse gas emissions and increasing our ability to cope with the effects of climate change.

Any consideration of a Federally funded and coordinated research program into geoengineering must be in the context of a strategic portfolio of responses to climate change, which leads with climate science, mitigation and adaptation.

Sincerely,

Thomas Ackerman, Ph.D.
Professor of Atmospheric Sciences, and
Director of the Joint Institute for the Study
of the Atmosphere and Ocean (JISAO)
University of Washington

Thomas Armstrong, Ph.D.
President, Madison River Group
Former Executive Director
U.S. Global Change Research Program

Scott Barrett, Ph.D.
Lenfest-Earth Institute Professor
of Natural Resource Economics
Columbia University

Wil Burns, Ph.D.
Co-Executive Director
Forum for Climate Engineering
Assessment, American University

Ken Caldeira, Ph.D.
Senior Scientist
Carnegie Institution for Science
Department of Ecology

Peter C. Frumhoff, Ph.D.
Director of Science and Policy
Chief Climate Scientist
Union of Concerned Scientists

Steven Hamburg, Ph.D.
Chief Scientist
Environmental Defense Fund

Katharine Hayhoe, Ph.D.
Director, Climate Science Center
Texas Tech University

David Keith, Ph.D.
Gordon McKay Professor of Applied
Physics, School of Engineering and
Applied Sciences, Harvard University

Andrew Light, Ph.D.
University Professor of Philosophy,
Public Policy, and Atmospheric
Sciences, George Mason University

Jane Long, Ph.D.
(retired) Former Principal Associate Director at Large
Lawrence Livermore National Laboratory

Frank Loy
(retired) Former Under Secretary of State for Global Affairs,
U.S. Department of State

Michael MacCracken, Ph.D.
Chief Scientist, Climate Institute
Former Executive Director
U.S. Global Change Research Program

Douglas MacMartin, Ph.D.
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Department of Mechanical and Aerospace Engineering
Cornell University
Research Professor, Computing and Mathematical Sciences, Cal Tech

M. Granger Morgan, Ph.D.
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Simon Nicholson, Ph.D.
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Edward A. Parson, Ph.D.
Dan and Rae Emmett Professor of Environmental Law
Faculty Co-Director, Emmett Institute on Climate Change and the Environment, UCLA

Alan Robock, Ph.D.
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Daniel Sarewitz, Ph.D.
Co-Director, Consortium for Science, Policy & Outcomes
Professor of Science and Society, School for the Future of Innovation in Society
Arizona State University

Daniel P. Schrag, Ph.D.
Sturgis Hooper Professor of Geology
Director, Harvard University Center for the Environment
Harvard University

Christina Swanson, Ph.D.
Director, Science Center
Natural Resources Defense Council

David W. Titley, Ph.D.
Rear Admiral USN (ret.)
Professor of Practice in Meteorology
Professor, Penn State School of
International Affairs
Director, Center for Solutions to
Weather and Climate Risk

David G. Victor, Ph.D.
Professor, School of Global Policy and
Strategy, UC San Diego
Director, the Laboratory on
International Law and Regulation

David Winickoff
Senior Policy Analyst
Organization for Economic Cooperation
and Development

STATEMENT SUBMITTED BY RANKING MEMBER
EDDIE BERNICE JOHNSON

Statement for the Record from
Floyd DesChamps
The Desner Group, LLC

Before the U.S. House of Representatives' Committee on Science, Space and Technology

Subcommittee on Environment and Subcommittee on Energy

Hearing on "Geoengineering: Innovation, Research, and Technology"

November 8, 2017

Chairmen Biggs and Weber, Ranking Members Bonamici and Veasey, and other distinguished members of the Environment and Energy Subcommittees, I thank you for holding this hearing on geoenginering, a growing area of interest and concern amongst those in the scientific and the policy fields. I am also thankful for the opportunity to submit this statement for the record.

In 2015, the National Academy of Sciences (NAS) issued its report, "Climate Intervention: Reflecting Sunlight to Cool Earth". In the report, the NAS recommended the initiation of a serious deliberative process to examine what types of research governance, beyond those that already exist, and the types of research that would require such governance. After reviewing the report and speaking with others familiar with the report, I could not identify anyone initiating any actions in response to the recommendation.

Given the interest in the governance aspects of geoengineering and the recommendation from a government-funded NAS report, I, along with other colleagues, decided to take action and develop a strategy that would address the need for a deliberative process. The strategy would be based upon the establishment of a national commission to develop a set of recommendations to provide to decision makers and other stakeholders. The commission would be based upon earlier commissions that have been used as models to establish policy in critical areas of research and technology.

In support of the commission concept, I have worked with other stakeholders and interested parties to form a working group to establish such a commission. I am not prescribing any particular solutions to the governance issues, but rather a process by which well informed recommendations supported by a robust research and outreach effort would be developed. The commission would be comprised of a diverse group of experts on governance matters from both the public and private sectors. It would represent a balance of political perspectives. It would incorporate a diversity of gender, ethnicity, and professions.

As far scope of the effort, the commission would consider all elements of the governance issue as identified in the 2013 Congressional Research Service report, *Geoengineering: Governance and Technology Policy*. If geoengineering research is to proceed forward in the U.S., it is imperative that a governance structure that fully addresses all elements, conducting research, funding, facilitating information exchange, regulating, and enforcing regulations, is implemented.

In conclusion, I applaud the subcommittees for holding this hearing. We believe geoengineering is a topic that deserves serious consideration by the Congress given the potential benefits of the technology while also acknowledging the associated risks.

Thank you.

Floyd DesChamps
President
The Desner Group, LLC