ENGINEERING THE CLIMATE: RESEARCH NEEDS AND STRATEGIES FOR INTERNATIONAL COORDINATION

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FOREWORD

Climate engineering, also known as geoengineering, can be described as the deliberate large-scale modification of the earth's climate systems for the purposes of counteracting and mitigating climate change. As this subject becomes the focus of more serious consideration and scrutiny within the scientific and policy communities, it is important to acknowledge that climate engineering carries with it not only possible benefits, but also an enormous range of uncertainties, ethical and political concerns, and the potential for harmful environmental and economic side-effects. I believe that reducing greenhouse gas emissions should be the first priority of any domestic or international climate initiative. Nothing should distract us from this priority, and climate engineering must not divert any of the resources dedicated to greenhouse gas reductions and clean energy development. However, we are facing an unfortunate reality. The global climate is already changing and the onset of climate change impacts may outpace the world's political, technical, and economic capacities to prevent and adapt to them. Therefore, policymakers should begin consideration of climate engineering research now to better understand which technologies or methods, if any, represent viable stopgap strategies for managing our changing climate and which pose unacceptable risks.

> *"We need the research now to establish whether such approaches can do more good than harm. This research will take time. We cannot wait to ready such systems until an emergency is upon us."*
>
> —Dr. Ken Caldeira, Geoengineering: Assessing the Implications of Large-Scale Climate Intervention (written hearing testimony) (2009).

Likewise, the impact of a moratorium on research should be carefully weighed against the importance of promoting scientific freedom and accountability. Scientific research and risk assessment is essential to developing an adequate scientific basis on which to justify or prohibit any action related to climate change, including climate engineering activities. Sound science should be used to support decision making at all levels, including rigorous and exhaustive examination of both the dangers and the value of individual climate engineering strategies. A research moratoria that stifles science, especially at this stage in our understanding of climate engineering's risks and benefits, is a step in the wrong direction and undercuts the importance of scientific transparency. The global community is best served by research that is both open and accountable. If climate change is indeed one of the greatest long-term threats to biological diversity and human welfare, then failing to understand all of our options is also a threat to biodiversity and human welfare.

There is no clear consensus as to which types of activities fall within the definition of climate engineering. For example, most ex-

perts on land-based strategies for biological sequestration of carbon, such as afforestation, do not identify the activities they study as climate engineering. The definition of the term also depends somewhat on the context in which it is used. For the purpose of developing regulations, for instance, the term may apply to a smaller set of higher-risk strategies than might otherwise be included for the purpose of crafting a broad interagency or international research initiative. In the interest of simplicity and consistency, the criteria used in this report are modeled off of the U.K. Royal Society Report, *Geoengineering the Climate: Science, Governance and Uncertainty*.[1] These criteria are inclusive of lower-risk activities such as reflective roofs, some types of carbon capture and sequestration, and distributed land management strategies, as well as more controversial proposals such as ocean fertilization and atmospheric aerosol injection.

Readers may notice that I use the term "climate engineering" instead of "geoengineering" throughout this report. While "geoengineering" is the term more commonly used to describe this category of activities, I feel that it does not accurately or fully convey the scale and intent of these proposals, and it may simply be confusing to many stakeholders unfamiliar with the subject. Therefore, for the purposes of clarity, facilitating public engagement, and acknowledging the seriousness of the task at hand, this report will use the term "climate engineering" in lieu of "geoengineering" going forward.

This report is informed by an extensive review of proposed climate engineering strategies and their potential impacts, including a joint inquiry between the U.S. House of Representatives Committee on Science and Technology and the United Kingdom House of Commons Science and Technology Committee (hereafter referred to as the "U.S. Committee" and the "U.K. Committee"), three Congressional hearings, review of scientific research relevant to climate engineering, and discussions with a number of experts, stakeholder groups, scientists and managers at federal agencies, and the Government Accountability Office (GAO).

As noted in the attached joint agreement between the U.S. and U.K. Committees, *Collaboration and Coordination on Geoengineering*,[2] the U.S. Committee investigated the research and development challenges associated with climate engineering, while the U.K. Committee focused on regulatory and international governance issues. Striking the right balance between research and regulation is critical as both should develop, to some degree, in parallel. Regulatory processes must be based on sound scientific information, and some climate engineering research will require regulation and government oversight. Furthermore, development of a comprehensive risk assessment framework to weigh the potential public benefits of climate engineering against its potential dangers will be needed to inform decision makers and the public as policies are crafted for research and possible deployment.

Equally important in the development of policies for climate engineering research will be transparency and public engagement. For

[1] JOHN SHEPHERD ET AL., GEOENGINEERING THE CLIMATE: SCIENCE, GOVERNANCE AND UNCERTAINTY (The U.K. Royal Society) (2009).
[2] *See infra* Appendix at p.47.

this reason, both the U.S. and U.K. Committees have sought to establish an official record through public proceedings with relevant background materials posted online. Just as full-scale deployment of climate engineering would necessarily have global effects, some large-scale field research activities will impact multiple communities and cross international borders. Furthermore, the impacts of climate engineering may be felt most by less economically-advanced populations that are particularly vulnerable to climatic changes, deliberate or otherwise. Widespread public understanding and acceptance is fundamental to any climate engineering policy that is both socially equitable and politically feasible.

It is my intent that this report, the U.S. and U.K. Committees' hearing records, the reports from GAO, and other forthcoming documents will make key contributions to the evolving global conversation on climate engineering and help guide future government and academic structures for research and development activities in this field. In addition, the bilateral cooperation between the U.S. and U.K. Committees on this topic should serve as a model for future inter-parliamentary collaboration. As nations become more technologically, economically, and ecologically interdependent, multilateral collaboration will be critical to developing policies that address an increasingly complex range of challenges.

Congressman Bart Gordon, Chairman
Committee on Science and Technology
United States House of Representatives

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Engineering the Climate: Research Needs and Strategies for International Coordination

This document has been developed by the Chairman and staff of the U.S. House of Representatives Committee on Science and Technology, for use by the Members of the Committee, the United States Congress, and the public. It has not been reviewed or approved by the Members of the Committee and may therefore not necessarily reflect the views of all Members of the Committee. This document has been printed for informational purposes only and does not represent either findings or recommendations adopted by the Committee.

This report should not be construed to provide any binding or authoritative analysis of any statute. This report also does not reflect the legal position of the United States.

BACKGROUND

During the 111th Congress, the U.S. Committee launched an initiative to better understand the issues surrounding climate engineering, and collaborated with the U.K. Committee to explore the subject. The U.S. Committee convened three public hearings to explore the science, governance, risks, and research needs associated with climate engineering. A summary of each hearing follows this section.

This report consolidates information gathered during eighteen months of inquiry, and focuses on the research needs associated with climate engineering. It identifies key research capacities, skills, and tools located within U.S. federal agencies that could be leveraged to inform climate engineering science responsibly. Included throughout the report are recommendations of the Chair in bold text.

Climate engineering, or geoengineering, can be defined as the deliberate large-scale modification of the earth's climate systems for the purpose of counteracting and mitigating anthropogenic climate change. The strategies which fall under this definition are loosely organized into two types: Solar Radiation Management and Carbon Dioxide Removal. Solar Radiation Management (SRM) methods propose to reflect a fraction of the sun's radiation back into space,[3] thereby reducing the amount of solar radiation trapped in the earth's atmosphere and stabilizing its energy balance. Carbon Dioxide Removal (CDR) methods, also known as Air Capture (AC), propose to reduce excess CO_2 concentrations by capturing CO_2 directly

[3] The proposed reductions in global solar radiation absorption are usually 1–2%; around 30% is already reflected naturally by the earth's surface and atmosphere. *See Geoengineering: Assessing the Implications of Large-Scale Climate Intervention Hearing Before the House of Representatives Committee on Science and Technology*, 111th Cong. (2009) (Hearing Charter).

from the air and storing the captured gases as a solid through mineralization, or consuming it via biological processes. CDR is different from direct capture, which targets carbon from a single point source and stores it in sedimentary formations. A comprehensive discussion of the variety of proposed strategies can be found in the U.K. Royal Society report, discussed below, although it is expected that some proposals for climate engineering will continue to evolve into completely new technical concepts over time.

While proposals for climate engineering in some form have been around for decades, climate change research and regulation efforts have been almost wholly focused on mitigation through emissions reductions and, more recently, adaptation to the effects of a changing climate. Because of the inherent risks and uncertainties, climate engineering, thus far, has not represented a technically viable, environmentally sound, or politically prudent option for preventing or adapting to climate change. However, in recent years a growing number of credible scientific bodies have engaged in more serious deliberation to the concept of climate engineering.

In September of 2009 the U.K. Royal Society published a comprehensive report entitled, *Geoengineering the Climate: Science, Governance and Uncertainty*.[4] In May 2010 the National Research Council released a pre-publication version of a congressionally requested report, *America's Climate Choices*,[5] which included discussion on several carbon dioxide removal strategies. In the spring of 2010 the bipartisan National Commission on Energy Policy (NCEP) announced its formation of a Task Force on Geoengineering to explore U.S. governmental approaches to research and governance issues. Since the U.S. Committee began its inquiry, at least three books dedicated exclusively to the topic of climate engineering have been released. Following on to its previous efforts, the U.K. Royal Society, in partnership with the Environmental Defense Fund (EDF) and the Academy of Sciences for the Developing World, initiated the Solar Radiation Management Governance Initiative (SRMGI) to ensure strict and appropriate governance of any plans for solar radiation management.

In addition to these efforts, the U.S. Committee commissioned both the Congressional Research Service (CRS) and the Government Accountability Office (GAO) to conduct their own inquiries. CRS reviewed the international treaties, laws and other existing regulatory frameworks that might apply if climate engineering were tested or deployed at a large scale. This report was released on March 11, 2010 and is contained in its entirety as part of the official Committee hearing records.[6] A second report was released by CRS in August 2010 containing a more detailed consideration of the potential regulatory issues of climate engineering.[7] GAO conducted a Committee-requested assessment of the current federal agency research activities directly related to climate engineering.

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[4] JOHN SHEPHERD ET AL., GEOENGINEERING THE CLIMATE: SCIENCE, GOVERNANCE AND UNCERTAINTY (The U.K. Royal Society) (2009).

[5] DIVISION ON EARTH AND LIFE SCIENCES, NATIONAL RESEARCH COUNCIL, AMERICA'S CLIMATE CHOICES: ADVANCING THE SCIENCE OF CLIMATE CHANGE p.299 (National Academies Press) (2010).

[6] H.R. REP. NOS. 111–62, 111–75, 111–88 (2010).

[7] KELSI BRACMORT ET AL., GEOENGINEERING: GOVERNANCE AND TECHNOLOGY POLICY (U.S. Congressional Research Service) (2010).

This GAO inquiry focused on the general state of the science and technology regarding climate engineering approaches and their potential effects, the extent to which the U.S. federal government is sponsoring or participating in climate engineering research or deployment, the views of legal experts and federal officials regarding the extent to which federal laws and international agreements apply to climate engineering activities, and some of the associated governance challenges. This report, *A Coordinated Strategy Could Focus Federal Geoengineering Research and Inform Governance Efforts*, was released in October 2010.[8] Also at the Chairman's request, a separate group of scientists and engineers within GAO are conducting a technology assessment on various climate engineering strategies and the related technical and societal considerations, with a report on their process and findings expected in early 2011. This GAO effort will include a survey of the knowledge base within the scientific community about leading climate engineering approaches, the public's general perception of those approaches, and the prospects for their potential development.

SUMMARY OF HEARINGS

The U.S. Science and Technology Committee held three public hearings to receive testimony from expert witnesses on climate engineering. The official record of these hearings, including discussion transcripts, witness testimony, questions for the record, and other supplementary materials, was finalized in July 2010 and will be available to academia, policy makers and the public.[9]

Geoengineering: Assessing the Implications of Large-Scale Climate Intervention

On November 5, 2009, with the Honorable Bart Gordon (D–TN) presiding, the U.S. Committee held a hearing to introduce the concept of climate engineering and explore some of the scientific, regulatory, engineering, governance, and ethical challenges. Five witnesses testified before the Committee:

- Professor John Shepherd, Professional Research Fellow in Earth System Science at the University of Southampton and Chair of the Royal Society working group that produced the report *Geoengineering the Climate: Science, Governance and Uncertainty*
- Dr. Ken Caldeira, Professor of Environmental Science, Department of Global Ecology at the Carnegie Institution of Washington and co-author of the Royal Society Report
- Mr. Lee Lane, Co-Director of the American Enterprise Institute Geoengineering Project
- Dr. Alan Robock, professor at the Department of Environmental Sciences in the School of Environmental and Biological Sciences at Rutgers University

[8] U.S. GOVERNMENT ACCOUNTABILITY OFFICE, A COORDINATED STRATEGY COULD FOCUS FEDERAL GEOENGINEERING RESEARCH AND INFORM GOVERNANCE EFFORTS (Publication No. GAO 10–903) (2010).

[9] Access to official hearing records is available at *<http://www.gpo.gov/congress/house/house14ch111.html>*.

- Dr. James Fleming, Professor and Director of the Science, Technology and Society Department at Colby College and author of *Fixing the Sky: The Checkered History of Weather and Climate Control*.

Chairman Gordon introduced some key challenges with climate engineering and described Committee plans for future discussion and international collaboration. He warned that climate engineering is no substitute for greenhouse gas mitigation and would require years of research before deployment.

During the witness testimony, Professor Shepherd described the goals and conclusions of the Royal Society report and recommended a multidisciplinary research initiative on climate engineering, including widespread public engagement at a global scale. Dr. Caldeira profiled the two major categories of climate engineering, solar radiation management (SRM) and carbon dioxide removal (CRM), and called for an interagency research program on both types. Mr. Lane argued for the economic viability of and environmental and political rationale for stratospheric injections, an SRM strategy. Dr. Robock identified some major risks and uncertainties of climate engineering. Specifically, he noted the problems of international disagreement, large-scale field testing, and the potential impacts of interruptions to large scale SRM systems, but argued for a comprehensive research program to help inform future climate policy decisions. Dr. Fleming provided a historical context on weather modification and its concurrent governmental challenges, arguing that any climate engineering initiative must be interdisciplinary, international, and intergenerational.

During the question and answer period, the Members and witnesses discussed: the eruption of Mt. Pinatubo in 1991 as an analog to stratospheric injections, the potential efficacy of greenhouse gas mitigation goals, the need for continued mitigation strategies and behavioral changes, the methane output of livestock, the environmental impacts of stratospheric injections, and the challenges of international collaboration and regulation. They also reviewed: climate modeling and simulation tools, anthropogenic climate change, the possibilities of distributed solar panels, potential roles for U.S. federal agencies in research and deployment, and how to prioritize the different suggested strategies. The panelists and Members agreed that no nation, including the United States or the United Kingdom, should deploy any climate engineering strategies before performing extensive research and establishing appropriate governance mechanisms. They also agreed that a comprehensive research program should be multi-disciplinary and internationally coordinated.

Geoengineering II: The Scientific Basis and Engineering Challenges

On February 4, 2010, with the Honorable Brian Baird (D–WA) presiding, the Subcommittee on Energy and Environment held a hearing to explore the scientific foundation of several climate engineering proposals and their potential engineering demands, environmental impacts, costs, efficacy, and permanence. Four witnesses testified before the Subcommittee:

- Dr. David Keith, Canada Research Chair in Energy and the Environment at the University of Calgary
- Dr. Philip Rasch, Laboratory Fellow of the Atmospheric Sciences & Global Change Division and Chief Scientist for Climate Science at Pacific Northwest National Laboratory
- Dr. Klaus Lackner, Ewing-Worzel Professor of Geophysics and Chair of the Earth & Environmental Engineering Department at Columbia University
- Dr. Robert Jackson, Nicholas Chair of Global Environmental Change and a Professor in the Biology Department at Duke University.

During the witness testimony, Dr. Keith emphasized the distinction between the two types of climate engineering, and compared climate engineering to chemotherapy as an unwanted but potentially necessary tool in the case of an emergency situation. Dr. Rasch described SRM strategies and suggested first steps for developing an SRM research program, noting that initial costs could be low but that more sensitive climate modeling tools would be needed. Dr. Lackner described the CDR strategies of carbon air capture and mineral sequestration. He noted that such technologies were compatible with a continued global dependence on fossil fuels and would address the causes, rather than symptoms, of climate change, but that high costs would be a challenge. Dr. Jackson discussed biological and land-based strategies in both the CDR and SRM categories. He explained that existing regulatory structures and expertise could accommodate many of these strategies fairly readily, but that both scalability and the foreseeable and unforeseeable impacts on other natural resources, such as water and biodiversity, would be problematic.

During the question and answer period, the Members and witnesses discussed: the front end costs of climate engineering compared to traditional mitigation alone, the costs and potential impacts of atmospheric sulfate injections, and creative strategies for chemical and geological carbon uptake. They also explored public education and opinion on climate engineering, the potential effects of increased structural albedo, and the greatest political challenges of climate management. The Members emphasized some existing tools that could reduce the need for climate engineering, such as unconventional carbon capture and sequestration (CCS) strategies, the availability and economic viability of fossil fuel alternatives, and energy conservation. All the witnesses agreed that a basic research program on the subject is likely needed, whether for the ultimate goal of deployment or for the sake of risk management.

Geoengineering III: Domestic and International Research Governance

On March 18, 2010, with the Honorable Bart Gordon presiding, the Committee held a hearing to explore the domestic and international governance needs to initiate and guide a climate engineering research program. The hearing also examined which U.S. agencies and institutions have the capacity or authorities to conduct climate engineering research. Five witnesses, divided into two panels, testified before the Committee.

Testifying via satellite on the first panel was Member of Parliament Phil Willis, then Chair of the Science and Technology Committee in the U.K. House of Commons and Representative of Harrogate and Knaresborough. Mr. Willis has subsequently been appointed Baron Willis of Knaresborough, Member of the House of Lords. In his opening statement, Chairman Gordon welcomed Chairman Willis as his honored guest. He emphasized that the scientific evidence of anthropogenic climate change is overwhelming and that a more robust scientific and political understanding of climate engineering is needed.

Chairman Willis testified on the U.K.–U.S. joint climate engineering inquiry and introduced his Committee's official report on the subject, *The Regulation of Geoengineering*.[10] He delineated some of the report's key findings and recommendations, including governing principles, and stressed that while climate engineering would be an extremely complex and challenging venture, it would be irresponsible not to initiate appropriate regulation and research. During the first question and answer period, Chairman Willis and the U.S. Committee Members discussed the potential value of a comprehensive international database on climate engineering information and activities, the future of research in the United Kingdom, and additional opportunities for bilateral cooperation between the Committees. They also discussed the role of public opinion and the media, and how the U.K. inquiry process engaged both the public and scientific experts.

The second panel consisted of:

- Dr. Frank Rusco, Director of Natural Resources and Environment at the Government Accountability Office (GAO)
- Dr. Scott Barrett, Lenfest Professor of Natural Resource Economics at the School of International and Public Affairs and the Earth Institute at Columbia University
- Dr. Jane Long, Associate Director-at-Large and Fellow for the Center for Global Strategic Research at Lawrence Livermore National Lab (LLNL)
- Dr. Granger Morgan, Professor and Head of the Department of Engineering and Public Policy and Lord Chair Professor in Engineering at Carnegie Mellon University.

During Panel II, Dr. Rusco summarized key findings of the GAO's ongoing inquiry on climate engineering, describing some of the existing relevant research activities in federal agencies, as well as some relevant international treaties. He also provided support for the near-term regulation of some climate engineering strategies. Dr. Morgan described climate engineering research at Carnegie Mellon University and argued for a cautious, risk-aware research program on solar radiation management. He also argued that the National Science Foundation should lead initial research efforts, that transparency should be a priority, and that the potential environmental impacts of specific research initiatives should inform the international agreements and laws intended to regulate them. Dr. Long discussed the key questions and principles for governance and

[10] SCIENCE AND TECHNOLOGY COMMITTEE, UNITED KINGDOM HOUSE OF COMMONS, THE REGULATION OF GEOENGINEERING (Stationery Office Limited) (2010).

risk management, and urged that the benefits of any program must very clearly outweigh the risks. Dr. Barrett assessed the different scenarios in which climate engineering might be needed, warning that there would necessarily be "winner and losers," and recommended seven key governance rules.

During the discussion period with this panel, the Members and witnesses discussed initial regulatory structures and debated the appropriate research and management roles for the U.S. Department of Energy (DOE), the National Science Foundation (NSF), the National Oceanic and Atmospheric Administration (NOAA), the National Aeronautics and Space Administration (NASA), and other U.S. federal agencies. They also discussed national security and geopolitical impacts of climate change itself and the need for adaptive management. All panelists and witnesses agreed that unilateral deployment of climate engineering could be very dangerous and should be avoided. There was also a consensus that climate engineering is a highly interdisciplinary, diverse topic, and that any federal research initiative may require several agency and university partners.

RESEARCH NEEDS

As stated, climate engineering research will be multi-disciplinary and require a coordinated effort to sufficiently inform testing or deployment of any of the proposed strategies.[11] While, some strategies, such as forest management, have a more extensive scientific foundation than others, an improved understanding of the potential efficacy and impacts of all proposals is needed.[12] Below are several key areas of research that may be needed to better understand the physical and chemical processes, and assess the technical and financial feasibility, engineering needs, and the environmental, ecological and societal implications of various climate engineering strategies. These areas of research are commonly recognized by climate engineering and earth sciences experts as fundamental to one or more of the main proposed strategies. They include but are not limited to:

- Greenhouse gas monitoring, accounting and verification
- Hydrologic cycle modeling
- Water and air quality modeling and monitoring
- Atmospheric dynamics and physics
- Ocean and lake dynamics and physics
- Atmospheric chemical composition (e.g. carbon dioxide, ozone, moisture, and other greenhouse gases such as methane)
- Ocean and terrestrial biology and ecosystems
- Invasive plant and animal species
- Risk assessment and risk management

[11] For a detailed discussion of each geoengineering strategy and its scientific basis, see JOHN SHEPHERD ET AL., GEOENGINEERING THE CLIMATE: SCIENCE, GOVERNANCE AND UNCERTAINTY (The U.K. Royal Society) (2009).

[12] See DIVISION ON EARTH AND LIFE SCIENCES, NATIONAL RESEARCH COUNCIL, AMERICA'S CLIMATE CHOICES: ADVANCING THE SCIENCE OF CLIMATE CHANGE p.297 (National Academies Press) (2010).

- Chemical, electrical and mechanical engineering [13]
- Earth systems environmental sciences [14], including modeling
- Weather systems, including monsoon cycles
- Forces impacting the ozone layer
- Impacts of forestry and agricultural practices on greenhouse gas emissions
- Biochar
- Terrestrial carbon sequestration
- Phytoplankton
- Ocean acidification and chemistry
- Recyclable carbon adsorbents
- Geologic/seismic imaging
- Radiation measurement
- Cloud microphysics
- Geochemical dynamics and carbon mineralization
- Sea ice dynamics and thermodynamics
- Genomic science
- Energy generation and use

The tools required to support these research needs include but are not limited to:

- High performance computing systems for modeling
- Weather and climate monitoring tools, including satellites, and ground-based and in situ instrumentation
- Land use change monitoring systems, including environmental satellites
- Networks of distributed water sampling tools for both fresh and ocean waters
- Geological imaging tools, such as spectroscopic remote sensing
- Chemical laboratories to measure and understand the role of chemistry in the earth system
- Biological and ecological observing systems and laboratories
- Engineering research laboratories with the ability to bench test, field test, and evaluate various climate engineering concepts

U.S. RESEARCH CAPACITIES

There is virtually no federal funding explicitly dedicated to "climate engineering" or "geoengineering" research. However, as discussed in their October report, GAO found that some federal agencies already conduct activities that address many of the research needs identified above, albeit without "climate engineering" as an express or intended goal.[15] This section, in contrast with the GAO

[13] *See Geoengineering: Assessing the Implications of Large-Scale Climate Intervention Hearing Before the House of Representatives Committee on Science and Technology*, 111th Cong. (2009) (John Shepherd Testimony).

[14] *Id.*

[15] *See for e.g.* STAFF OF HOUSE OF REPRESENTATIVES COMMITTEE ON SCIENCE AND TECHNOLOGY, 111TH CONG., REPORT ON GEOENGINEERING III: DOMESTIC AND INTERNATIONAL RE-

report, explores some of the existing tools and competencies in federal agencies that could contribute to climate engineering research. **It is the opinion of the Chair that any federal climate engineering research program should leverage existing facilities, instruments, skills, and partnerships within federal agencies.**

National Science Foundation

The National Science Foundation (NSF) supports basic research and education across all fields of fundamental science and engineering. Most of NSF's budget is dedicated to supporting investigator-initiated, merit-reviewed, and competitively-selected awards and contracts to researchers and teams primarily from U.S. colleges and universities, but also, including non-profit organizations and private sector firms. A smaller portion of NSF funding goes to support major research centers and cutting-edge tools and facilities. NSF also has a long history of fostering and conducting international scientific collaborations on both small and large-scale research projects. **Therefore, of the federal research agencies, the National Science Foundation (NSF) may have the greatest capacity to engage in research related to the nascent field of climate engineering, and it is the opinion of the Chair that NSF should support merit-reviewed proposals for climate engineering research.**

> ***An Example of an NSF Grant*** *Researchers at Rutgers University have received a grant, through the NSF Geosciences (GEO) Directorate, to explore stratospheric injections and sunshading. The team has conducted climate model simulations of the various scenarios of artificially introduced particles in the stratosphere. And they have investigated the potential impacts of stratospheric injections on precipitation, as well as the ethical implications of some climate engineering proposals. As of November 2009 the team had produced five peer-reviewed journal articles on its research.*

Research Directorates

NSF is divided into the following seven Directorates that support science and engineering research and education: Biological Sciences; Computer and Information Science and Engineering; Education and Human Resources; Engineering; Geosciences; Mathematical and Physical Sciences; and Social, Behavioral and Economic Sciences. Each Directorate is subdivided into divisions. All Directorates, with the likely exception of Education and Human Resources, support research needs associated with climate engineering. For example, the Engineering Directorate currently supports fundamental research on the development of materials, methods, and innovative processes for the separation and removal of contaminants such as carbon dioxide from the air. The Geosciences (GEO) Directorate supports research on the chemistry of ocean acidification, including the interplay of acidification and the biochemical and physiological processes of organisms, and the implications of these effects for ecosystem structure and function. In addi-

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SEARCH GOVERNANCE BEFORE THE HOUSE OF REPRESENTATIVES COMMITTEE ON SCIENCE AND TECHNOLOGY HEARING (Comm. Print 2010) (Frank Rusco Responses to Questions for the Record).

tion, the Biological Sciences (BIO) Directorate supports research on the complexity and adaptability of biological systems and their interface with the carbon and water cycles. Research activities that could contribute to ocean fertilization or terrestrial CDR strategies, for example, are already being addressed under the BIO and GEO portfolios. **It is the opinion of the Chair that the National Science Foundation (NSF) should consider how all of its grant programs could contribute to a climate engineering research agenda.**

Centers and Facilities

While NSF does not operate its own laboratories, it supports construction and operations for an array of advanced instrumentation and major research facilities, including oceanographic research vessels. For example, through its Major Research Equipment and Facilities Construction account, NSF is currently supporting development and construction of the National Ecological Observatory Network (NEON, see inset) and the Oceans Observatory Initiative. NSF is also the primary sponsor for the National Center for Atmospheric Research (NCAR). NCAR supports research in areas such as atmospheric chemistry, climate change, cloud physics, solar radiation, and related physical, biological, and social systems. NCAR is home to a number of world-class experts and tools, including an atmosphere-ocean general circulation model, which could contribute to climate engineering research. In fact, NCAR researchers have already begun to explore how sulfate particles behave in the stratosphere and their effects on the ozone layer.

National Ecological Observatory Network *The NSF-funded National Ecological Observatory Network (NEON) ecological observation program is the most ambitious U.S. attempt to assess environmental change to date. The program has divided the United States into 20 eco-climatic domains and will monitor the regions over 30 years through site-based and geological data and airplane observations. The results will inform how land use change, climate change, and invasive species affect ecosystems.*

NEON's activities will include soil analysis, measuring land use and vegetation changes, and monitoring forest canopy heights and biomass. Its data will enable researchers to quantify forces regulating the biosphere and predict its response to change. NEON infrastructure will include towers and sensor arrays, remote sensing, cutting-edge instrumentation, and facilities for data analysis, modeling, and forecasting. The level of detail and uninterrupted data sets expected from NEON and the experts that analyze its data could inform research on land-based climate engineering, such as afforestation and reforestation, reflective crops, and biochar. NEON could also contribute to the eventual monitoring of other CDR strategies.

Political and Ethical Research

Understanding the full range of impacts of climate engineering will entail a unique set of challenges outside of the scientific and engineering categories identified earlier. Research underlying areas such as domestic and international governance, economics, and risk assessment and management, will likely be required as long as climate engineering remains an option. There are also significant ethical considerations with the large-scale testing and deployment of climate engineering, since some strategies may benefit certain populations at the expense of others. Likewise, there are ethical con-

siderations in choosing to not deploy a strategy, should it prove viable.

NSF, with its capacity to support research in the social and political sciences, may be an appropriate body to lead federal research in these areas. The Social, Behavioral, and Economic Sciences (SBE) Directorate, for example, has funded research proposals on the societal implications of environmental events, such as earthquakes. The Directorate's Sociology Program recently funded a workshop to explore the sociological dimensions of climate change and climate change solutions, including how the social sciences might be incorporated into existing data infrastructure.[16] At this time NSF is the only federal body with such formalized capacities for research on the social and political dimensions of science and emerging technologies.

As with any government initiative in the development of nascent technologies that provoke some measure of controversy, transparency, and public engagement will be critical to a successful research program on climate engineering. Moreover, public engagement will be most effective if it is incorporated early, when strategies are still being considered and a diversity of perspectives can be incorporated.[17] **The Chair agrees with the U.K. Committee recommendation that governments should make public engagement a priority of any climate engineering effort. Furthermore, the National Science Foundation (NSF), with its institutional history of engaging the public on nascent technologies and funding research in the social and behavioral sciences, should play a critical role in informing public engagement strategies.**

International Collaboration

In addition to supporting basic research and early-stage development of nascent and transformative technologies, NSF has unique capacities for fostering international scientific collaboration. The Office of International Science and Engineering (OISE) supports some of its own internationally focused research and education programs and facilitates collaboration between NSF-funded researchers and international partners across the Foundation. However, NSF grant programs may fund only the U.S. portion of research projects being conducted by international teams of scientists and engineers. For example, the Division of Earth Sciences has recently granted funds to researchers at the University of Maryland to explore carbon monoxide oxidation and production, and these efforts will be complemented by activities funded separately at the Russian Kamchatka Institute of Volcanology and Seismology and the Russian National Academy of Sciences.[18] The Dimensions on Bio-

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[16] JOANE NAGEL ET AL., WORKSHOP ON SOCIOLOGICAL PERSPECTIVES ON GLOBAL CLIMATE CHANGE (National Science Foundation) (2009). *Available at <http://ireswb.cc.ku.edu/~crgc/NSFWorkshop/Readings/NSF_WkspReport_09.pdf>.*

[17] Daniel Sarewitz, *Not By Experts Alone*, 466 NATURE p.688 (2010).

[18] For example, Dr. Frank Robb at the University of Maryland Biotechnology Institute received a National Science Foundation Collaborative Research grant, number 0747394, entitled "Carbon Monoxide Dynamics in Geothermal Mats and Earth's Early Atmosphere." For more information see the National Science Foundation's website at *<http://www.nsf.gov/awards/award_visualization_noscript.jsp?org=EAR&showAwardDollars=true&showPerCapita=true&region=US-MD&instId=5300000455>.*

diversity initiative will fund a set of coordinated proposals researching the role of biodiversity in ecological and evolutionary processes. The solicitation for this initiative encourages investigators to develop international collaborations, either through direct research partnerships or the development of international coordination networks.[19] NSF's support of U.S. participation in international scientific and engineering efforts may prove critical to any significant international climate engineering research effort, in particular for those strategies with geographically dispersed impacts, such as stratospheric injections, marine cloud whitening, and ocean fertilization.

Challenges in Europe *There are lessons to be learned from the European experience with the still-nascent field of synthetic biology. The potential applications of synthetic biology, including its capacity to modify the genetic makeup of food crops to increase crop yields and provide greater pest resistance have been met with uncertainty. Public confusion about governmental motivations for agricultural biotechnology led to a virtual moratorium on genetically modified (GM) foods. Having learned from these challenges, both German and British national research councils have recently committed to a thorough public dialogue regarding synthetic biology as they seek to jump start development in the field.*[a] *A number of unresolved questions on the ethical and environmental implications of synthetic biology remain, and international standards are minimal or nonexistent. Better public engagement in Europe is seen as a fundamental step in the development of this field.*

[a] Colin Macilwain, *Talking the Talk: Without Effective Public Engagement, There Will Be No Synthetic Biology in Europe*, 465 NATURE p.867 (2010).

National Oceanic and Atmospheric Administration

The National Oceanic and Atmospheric Administration (NOAA), through its research laboratories and partners, and the Climate Program Office, conducts broad ranging research into complex climate systems with the aim of improving our ability to understand these systems and predicting climate variation and change over a range of temporal and spatial scales. NOAA's research capacities and monitoring and modeling tools make it an appropriate venue for climate engineering research—to understand how such activities could be conducted and what effects, both desired and unknown, may occur as a result.

Office of Oceanic and Atmospheric Research

The Office of Oceanic and Atmospheric Research (OAR) is NOAA's primary research body, providing the research foundation for understanding the complex systems that support the planet. The role of OAR is to provide unbiased science to better manage the environment, on a national, regional, and global scale. To do this, OAR administers collaborative partnerships with universities and other research bodies and works with its own research laboratories to advance climate science. As the primary research and development organization within NOAA, OAR explores the earth and atmosphere from the surface of the sun to the depths of the ocean

[19] *See* National Science Foundation, *Program Solicitation: Dimensions of Biodiversity* (Mar. 10, 2010). Available at *<http://nsf.gov/publications/pub_summ.jsp?WT.z_pims_id=503446&ods_key=nsf10548>*.

to provide products and services that describe and predict changes in the environment and inform effective decision making.

Current research priorities at OAR could be leveraged to support future climate engineering research initiatives. For example, the Climate Program Office manages and awards funding through competitive research programs on high-priority topics in climate science, including atmosphere, Arctic ice, the global carbon cycle, climate variability, and oceanic conditions. Several types of climate engineering research needs could fit into these existing, broad research categories. In addition, the Climate Observations and Monitoring program maintains a highly integrated and complex network of observing instruments to gather climate data, which are then used for national and international assessment projects. Such a network would be pertinent to informing the scope of potential ecosystem impacts from climate engineering.

Another pertinent mission at OAR is Weather and Air Quality. This mission focuses on forecasting and hazard warnings as well as on the chemical and physical makeup of the atmosphere, circulation patterns, and changes caused by chemical inputs. Although many of OAR's ocean and freshwater activities relate to traditional NOAA missions, such as fisheries management and coastline restoration, OAR also conducts a great measure of research on issues relevant to climate engineering research such as aquatic invasive species, freshwater contamination, the nutrient pollution cycle, and ocean acidification.

OAR's laboratories support these research missions and conduct cutting-edge technology development and analysis. Specifically, the Geophysical Fluid Dynamic Laboratory (GFDL) and Earth Systems Research Laboratory (ESRL) support a host of key activities relevant to climate engineering. OAR research is also informed by an array of cutting-edge field observation tools and sensors, including surface networks, stratospheric balloons, ocean buoys, and aircraft, that would be uniquely suited to atmosphere-based climate engineering research and monitoring. Each program office uses powerful computing systems to assess and predict changes in the ecosystems. Any number of OAR's ongoing research activities could directly and immediately inform climate engineering. For example, the Arctic Research Office could explore the potential of geographically-localized SRM to protect polar ice. In addition, OAR expertise on biological emission and absorption of greenhouse gases and carbon storage in oceans could be leveraged to predict the impacts of any potential CDR strategy.

Research at the Earth Systems Research Laboratory *Scientists at the Earth Systems Research Laboratory (ESRL) have begun to explore the potential impacts of SRM on solar power production. In March 2009 the Chemical Sciences Division published a paper on how atmospheric sulfate injections may significantly decrease power generation from solar facilities.*[b] *The paper suggests that for every percentage of direct sunlight reflected to outer space, solar power output would decrease by four or five percent. In addition, there is the even more troubling concern that atmospheric SRM could negatively impact food crops growth and decrease yields. Any atmospheric*

SRM research program must be subject to robust risk assessment and management procedures, including modeling exercises on the secondary impacts that a reduction in direct sunlight could have on both solar power installations and plant growth.

[b] Daniel M. Murphy, *Effect of Stratospheric Aerosols on Direct Sunlight and Implications for Concentrating Solar Power*, 43 ENVIRONMENTAL SCIENCE AND TECHNOLOGY p.2784 (2009).

National Environmental Satellite Data and Information Service

The National Environmental Satellite, Data, and Information Service (NESDIS) is NOAA's satellite observation systems and data collection service. NESDIS transmits real time data from both orbiting and geo-stationary satellites for a host of research objectives such as weather forecasting and earth and ocean science, and manages the development of environmental satellite products. Like the environmental satellite capabilities within NASA, the NESDIS observing system can collect data on a wide variety of environmental factors including the motion of particles in the atmosphere, cloud, air and ocean temperatures, ocean dynamics, global vegetation, atmospheric humidity, and land cover. NESDIS also holds thorough data records on Arctic sea ice, which is measured via satellites and verified with "ground-truthing" equipment and software. Long term measurements on Arctic sea ice would be needed to verify the effectiveness of any climate engineering program, as well as the inadvertent and indirect effects of such programs.

The information collected by NESDIS is processed, analyzed, and disseminated through NOAA's data centers. One of these data centers, the National Climatic Data Center (NCDC), provides for the long-term archiving of weather and climate data and is the world's largest active archive of these types of information. NESDIS also oversees six Regional Climate Centers (RCCs), a network of data management sites providing climate information at the state and local levels, as well as nine Regional Integrated Sciences and Assessments (RISA) offices, which deliver climate information to regional and local decision-makers. The National Oceanographic Data Center (NODC) maintains physical, biological, and chemical measurements from oceanographic observations, satellite remote sensing, and ocean modeling. The National Geophysical Data Center (NGDC) manages the National Snow and Ice Data Center, and also holds over 400 digital and analog databases on geophysical ground- and satellite-based measurements, including geochemical makeup and carbonate data. Data holdings from all NESDIS Centers are currently used to answer questions about climate change and natural resources, and would be useful to inform the early stages of climate engineering research. The Centers may also serve as repositories for any new data gathered in the course of climate engineering research.

The NOAA satellite systems provide a range of data sets on atmospheric, oceanic, and geologic conditions, and new systems with improved instrumentation are planned for deployment. For example, the Geostationary Operation Environmental Satellite R–Series (GOES–R), is a joint NOAA–NASA satellite project based out of Goddard Space Flight Center. The two satellites in this system are expected to launch in 2015 and 2017, and will provide data on sea surface temperature, cloud top height and temperature, and aerosol

detection, among other baseline products. These tools could inform research on stratospheric aerosol injection, marine cloud whitening, ocean fertilization, and other climate engineering strategies.

Lessons can also be learned from another NOAA–NASA joint project, the Joint Polar Satellite System (JPSS),[20] formerly known as the National Polar-orbiting Operation Environmental Satellite System (NPOESS). The program was initiated in 1994 and was slated to launch six environmental monitoring satellites starting in 2009. However, due to management challenges, explosive growth in life-cycle cost estimates, and schedule delays the program will instead launch two separate satellite systems managed by NOAA and DOD, respectively, with NASA serving as NOAA's technical support arm. The first JPSS satellite is scheduled to launch in 2014. While JPSS promises to deliver robust capabilities for weather and climate forecasting, due to the aforementioned issues, the system's capabilities will be significantly reduced. For instance, the aerosol polarimetry sensors, which retrieve specific measurements on clouds and aerosols in the atmosphere, were cancelled from two of the satellites, thus cancelling two of the key information products, aerosol refractive index and cloud particle size and distribution, which could have provided the types of data that atmospheric-based climate engineering research requires. The NPOESS/JPSS project also demonstrates how easily large and complex research projects can fall victim to financial and management challenges, as well as the importance of mission consistency and data continuity in the success of any comprehensive research program.

Environmental Impact Research: The Oceans

Ocean fertilization is the intentional introduction of nutrients, such as iron, into the surface waters of the ocean to stimulate the growth of phytoplankton and thereby the uptake of carbon dioxide from the atmosphere. Phytoplankton are photosynthetic; they use energy from the sun to naturally convert carbon dioxide and water into organic compounds and oxygen. Iron is necessary for photosynthesis to occur and in many areas of the ocean iron is not abundant, thereby limiting the growth of phytoplankton. The idea behind ocean fertilization projects is to use relatively small amounts of iron in iron-deficient zones to trigger large phytoplankton blooms. At least half of the carbon-rich biomass generated by such plankton blooms would be consumed by animals such as zooplankton and small fish, and about a third would sink into the cold, deep ocean water where it would be effectively isolated from the atmosphere for centuries. Fertilization does occur through natural processes such as glacial runoff, dust storms, and through ocean upwelling that carries cold, nutrient rich water to the surface. Since the early 1990s, a number of scientists and entrepreneurs from around the world have explored ocean fertilization

[20] The U.S. Science and Technology Committee held seven hearings on challenges facing the NPOESS program over the last seven years before the Investigations and Oversight and Energy and Environment Subcommittees. *See for e.g. Continuing Independent Assessment of the National Polar-orbiting Operational Environmental Satellite System Hearing Before the House of Representatives Committee on Science and Technology Subcommittee on Energy and Environment*, 111th Cong. (2009). Available at *<http://science.house.gov/publications/hearings_markups.aspx>*.

as a means to sequester atmospheric carbon dioxide in the deep ocean.[21]

Several concerns have been voiced from the scientific community over the efficacy and ethics of ocean fertilization. For example, some phytoplankton blooms (e.g., harmful algal blooms or HABs) produce toxins that are extremely detrimental to human health and coastal economies. HABs impacts in the Great Lakes, Gulf of Mexico, and the Pacific Northwest have been particularly severe and have led to the creation of "dead zones."[22] The increase of HABs is a concern from ocean fertilization projects because it is not known what types of plankton will "bloom" after fertilization. Research is ongoing to understand how to control, mitigate, and effectively respond to HABs events. That said, much research remains to be done in this arena, and the potential to exacerbate HABs is only one of the ecological hazards that could be caused by large-scale iron fertilization. In addition to this and other potential ecological effects, the efficiency of fertilization as well as the ability to verify the resulting sequestration of carbon dioxide are issues that have yet to be resolved.[23] **Therefore, it is the opinion of the Chair that the National Oceanic and Atmospheric Administration (NOAA), with its unique expertise and research capacities on ocean chemistry, should have a lead role in researching and assessing the environmental impacts of any climate engineering strategy involving chemical inputs into the environment that would directly or indirectly impact ocean waters, e.g. stratospheric sulfate injections and ocean fertilization.**

Environmental Impact Research: The Ozone Layer

Some researchers have expressed concern that aerosols from stratospheric sulfate injections will exacerbate the effects of materials remaining in the atmosphere from the past usage of chlorofluorocarbons (CFCs).[24] CFCs were once sold in popular consumer products such as aerosol spray cans and refrigerants, but were found to decay the atmospheric ozone layer that moderates the amount of ultraviolet light reaching the earth's surface. In response to these risks, the United States initiated bans on CFCs beginning in 1978, and these substances were essentially phased out of commerce worldwide via the Montreal Protocol. Since these bans have taken effect, the ozone layer has shown a marked recovery, but the atmospheric system will remain sensitive to damage in the future from CFCs or other hazardous compounds that have yet to be identified. In addition, human activities that stimulate ozone-de-

[21] P.W. Boyd et al., *Mesoscale Iron Enrichment Experiments 1993–2005: Synthesis and Future Directions*, 315 SCIENCE p.612 (2007).

[22] *Harmful Algal Blooms: Formulating an Action Plan, 2009: Hearing on The Harmful Algal Blooms and Hypoxia Research and Control Act Hearing Before House of Representatives Committee on Science and Technology Subcommittee on Energy and Environment*, 111th Cong. (2009) (Hearing Charter).

[23] Anand Gnanadesikan et al., *Effects of Patchy Ocean Fertilization on Atmospheric Carbon Dioxide and Biological Production*, 17 GLOBAL BIOGEOCHEMICAL CYCLES p.1050 (2003).

[24] David Keith, *Geoengineering the Climate: History and Prospect*, 25 ANNUAL REVIEW OF ENERGY AND THE ENVIRONMENT p.245 (2000).

structive materials could slow or even reverse the recovery process.[25]

NOAA scientists were among the first to identify the risks presented by ozone-depleting chemicals, and OAR remains the federal government's primary authority on the ozone layer. NOAA uses satellite and ground-based measurements to continually monitor stratospheric ozone as well as other conditions, such as the presence of certain chemicals which can detrimentally impact the atmosphere. NOAA's Earth Systems Research Laboratory (ESRL), the Climate Prediction Center, and the National Climatic Data Center (NCDC) are all engaged in improving data holdings and information on ozone. **It is the opinion of the Chair that due to its experience in researching ozone and the chemicals that could harm the ozone layer, the National Oceanic and Atmospheric Administration (NOAA) should lead federal efforts to explore the potential impacts of sulfates on the stratospheric ozone layer.**

Department of Energy

Several program offices within the Department of Energy (DOE) house activities and expertise that could inform research on climate engineering strategies.

Office of Science

The bulk of climate change research expertise at DOE may be found within the Office of Science, which is responsible for about 40% of the overall federal R&D investment in the physical sciences. Of the six program offices within the Office of Science, at least three contain climate engineering-relevant research capabilities: Biological and Environmental Research (BER), Basic Energy Sciences (BES), and Advanced Scientific Computing Research (ASCR).

Biological and Environmental Research Program

The Biological and Environmental Research (BER) program office supports interdisciplinary research and user facilities to explore biological sciences, bioenergy, climate change, carbon sequestration, subsurface contamination, hydrology, and the interface between biological and physical sciences, among other topics. While the program is most widely known for its work in human genome sequencing, and many BER activities are not directly related to climate engineering, a major relevant focus of BER is its work in genomics and biosequestration. BER studies the fundamental biological processes found in microbes and plants, and specifically how these processes influence the highly complex and interlinked global carbon cycle. As part of that charge, BER explores the potential of biosequestration, or the storage of organic carbon in ecosystems, and how it might contribute to future climate change adaptation and mitigation strategies. Additionally, BER genomics activities are at the frontier of biotechnology research, using innovative tech-

[25] Simone Tilmes et al., *The Sensitivity of Polar Ozone Depletion to Proposed Geoengineering Schemes*, 320 SCIENCE EXPRESS p.1201 (2008).

nologies to influence the uptake, fixation, and storage of carbon in microbes and plants. In this regard, BER's capabilities could help inform land-based climate engineering strategies for large-scale planting of indigenous or non-indigenous plants to encourage biological carbon consumption. Additionally, some strategies call for the genetic altering or cross-breeding of plants or trees to enhance their capacities to reflect sunlight, to accelerate carbon uptake, or both.

In addition, BER's Climate and Environmental Sciences Division (CESD) supports basic research in a broad variety of relevant subject areas, including atmospheric systems, high performance computer modeling, the role of terrestrial ecosystems in carbon cycling, subsurface biogeochemical processes, and other multi-scale processes and anthropogenic and natural activities that affect the climate. This division of BER supports the Carbon Dioxide Information Analysis Center (CDIAC) located at Oak Ridge National Laboratory. CDIAC is the primary climate-change data and information analysis center of DOE, and is considered to be one of the world's most comprehensive archives and managers of diverse climate data sets. CDIAC gathers and consolidates environmental data from a wide variety of sources, maintains and regularly updates that data, and makes the data available for free to a large international user database. A major source of data for CDIAC is the AmeriFlux observation network. Established in 1996, AmeriFlux tracks the carbon, water, and energy cycles in North America from approximately 100 sites distributed primarily throughout North America, with some sites in Central and South America. Ameriflux could contribute to carbon accounting and verification programs needed to monitor the effectiveness of carbon dioxide removal (CDR) climate engineering strategies. Ameriflux also coordinates with the global "network of regional networks," FLUXNET, to share and validate data measurements worldwide. The networks comprising FLUXNET utilize complementary methodologies and instrumentation, and perform cross-comparisons of data sets to verify their results. The internationally-coordinated mission and the collaborative, communicative structure of AmeriFlux and FLUXNET could provide a model for what would be required to identify the global impacts and effectiveness of any climate engineering strategy, in particular carbon removal strategies.

BER also manages several user facilities that could support climate engineering research. The Atmospheric Radiation Measurement (ARM) Climate Research Facility (ACRF) conducts aerial and land-based sampling over different climate regions to measure changes in sea surface temperatures, cloud life cycle, and other radiative properties of the atmosphere. The ACRF collects and archives data, and makes it available to the scientific community. This information is used to illuminate how particles in the atmosphere affect the earth's radiation balance, information that would be critical to any atmospheric-based climate engineering strategies. And like Ameriflux, ACRF can also contribute to carbon accounting and verification programs that would be needed to understand the effectiveness of any carbon dioxide removal (CDR) program. BER also funds the Environmental Molecular Sciences Laboratory

(EMSL) at Pacific Northwest National Lab. EMSL supports research in biogeochemistry and atmospheric chemistry at the molecular level, including research in areas such as aerosol formation, with capabilities that include supercomputing for modeling molecular-level processes and advanced terrestrial imaging. The scientific and technical experts and unique tools at EMSL could inform climate engineering research in areas such as geological and biological sequestration and stratospheric injections.

> ***Aerosol Research*** *A working group within the Atmospheric Radiation Measurement program has recently published a paper on predicting which types of atmospheric particles will act as cloud condensation nuclei, or CCN. CNN are the tiny airborne "seeds" around which water vapor will condense and form droplets. Different types of CCN influence a cloud's particular brightness and lifetime. A better understanding of CCN is critical to informing marine cloud whitening, because specific types of CCN would be needed to most effectively increase a cloud's size and reflectivity.*[c]

[c] S.M. King et al., *Cloud Droplet Activation of Mixed Organic-Sulfate Particles Produced by the Photooxidation of Isoprene*, 10 ATMOSPHERIC CHEMISTRY AND PHYSICS p.3593 (2010).

Basic Energy Sciences Program

The Basic Energy Sciences (BES) program office supports fundamental research on materials sciences, physics, chemistry, and engineering, with an emphasis on energy applications. Its work is divided into three divisions: Materials Sciences and Engineering; Chemical Sciences, Geosciences and Biosciences; and Scientific User Facilities. BER's work in geosciences and chemical research may be particularly pertinent to climate engineering research. The Geosciences Research program promotes understanding of earth processes and materials, such as the basic properties of rocks, minerals, and fluids, and it supports computational modeling and imaging of geophysical landscapes over a wide range of spatial and time scales. These activities are often conducted at DOE national labs and in concert with NSF or the USGS. Thus, Geosciences Research at BER may inform the fundamental chemical and technological requirements, as well as the long-term viability of potential sites, for non-traditional carbon sequestration, in which captured carbon would be stored and mineralized into a solid or liquid form in specific types of geologic systems, such as basalt sands. The Chemical Research program could support unconventional carbon capture and sequestration (CCS) by informing the chemical processes through which carbon dioxide or other greenhouse gases can be mineralized for storage, as well as the characterization and development of chemicals, such as amines, to capture carbon from the air.

BES also manages the Energy Frontier Research Centers, a set of temporary, highly focused, transformative energy research collaborations. The EFRC program is structured to fund the country's best talent in research to address fundamental scientific barriers to energy security and key energy challenges. Forty-six EFRCs are currently being funded over a five year period, and several of these

are intended to address geologic capture and storage of CO_2.[26] The new information from these EFRCs can contribute greatly to the body of information on unconventional CCS.

Advanced Scientific Computing Research Program

The Office of Science's Advanced Scientific Computing Research (ASCR) program stewards several of the largest computational facilities in the world dedicated to unclassified scientific research. Its broad and varied capabilities include producing high-fidelity, highly complex simulations of the earth's systems and the potential changes they might undergo. This allows scientists, from both the private and public sectors, to analyze theories and experiments on weather patterns, the water cycle, changes in atmospheric carbon, and others that are too dangerous, expensive, or simply impossible to test otherwise. The Scientific Discovery through Advanced Computing (SciDAC) Program within ASCR integrates with other research efforts at DOE to explore application-focused research initiatives, including climate activities. For example, SciDAC has provided detailed climate simulations to the Biological and Environmental Research (BER) program. One SciDAC project will develop and test a global cloud resolving model (GCRM) that divides global atmospheric circulation into grid cells approximately 3 km in size.[27] The level of complexity and number of variables in the atmospheric system can only be modeled at such a refined spatial resolution through highly powerful computing systems.

Given the wide variety of climate engineering's potential unintended impacts on earth systems, exhaustive efforts must be made to identify and avoid the most dangerous of those before a climate engineering program is tested or deployed at any scale. The complex modeling capacities through ASCR could provide valuable predictions as to the potential impacts of climate engineering without the risks of large scale field testing. **Therefore, it is the opinion of the Chair that the expertise and the high-end computing facilities overseen by the Advanced Scientific Computing Research (ASCR) program, or other comparable high-performance computing tools, should be used to model the impacts of climate engineering before field testing is performed.**

Other Research Activities at DOE

Office of Energy Efficiency and Renewable Energy

The Office of Energy Efficiency and Renewable Energy (EERE) is responsible for working with industry and other stakeholders to advance a diverse supply of energy efficient and clean energy technologies and practices, through research in areas such as wind and solar energy generation and advanced vehicle technologies. In contrast to the basic research activities in the Office of Science's BER

[26] For example, the objective of the Energy Frontier Research Center located at Lawrence Berkeley National Laboratory is to establish the scientific foundations for the geological storage of carbon dioxide. For more information see the Energy Frontier Research Center website <*http://www.er.doe.gov/bes/EFRC/CENTERS/NCGC/efrc_NCGC.html*>.

[27] DAVID A. RANDALL, ON A CLOUDY DAY—THE ROLE OF CLOUDS IN GLOBAL CLIMATE (Colorado State University) (2007). Available at <*http://www.scidac.gov/climate/climate.html*>.

program, the Biomass Program within EERE represents the application side of DOE's biomass efforts, consolidating research on biomass feedstocks and conversion technologies, biofuels, bioproducts, and biopower. The Program works closely with BER and in coordination with the USDA to translate basic scientific information to deployable and commercializeable technologies. In this way, the Biomass Program could inform land and biological-based strategies by drawing on its collective expertise on biochar and biomass-related carbon sinks and releases from land use changes. For example, the Biomass Program examines how biomass is converted to both biochar (solid) and bio-oil (liquid) by heating it in the absence of air, a conversion technology process called pyrolysis. Biochar may have potential as an efficient method of atmospheric carbon removal, via plant growth, for storage in soil. Biochar is a stable charcoal-solid that is rich in carbon content, and thus can potentially be used to lock significant amounts of carbon in the soil. The bio-oil can be converted to a biofuel after an additional, costly conversion process. The Biomass Program focuses on how to reduce costs of the conversion process and how to manipulate product ratios for more or less bio-oil and biochar. Additionally, the Biomass Program has funded joint research with the EPA and USDA to develop quantitative models of international land use changes associated with increased biofuel production, including life-cycle analyses. These types of activities would help in determining the life-cycle carbon impacts of large scale biomass production.

Office of Fossil Energy

The Office of Fossil (FE) seeks to develop technologies to enhance the clean use of domestic fossil fuels, reduce emissions from fossil-fueled power plants, and maintain secure and reasonably priced fossil energy supplies. FE's mission is supported by research activities at the National Energy Technology Lab (NETL), which has sites in five U.S. cities.

Through the Office of Fossil Energy and in part, the National Labs, DOE has spent a number of years on near- and long-term strategies to accelerate research, development, and demonstration of carbon capture from fossil-fueled power plants and geologic storage in deep saline aquifers, depleted oil and gas fields, and sedimentary formations. Its activities have included the Clean Coal power Initiative, FutureGen, the Innovations for Existing Plants Program, the Advanced Integrated Gasification Combined Cycle (IGCC) Program, and the Carbon Sequestration Regional Partnerships. DOE has also represented the United States in international research consortia on CCS such as the Carbon Sequestration Leadership Forum (CSLF). The CSLF is comprised of 24 member countries and the European Commission, and is organized by DOE. The purpose of the CSLF is, through international cooperation, to facilitate CCS technology development, and to overcome technical, economic, environmental, regulatory, and financial obstacles.

The climate engineering strategy of air capture, by comparison, captures carbon dioxide directly from ambient air rather than from a point source like the flue gas stream of a coal-fired power plant. The captured gases could be stored in "alternative" geologic formations such as basalt sands, in formations under the oceans, or con-

verted to different products altogether. The existing skill sets and resources at DOE could readily translate to research on air capture and unconventional sequestration. In fact, NETL has already awarded grant funding to explore the options for carbon storage in alternative materials for "beneficial reuse," such as a concrete, rather than storage in the more commonly suggested depleted oil fields and sedimentary geologic formations.[28] **Therefore, it is the opinion of the Chair that the Department of Energy (DOE) should lead any federal research program into air capture and non-traditional carbon sequestration.**

> *"Because of the similarities with CCS, it makes some sense to augment current research by DOE's Fossil Energy program in CCS to include separation technology related to air capture of CO_2. There are technical synergies in the chemical engineering of these processes and the researchers are in some cases the same. The research is complementary. The governance issues related to geologic storage are exactly the same."*
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> —Dr. Jane Long, Geoengineering III: Domestic and International Research Governance (hearing testimony) (2010).

National Aeronautics and Space Administration

The National Aeronautics and Space Administration (NASA) houses robust airborne and satellite-based environmental monitoring capacities and facilities devoted to studying geologic and atmospheric conditions. In addition, NASA employs to high-performance modeling tools that could support climate engineering research.

Earth Science Division

NASA's Earth Science Division, under its Science Mission Directorate, is responsible for advancing understanding of the earth's systems and demonstrating new technologies and capabilities through research and development of environmental satellites. The Earth Science Division measures climate variability through various satellite and airborne missions and performs basic research and advanced modeling of earth's systems.[29] The tools and expertise located within the Earth Science Division could inform any number of climate engineering applications through modeling, observing, and analyzing land use and atmospheric change to attempt to predict, and ultimately monitor, the impacts of large scale testing and deployment of such climate engineering applications.

Satellites

The Earth Science Division operates a set of coordinated satellites that could contribute to climate engineering research in a number of ways. These satellites record perturbations in a variety of earth systems, including the land surface, biosphere, sea ice, atmosphere, and oceans. These measurements help construct a de-

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[28] Winning projects were announced on July 22, 2010 and will receive funding via the American Reinvestment and Recovery Act (ARRA). *See <http://fossil.energy.gov/recovery/projects/beneficial_reuse.html>.*

[29] *See* NATIONAL AERONAUTICS AND SPACE ADMINISTRATION, RESPONDING TO THE CHALLENGE OF CLIMATE OF ENVIRONMENTAL CHANGE: NASA'S PLAN FOR A CLIMATE-CENTRIC ARCHITECTURE FOR EARTH OBSERVATIONS AND APPLICATIONS FROM SPACE (2010). *Available at <http://science.nasa.gov/earth-science/>.*

tailed picture of global change, especially when augmented by land- and ocean-based data from other sources. In addition, some of these missions involve international partnerships, which, in the case of deployment of climate engineering applications, would likely be necessary to ensure global coverage in monitoring. Two currently operating satellites systems and one being planned for launch are profiled as examples below. A host of other NASA observing data and instruments may be useful for informing climate engineering strategies. Ultimately, the chosen climate engineering strategy would determine the specific requirements of the space-based system intended to monitor its effects.

Stratospheric Aerosol and Gas Experiment

First launched in 1979, the Stratospheric Aerosol and Gas Experiment (SAGE) series, which measures changes in the ozone layer and the presence of aerosols in the atmosphere. SAGE I measured sunlight absorption from 1979–1981. Launched in 1984, SAGE II provided information about the ozone layer and atmospheric water vapor for over twenty-one years. SAGE III was launched in 2001 and provided information on ozone and the presence of water vapor and aerosols in the atmosphere. It was terminated in 2006 due to loss of communication with the satellite. At the first Committee hearing, Dr. Alan Robock noted in his testimony:

> While the current climate observing system can do a fairly good job of measuring temperature, precipitation, and other weather elements, we currently have no system to measure clouds of particles in the stratosphere. After the 1991 Pinatubo eruption, observations with the SAGE II instrument . . . showed how the aerosols spread, but it is no longer operating. To be able to measure the vertical distribution of the aerosols, a limb-scanning design, such as that of SAGE II, is optimal.

As volcanic eruptions can serve as a natural analog for stratospheric injections, careful monitoring of major eruptions through satellites could greatly inform certain SRM strategies.[30] Marine cloud whitening and stratospheric injections strategies would also require robust information on atmospheric particles and aerosol movement and distribution. Many experts have argued that the U.S. research and monitoring infrastructure on the behavior of atmospheric particles would require significant improvement to sufficiently inform climate engineering. For these reasons instruments for measuring atmospheric aerosols would be critical to a climate engineering research program, in particular for the atmosphere-based strategies.[31]

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[30] Committee witness, Dr. Granger Morgan, equated volcanic eruptions to "natural SRM experiments." *See Geoengineering III: Domestic and International Research Governance Hearing Before the House of Representatives Committee on Science and Technology*, 111th Cong. (2010) (Granger Morgan Written Testimony).

[31] NASA has begun plans to refurbish SAGE III with the President's Fiscal Year 2011 budget request. Its launch date goal is as early as late 2014. *See* NASA, RESPONDING TO THE CHALLENGE OF CLIMATE AND ENVIRONMENTAL CHANGE: NASA'S PLAN FOR A CLIMATE-CENTRIC ARCHITECTURE FOR EARTH OBSERVATIONS AND APPLICATIONS FROM SPACE (2010). *Available at <http://science.nasa.gov/earth-science/>.*

Landsat

Landsat is a series of seven satellites constructed by NASA and operated by the U.S. Geological Survey (USGS). The first satellite was launched in the early 1970s to collect spectral information from the earth's surface. The program has since produced an archive of over thirty-seven years of uninterrupted data on land cover, making it the world's oldest continuous record of global imagery.[32] This information, taken at a spatial resolution of just 30 m units, can be used in comparison with local and regional climate data to determine the impacts of specific land use changes on temperature, precipitation, evapotranspiration, and reflectivity. In this manner Landsat could be used for researching and monitoring land-based geoengineering strategies, such as aggressive afforestation and reforestation and reflective crops. In fact, Brazil already leads a forest carbon tracking program largely based on Landsat data. However, at present only two satellites, Landsat-5 and Landsat-7, launched in 1984 and 1999 respectively, continue to supply imagery, and have already outlived their projected lifespans. In anticipation of service interruption, NASA and USGS are developing a follow-on satellite as part of the Landsat Data Continuity Mission (LDCM), and hope to launch it in late 2012.[33] Success of the LDCM is critical to maintaining data continuity of moderate resolution remote sensing imagery.

The Orbiting Carbon Observatory *Several experts have noted the role that Orbiting Carbon Observatory (OCO) might have played in researching topics related to climate engineering. The project, initiated in NASA's Earth System Science Pathfinder Program, was intended to take precise space-based measurements of the carbon concentrations in Earth's atmosphere and improve understanding of the processes that regulate atmospheric* CO_2*. However, a launch-related failure caused the OCO to crash into the Pacific Ocean upon launch in February 2009. This data could have informed the effectiveness of any CDR strategy. This capability could be realized again if NASA successfully launches and deploys its second version of the satellite by 2013, as planned.*

MODIS

Data collected by the Moderate Resolution Imaging Spectroradiometer (MODIS) instrument is an example of how NASA could inform ocean-based climate engineering strategies. Launched in 1999 on board the Terra Satellite, and in 2002 on the Aqua satellite, MODIS instruments work in-tandem to record changes occurring on land, in the oceans, the lower atmosphere, and the water cycle. MODIS' ocean color sensing capabilities could be used to identify the growth and motion of carbon-consuming plankton, which is purported to be stimulated by the inputs of iron or other chemicals into ocean waters. MODIS can measure carbon levels on land, as well, by recording the levels of photosynthesis conducted by plants. MODIS also records measurements on sea surface height and temperature that could monitor the effectiveness of a strategy once it has been deployed. It records data on cloud type, the percentage of the earth's surface that is covered by

[32] The data continuity of Landsat is required by law. 15 U.S.C. § 5601 *et seq*.
[33] CARL E. BEHRENS, LANDSAT AND THE DATA CONTINUITY MISSION p.4 (U.S. Congressional Research Service) (2010).

clouds on a given day, and the amounts of aerosols present in the troposphere. In fact, the MODIS instruments on both Terra and Aqua were key to distinguishing clouds from the ash plume created by 2010 eruption of the Eyjafjallajökull volcano in Iceland.[34] Each of these capacities would be pertinent to one or more strategies, most notably marine cloud whitening and stratospheric injections.

Landsats 5 and 7, Terra and Aqua are among the 13 monitoring satellites NASA has in operation, and an additional 20 satellites, including OCO–2, are being planned as of July 19, 2010. NASA's existing satellite-based information could not only help increase understanding of global processes and feedback, but could also provide the long-term data sets needed to identify the "fingerprints" of human activity, both unintentional and intentional. **The Chairman recommends that the National Aeronautics and Space Administration's (NASA) previously collected earth systems data and its future observations of any relevant naturally occurring environmental event, such as volcanic eruptions, be integrated as appropriate into any comprehensive federal climate engineering research program.**

Basic Research and Modeling

Complementing the satellite portfolio, NASA's Earth Science Research program supports a variety of climate engineering-relevant research activities, including carbon cycling, global climate and environmental models, ozone trends, and biogeochemistry. The Earth Science Division also supports high-end computing capabilities, in particular through the Ames Research Center and Goddard Space Flight Center. In June 2010 the Goddard Space Flight Center introduced its NASA Center for Climate Simulation (NCCS), which more than doubles the computing capacity at Goddard and will provide visualization and data interaction technologies for climate prediction and modeling elements of the biosphere such as ice cover. The Goddard Institute for Space Studies (GISS) is the research center housing NASA's primary climate modeling and research capabilities, including general circulation models (GCMs) that study the potential for humans to impact the climate. Computing modeling capacities at the Goddard Institute for Space Studies have already been used to carry out simulations of sulfate aerosols at different various altitudes and latitudes in the atmosphere through climate modeling grants.[35] Researchers at GISS also perform data analysis on key climate information that could eventually inform the effectiveness of climate engineering applications. In the last year, for example, GISS has launched at least two new research campaigns on the behavior of aerosols in the atmosphere,[36] which may help inform the scientific theory behind atmosphere-based climate engineering. Basic climate research, modeling, and computing

[34] *Mitigating the Impact of Volcanic Ash Clouds on Aviation—What Do We Need to Know? Hearing Before the House of Representatives Committee on Science and Technology Subcommittee on Space and Aeronautics*, 111th Cong. (2010) (Jack Kaye Testimony).

[35] Philip J. Rasch et al., *An overview of Geoengineering of Climate Using Stratospheric Sulphate Aerosols*, 366 PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A p.4007 (2008).

[36] *See for e.g.* NASA's Goddard Institute for Space Studies (GISS) research initiative on carbonaceous aerosols, which is contributing to the U.S. Department of Energy's larger Carbonaceous Aerosol and Radiation Effects Study (CARES) campaign. *Available at <http://www.giss.nasa.gov/research/news/20100701/>.*

at NASA could contribute in a number of ways to a federal climate engineering research program.

Adaptive Management and Complex Missions

NASA scientists and engineers may also be uniquely suited to research some climate engineering applications due to an institutional capacity for complex, technical missions and highly adaptive design capabilities. Space-based applications at NASA are original designs, developed to fulfill specific, and often changing, mission objectives. For this reason NASA has a unique capacity for risk assessment, managing complex operating environments and accommodating significant unknowns. As Dr. Jane Long noted in her testimony, these skills, known as "adaptive management," would be critical to modifying a complex, non-linear system, such as the climate, successfully.[37]

Environmental Protection Agency

As the federal body responsible for protecting human health and safeguarding the natural environment, including air quality, water quality, soils, and biodiversity, the Environmental Protection Agency (EPA) would be needed to regulate many of the proposed climate engineering activities if tested or deployed. The Agency also contains a broad set of research capacities that could contribute to the scientific foundation of climate engineering. The Office of Research and Development (ORD), one of EPA's twelve headquartered offices, serves as the Agency's primary research arm to inform a variety of environmental topics, such as nanotechnology and global climate change, as well as risk assessment, risk management and region-specific technical support. Contained within ORD are seven Research Fields:

- National Center for Environmental Assessment (NCEA)
- National Center for Environmental Research (NCER)
- National Center for Computational Toxicology (NCCT)
- National Homeland Security Research Center (NHSRT)
- National Risk Management Research Laboratory (NRMRL)
- National Exposure Research Laboratory (NERL)
- National Health and Environmental Effects Research Laboratory (NHEERL)

The information gathered and synthesized at ORD provides the scientific foundation for the other EPA program offices, such as Office of Air and Radiation, to most appropriately regulate activities that impact the environment.

ORD's research on potential climate engineering activities could inform EPA's position on which strategies have unacceptable environmental risks, how specific strategies are likely to impact natural resources, and the potential consequences to human health. **It is the opinion of the Chair that as the Environmental Protection Agency's (EPA) steward of basic research, the Office of**

[37] *Geoengineering III: Domestic and International Research Governance Hearing Before the House of Representatives Committee on Science and Technology*, 111th Cong. (2010) (Jane Long Testimony).

Research and Development (ORD) should be a partner in any climate engineering research program.

National Center for Environmental Economics

The National Center for Environmental Economics (NCEE) within EPA's Office of Policy, Economics and Innovation (OPEI) is responsible for developing cost-benefit analyses of environmental policies and their secondary impacts. NCEE releases journal articles, Environmental Economics reports, and research papers to compare costs and assess risks in specific cases, such as the effects of acidic air pollutants on crop yields. Such analysis could be used to compare climate engineering strategies and provide an economic baseline to help determine which strategies appear economically undesirable in comparison with traditional mitigation strategies. Tools such as those within NCEE may also be particularly important with regards to those climate engineering strategies where financial cost is not a significant consideration when compared to alternatives. Stratospheric aerosols, for example, are expected to be deployable at a relatively low direct cost. However, their indirect economic impacts, such as changes to natural resources and the productivity of solar power arrays, could far outweigh the immediate expense of deployment. NCEE could analyze and report on the potential secondary costs of climate engineering in order to properly incorporate them in objective economic cost-benefit analyses. NCEE could also provide useful risk assessment information and identify avenues to link climate engineering to the social sciences.

Early Regulatory Needs

Outside of its potential contributions to the basic research needs associated with climate engineering, EPA may also be needed to explore the regulatory needs and options as the science develops. At this time the Agency is finalizing its rules on carbon sequestration in underground geological formations, via its authority under the Safe Drinking Water Act (SDWA). In developing these regulations EPA has sought to use the best science in order to perform risk assessments and identify and qualify the events that might endanger drinking water safety and human health, such as the potential for contaminant leakage. If climate engineering deployment becomes a more serious option, EPA should stay abreast of the evolving science and be prepared with the most appropriate regulatory options. Furthermore, EPA may be needed to regulate research in the case of large-scale field tests. One common concern about climate engineering research is that because the climate system is so complex and interconnected, for field testing to be useful, it would have to be conducted at near-deployment scale to fully determine a strategy's effectiveness and secondary impacts. While overly-restrictive regulations that unnecessarily hinder our ability to inform the risks and opportunities of climate engineering should be avoided, some proposed field research activities could have meaningful impacts on our ecosystems. In the interest of protecting human health and natural resources, EPA may be needed to apply existing

regulations or develop frameworks for new regulations should large-scale field testing commence.

U.S. Department of Agriculture

The United States Department of Agriculture's (USDA) ability to monitor and research land use change, agriculture practices, forestry, and biological sequestration could be informative to a range of climate engineering strategies. The USDA is broken into several sub-agencies based on program missions, and of these, the Agricultural Research Service houses a number of relevant tools and skill sets, along with the U.S. Forest Service and the Economic Research Service.

Agricultural Research Service

The Agricultural Research Service (ARS) is the USDA's primary research arm and is responsible for, among other activities, exploring the interaction of agriculture and the environment. Its activities are organized into National Programs (NPs) that focus on specific topics, and several of the active NPs have clear relationships to climate engineering, such as Soil Resource Management, Air Quality; Global Change; Integrated Agricultural Systems; and Climate Change, Soils and Emissions.

The Bioenergy NP, for example, is the USDA initiative primarily responsible for research on the production and use of biochar and bioenergy. As described earlier in the section on Department of Energy activities, biochar, a charcoal produced from carbon-rich organic materials, could be developed and deployed as a biological climate engineering strategy. Biochar may be used for several purposes: to produce energy, to produce soil fertilizers, and simply to biologically sequester carbon from the atmosphere. USDA, along with DOE, has been responsible for the bulk of research on biochar feedstocks and land issues at the federal level, and could use its expertise to inform scientific research and biomass related strategies. It is to be noted that while the USDA and DOE have done significant research on biochar, it has been in pursuit of beneficial soil amendments and/or bio-oil, which can be used for fuel, with a lesser focus on carbon sequestration goals. The USDA has not examined in detail the singular goal of using biochar to achieve climate engineering-scale changes in atmospheric carbon levels. Biological or land-based strategies would likely be needed over vast parcels of land, perhaps millions of acres,[38] in order to be effective. Biochar deployment activities at this scale would entail considerable economic challenges. The USDA's Economic Research Service, described below, has the skill set to inform the economic viability of biochar at a climate engineering scale.

The potential contributions of ARS extend beyond understanding the impacts of land-based climate engineering strategies. Atmosphere-based strategies for increasing global albedo would purportedly control temperature increases that could be harmful to agriculture and forest growth, at least for some period of time. How-

[38] *Geoengineering II: The Scientific Basis and Engineering Challenges Hearing Before the House of Representatives Committee on Science and Technology Subcommittee on Energy and Environment*, 111th Cong. (2010) (Robert Jackson Testimony).

ever, reflecting 1–2% of incoming solar radiation, as most SRM strategies recommend, may also be detrimental to plant growth. All plants require sunlight for photosynthesis to grow and reproduce, so a decrease in direct sunlight could negatively impact crop yields. In addition, it remains unclear how chemical inputs to the atmosphere could affect plant growth and soils. Atmospheric modeling suggests that particles injected into the stratosphere, such as sulfates and salts, would eventually fall into the troposphere and "rain out" onto land and water surfaces below. In sufficient quantities, these materials could have negative impacts on both existing plants and soil content. Both to protect the livelihood of farmers and to protect the health of food sources and ecosystems in general, ARS could help predict and quantify the extent of these negative impacts on land and water and provide a valuable contribution to the overall risk analysis of climate engineering.

U.S. Forest Service

The U.S. Forest Service, which manages the 155 U.S. national forests and 20 U.S. national grasslands, since 1905 has maintained its own Research and Development organization. The R&D branch collaborates closely with the ARS, and its more than 500 researchers study, among other topics: forest and grassland health, sustainable forest management, invasive species, aquatic ecosystems, tree growth and mortality, and forest inventories. The institutional knowledge and management skills within the R&D branch could be used to inform aggressive afforestation and reforestation strategies, both by issuing projections on how effective a strategy might be and also for identifying key risks associated with climate engineering-scale forest management. For example, its Invasive Species Research Program develops tools to predict and prevent the introduction of invasive species. Modification to plant growth at a large-scale, in particular via monoculture cropping, can make an area particularly susceptible to damage from non-native and invasive insects or plants. A research program on man-made forests for carbon storage or reflective grasses intended to increase local albedo, might benefit from such expertise.

Forest Service R&D also performs a wide variety of research activities on the sequestration capacity of soils, vegetation, and forests. Additional research is conducted to inform our understanding of how soil capacity will change over time with the climate. Higher atmospheric carbon levels and changes in the earth's water cycles caused by climate change may make the sequestration potential of plant growth better or worse, and at a very large scale, these potential fluctuations could significantly alter the impacts of carbon-sensitive land management. Furthermore, resource specialists in the Forest Service work with the Economic Research Service to explore land use competition and prioritize uses for economical and environmental activities. Such analysis could be important because of the economic pressure these activities will put on natural resources.

In addition, the U.S. Forest Service recently established a National Roadmap for Responding to Climate Change to guide forest managers in implementing the USDA climate change strategy. The program details the potential of forests and soils to mitigate atmos-

pheric greenhouse gas concentration through biological storage. This information could ultimately inform forest management as part of a larger climate engineering program. In addition, while the Roadmap is intended for climate change mitigation and adaptation, and does not address climate engineering specifically, it proposes frameworks for a communication network with regional managers regarding short- and long-term goals and best practices, plans for public education and outreach, and thorough coordination with other agencies and groups. The plan's emphasis on adaptation needs and a communications strategy is somewhat unique to current federal climate change efforts. These elements would augment any large-scale climate engineering effort, and, as such, the Forest Service Roadmap may be a valuable model for coordinating activities to educate land managers on climate engineering-scale forestry and biological sequestration.

Economic Research Service

The USDA's Economic Research Service (ERS) informs public and private decision-making on economic issues related to agriculture and natural resources. This resource could be adapted to assess the economic viability of biological climate engineering activities. Any strategy would alter and create competition for natural resources.

> *"Biological and land-based geoengineering alters carbon uptake, sunlight absorption, and other biophysical factors that affect climate together. Geoengineering for carbon or climate will alter the abundance of water, biodiversity, and other things we value."*
>
> —Dr. Robert Jackson, Geoengineering II: The Scientific Basis and Engineering Challenges (written hearing testimony) (2010).

For example, large-scale afforestation could require a significant input of water, so benefits such as air quality and decreases in atmospheric carbon concentrations would be balanced against greater competition for local water resources that could be needed for other uses. Similarly, since certain strategies could be particularly land-intensive, climate engineering could cause added competition for land use. The ERS, which employs both economists and social scientists to conduct its research, may be needed to explore potential trade-offs and inform how a land-based strategy could be economically viable. The ERS also conducts research on financial instruments, such as tax credits, that might encourage private landowners to undertake specific climate engineering strategies, such as distributed carbon management activities.[39]

Other Federal Agencies

A number of other federal agencies have capacities that could inform climate engineering research.

The **Department of Defense (DoD)** has significant expertise and experience in relevant areas such as large-scale engineering projects and airborne missions. Several experts recommend that

[39] *See for e.g.* JAN LEWANDROWSKI ET AL., ECONOMICS OF SEQUESTERING CARBON IN THE U.S. AGRICULTURAL SECTOR (U.S. Department of Agriculture—Economic Research Service) (2004). *Available at <http://ssrn.com/abstract=552724>.*

this knowledge-base could complement climate engineering-specific programs. However, it should be noted that given the lack of transparency of defense research and programs, leveraging the capabilities of DoD could result in an adverse impact on the goal of public engagement and education on the issue of climate engineering. **It is the opinion of the Chair that if the Department of Defense's (DoD) expertise were to be engaged in a national climate engineering research strategy, special attention must be paid to public engagement and transparency, and all research efforts must be committed solely to peaceful purposes.**

The **U.S. Geological Survey (USGS)**, within the Department of the Interior, would also have a role in research on land- and bio-based climate engineering strategies. The diverse USGS team, which includes geoscientists, biologists, chemists, geographers, hydrologists, statisticians, and ecologists, supports a breadth of scientific research, monitoring, and analysis. For example, the USGS conducts programs to detect, monitor, and control invasive species, catalogue land use and the impacts of land use change, and examine the biological, chemical, and environmental factors affecting water quality. In addition to its contributions to joint research and satellite monitoring programs such as Landsat, USGS has unique remote sensing capabilities that provide data on natural resources and how they are affected by change. These data sets, such as those managed through the USGS' National Satellite Land Remote Sensing Data Archive, can work in concert with "ground-truthing" data gathered by researchers within the agency or outside groups. The USGS also has institutional expertise in basic science and monitoring capacities to augment carbon mineralization research. Recently USGS established a methodology to define and map a comprehensive inventory of underground pore space in the U.S. that could be used for mineral sequestration of carbon, such as basalt sands.

Furthermore, some strategies call for the distribution of certain chemicals over land or oceans to stimulate processes that consume carbon, either by mineralizing the carbon into a solid through chemical reactions, by stimulating the growth of carbon-consuming organisms, or by increasing the ocean's capacity to store CO_2. The USGS maintains the federal government's most comprehensive commodities survey on mineral resources, and may be needed to inform the available quantities and ease of access to specific materials, if any of these mineral distribution strategies are deemed to be scientifically plausible. In addition, if climate engineering were ultimately deployed, the USGS would be needed to monitor program impacts on natural resources. The USGS maintains a commitment to scientific integrity and the sharing of information freely with the public.[40] Objective and transparent science will be especially critical for identifying and analyzing negative and unintended consequences on ecosystems that may emerge if climate engineering is deployed.

[40] U.S. GEOLOGICAL SURVEY, FUNDAMENTAL SCIENCE PRACTICES (2006). *Available at <http://www.usgs.gov/usgs-manual/500/502-1.html>.*

The **U.S. Department of State** is the best equipped federal body to facilitate an international forum for guiding research and regulation and pursuing intergovernmental consensuses as the discipline develops. The State Department coordinates cooperative research between the United States and other nations, represents the U.S. in international climate negotiations, and also acts as the official point of contact to the Intergovernmental Panel on Climate Change (IPCC). Furthermore, the United States Agency for International Development (USAID), a division of the State Department, contributes funding to the U.S. Global Change Research Program (USGCRP). While basic research activities within U.S. federal agencies may not require participation from the State Department, the potential impacts of climate engineering are necessarily international in scale. Those strategies that would result in transboundary impacts, such as changes in monsoon patterns and sunlight availability, would necessitate international coordination and governance at an early stage. If the United States were to formalize research activities on climate engineering, complementary international discussions on regulatory frameworks would be required.

ORGANIZATIONAL MODELS

As noted above, there is growing consensus that a comprehensive climate engineering research strategy would require the engagement of a wide range of disciplines, and would likely call for an interagency initiative to coordinate research activities and findings. Several models and lessons on interagency coordination are profiled below. However, any attempt to field test or deploy large scale climate engineering would likely require coordination at far greater scales and with international partners.

> *"In my opinion before a nation (or the world) ever decided to deploy a full-scale geoengineering project . . . it would require an enormous activity, equivalent to that presently occurring within the modeling and assessment activities associated with the Intergovernmental Panel on Climate Change (IPCC) activities, or a Manhattan Project, or both. It would involve hundreds or thousands of scientists and engineers and require the involvement of politicians, ethicists, social scientists, and possibly the military."*
>
> —Dr. Philip Rasch, Geoengineering II: The Scientific Basis and Engineering Challenges (written hearing testimony) (2010).

Council on Environmental Quality

The White House Council on Environmental Quality (CEQ) coordinates Federal environmental efforts and works closely with agencies and other White House offices in the development of environmental policies and initiatives. The Council's Chairman also serves as the principal environmental advisor to the President. CEQ provides recommendations on comprehensive national environmental strategies to the President on specific issues, such as carbon capture and storage, Gulf Coast ecosystem restoration, and climate change adaptation. The CEQ also has a unique capacity to engage a range of stakeholders and balance the competing interests among federal agencies and state and local governments.

In pursuit of environmental goals on specific topics, CEQ may establish a task force and other comprehensive, interagency initiatives, when appropriate. For example, in June 2009 the President distributed a memorandum to the leaders of executive departments and federal agencies establishing an Interagency Ocean Policy Task force, to be led by CEQ. This Task Force is charged with developing recommendations over several government agencies on how to enhance ocean stewardship and resource use. The Task Force has since released interim reports, containing recommendations on ocean governance and interagency coordination, and received comments from a wide variety of stakeholders. As the national and international discussion advances, it may be helpful for CEQ to explore options for a similarly-structured body that will provide a forum for stakeholder input and early, foundational coordination between agencies.

Office of Science and Technology Policy

The White House Office of Science and Technology Policy (OSTP), established in 1976, advises the President on broad science and technology issues, provides scientific assessments to inform Executive Branch policies, and coordinates scientific and technical work within the Executive Branch. In order to accomplish this broad mission, OSTP often hosts public and private sector summits, issues reports, coordinates activities within existing Committees and interagency bodies, and publicizes work conducted by federal bodies. OSTP is divided into four divisions—Science, Technology, Energy & Environment, and National Security & International Affairs—each of which could be instrumental in coordinating early-stage climate engineering research. Two initiatives under OSTP in the last few years may be useful models for structuring a federal research program. The National Nanotechnology Initiative, profiled below, and the Networking Information Technology Research and Development (NITR–D) program are both of examples of interagency entities established to address complex and interdisciplinary emerging technologies.

The OSTP also serves as co-chair of the President's Council of Advisors on Science and Technology (PCAST), a council of independent experts that provide advice to the President. Established in 2001, PCAST consists of 35 individuals drawn from industry, academia, and other nongovernment organizations, as well as the Director of the OSTP. The Council receives information from the private and academic sectors on a variety of issues in science and technology and prepares recommendations on specific topics, most often at the President's request. While its efficacy and influence is somewhat fluid and may change over different Presidential administrations, PCAST has experience guiding policy on nascent technologies. PCAST may be needed to provide the President with reliable and independent assessments of how federal policy should best regulate climate engineering research.

U.S. Global Change Research Program

The U.S. Global Change Research Program (USGCRP), initiated in 1989 and mandated by Congress in 1990, coordinates and inte-

grates federal research on changes in the global environment and impacts on the public.[41] The program is managed by the Committee on Environment and Natural Resources under OSTP. Thirteen federal departments and agencies participate in USGCRP, with the biggest contributions coming from DOE, NOAA, NASA and NSF. USGCRP's mission is to improve knowledge of earth's climate, environment, and natural and anthropogenic variability; to better understand the forces of change in earth's climate and related systems; to predict and reduce uncertainty in projections for climate change in the future; understand the sensitivity and adaptability of ecosystems and human systems to global change; and manage risks and opportunities related to global change. To support these goals the participating agencies coordinate their activities through ten Interagency Working Groups that address specific challenges of climate change. The multi-disciplinary, coordinated structure of the USGCRP makes it an appropriate model for, and possible steward of, climate engineering research.

One proposal for incorporating climate engineering into USGCRP's jurisdiction includes the creation of one or more new working groups exclusively focused on the strategies not otherwise informed by existing USGCRP activities. Another proposal is to accommodate climate engineering within existing working groups according to the key research needs associated with particular strategies. However, it has been noted that an evaluation of USGCRP's successes and challenges would be needed before attempting to incorporate another large, comprehensive agenda into this program. There has been some concern that introducing climate engineering into USGCRP's jurisdiction would draw resources and attention away from the primary Program mission of understanding, assessing, predicting and responding to climate change through mitigation and adaptation programs. However, it appears that a comprehensive interagency research agenda on climate engineering would call for participation from the same agencies in the USGCRP and would likely be managed under a similar structure.

U.S. Group on Earth Observations

The U.S. Group on Earth Observations (USGEO) is charged with developing, coordinating, and managing an integrated U.S. earth-observation system through ground, airborne, and satellite measurements. The group was established in 2005 under the National Science and Technology Council's Committee on Environment, Natural Resources, and Sustainability within the OSTP. USGEO is made up of representatives from 17 federal agencies with a role in earth observations,[42] and is co-chaired by representatives of OSTP, NOAA, and NASA. USGEO also supports the Global Earth Observation System of Systems (GEOSS), an international effort to share environmental data to support decision-making in nine societal

[41] Global Change Research Act, 15 U.S.C. § 2931 et seq. The USGCRP was known as the U.S. Climate Change Science Program (CCSP) between 2002 and 2008. Interagency climate research and technology activities have undergone several iterations over the last two years. *See generally* MICHAEL SIMPSON & JOHN JUSTUS, CLIMATE CHANGE: FEDERAL EXPENDITURES FOR SCIENCE AND TECHNOLOGY (U.S. Congressional Research Service) (2005).

[42] USGEO is comprised of all the agencies including the USGCRP, the Department of Homeland Security (DHS), Centers for Disease Control and Prevention (CDC), the Office of Management and Budget (OMB), and OSTP.

benefit areas. The goal of this initiative is to provide the overall conceptual framework needed to move toward globally-integrated earth observations. By 2009, seventy-nine countries, the European Commission and several dozen international organizations had joined the GEOSS, which will deliver detailed and verifiable climate data at local, regional, and global scales.

In several recent reports on the state of U.S. satellite systems, GAO identified some challenges for USGEO [43]—namely, that its required Strategic Assessment Report on opportunities and priorities for space observation has not yet been approved by the USGEO managers in OSTP, and as of July 2010 had not scheduled a date for releasing the final Report. The GAO expressed concern that the draft version of this report did not address costs, schedules or plans for long-term satellite data needs, and that even once the Strategic Report is finalized, it is not clear how the OSTP and Office of Management and Budget (OMB) will ensure the interagency strategy is consistent with the individual agencies' plans and budgets. These difficulties demonstrate that coordinating data sources between federal agencies, not to mention between several nations, requires careful planning and execution. Any successful inter-agency effort will require open and frequent communication, effective leadership, and a clear delineation of responsibilities.

National Nanotechnology Initiative

The United States' experience with nanotechnology research across federal agencies can provide valuable insight into a potential federal, interagency research initiative on climate engineering. Nanotechnology, the collective term for nano-scale science and technology applications, is a nascent field that is rapidly attracting public interest and investment around the world. In 2000, President Clinton launched the National Nanotechnology Initiative (NNI) to coordinate federal research and development on nanotechnology, and in 2003, Congress enacted the 21st Century Nanotechnology Research and Development Act [44] to provide a statutory foundation and organize the Initiative. The America COMPETES Reauthorization Act of 2010, which contains a number of amendments to NNI, was approved by the House in May 2010.[45]

While nanotechnology may eventually contribute revolutionary advances to any number of public goods, concerns have been raised about the potential negative impacts of nanotechnologies on human health and the environment.[46] For example, it has been proposed that the small size of nanoscale particles could allow them to penetrate and damage human organs, such as the lungs. In its June 2, 2010 report the Congressional Research Service (CRS) observed that public attitudes and perception of risks leaves the still-nascent

[43] *See* U.S. GOVERNMENT ACCOUNTABILITY OFFICE, ENVIRONMENTAL SATELLITES: PLANNING REQUIRED TO MITIGATE NEAR-TERM RISKS AND ENSURE LONG-TERM CONTINUITY (Publication No. GAO–10–858T) (2010) *and* U.S. GOVERNMENT ACCOUNTABILITY OFFICE, ENVIRONMENTAL SATELLITES: STRATEGY NEEDED TO SUSTAIN CRITICAL CLIMATE AND SPACE WEATHER MEASUREMENTS (Publication No. GAO–10–456) (2010).

[44] § 15 U.S.C. § 7501 *et seq*.

[45] H.R. 5116, 111th Cong. (2010). *Also see* H. REP. NO. 111–478.

[46] *See* JOHN F. SARGENT JR., NANOTECHNOLOGY: A POLICY PRIMER (U.S. Congressional Research Service) (2010).

nanotechnology industry and research community vulnerable to a negative event, such as an accidental or harmful release.

The NNI is comprised of thirteen federal agencies that conduct nanotechnology research and development and another twelve that would regulate and enable education and training on nanotechnology. In addition to conducting research and exploring regulatory issues related to the environmental, health and safety issues, the NNI also conducts public outreach activities through written materials, public meetings, a comprehensive website, and other educational resources to the public. NNI agencies also engage with international consortia such as the Organization for Economic Cooperation and Development (OECD) to address nano-safety issues. By recognizing that risks and impacts of nanotechnology must be better understood by key stakeholders, and that public acceptance is critical to realizing the full benefits it may ultimately bring to bear, NNI can serve as a model for what might be needed if climate engineering research is undertaken at the federal level.

It should also be noted that NNI has had an immense impact on global interest in nanotechnology. Before the U.S. initiated the NNI, nanotechnology research worldwide was generally piecemeal and modest. Since the establishment of NNI, over sixty countries have initiated government-led nanotechnology programs. While a heightened profile for technology development and commercialization has been a positive development for nanotechnology, increased interest in climate engineering may introduce new risks, such as the possibility of unilateral deployment. The existence of a dedicated research program on the part of the U.S. or its partners might serve to legitimize efforts by other nations to act on their own.

Lastly, the NNI has had to address the fundamental question of what is included in the category of nanotechnology. Initially, federal agencies were unclear about what activities should be reported as nanotechnology, and which would instead qualify as chemistry or materials science research. The Office of Management and Budget identified explicit criteria on nanotechnology for the purposes of quantify funding levels for research. International standards for nanotechnology also continue to evolve; for five years the International Standards Organization has been working to identify core parameters. Climate engineering would be faced with a similar challenge. There is no clear consensus as to which strategies constitute climate engineering, and for what purposes the category must be defined. For instance, for the purpose of developing regulations and restrictions, the term could be used to apply to a smaller set of higher-risk strategies than might otherwise be included for the purpose of developing a broad interagency research effort. If research were initiated and coordinated at the federal level, a more consistent vocabulary that takes into consideration the gaps in funding, research, risk assessment, and governance would be required.

National Academy of Public Administration

The National Academy of Public Administration (NAPA) is a non-profit and non-partisan coalition of management and organizational experts chartered by Congress to improve the effectiveness

of public programs. NAPA was established in 1967 and advises federal agencies, Congress, state and local governments, academia, and various foundations on how to manage the structure, administration, operation and performance of existing programs and helps identify potential emerging management challenges. NAPA also assesses the proposed effectiveness, structure, administration, and implications for proposed public programs, policies, and processes and recommends specific changes to improve the proposed program. The NAPA coalition of experts is comprised of several hundred Fellows with robust and varied management experience, including former members of Congress, governors and mayors, business executives, foundation executives, and academia.

NAPA carries out activities both at its own discretion and by Congressional request. For example, NAPA recently completed a congressionally mandated study[47] on structuring a NOAA Climate Service.[48] A Climate Service would coordinate and distribute climate change information gleaned from a variety of research programs and monitoring systems to aid the public and local, state, and federal decision makers. While the overall goal of a NOAA Climate Service is very different than a potential coordinated climate engineering research strategy, the two would share a number of key objectives and challenges. Both must gather information and expertise from a wide range of sources and organize and disseminate it in a consistent and usable format and both must leverage specific program office strengths and ensure stakeholder communication. NAPA has explored these topics in great detail, as well as how private, university, and non-governmental organizations might contribute to data holdings and communication efforts, how the proposed NOAA Climate Service would help support public understanding and inter-user dialogue, and how to increase usability of existing climate data. With its established format for exploring these considerations, as well as a robust body of work consisting of other relevant independent projects and publications, NAPA may be needed to study in greater depth the potential organizational tools and other useful model programs that could support and inform a climate engineering program.

GENERAL FINDINGS AND RECOMMENDATIONS

Immediacy

In *The Regulation of Geoengineering* report, the U.K. Committee recommended that serious consideration of the regulatory frameworks for climate engineering technologies start now, and not be delayed until either highly disruptive effects of climate change are observed or deployment of a climate engineering scheme is underway. Similarly, a robust understanding of the potential environmental impacts will be needed in advance of a "climate emergency" so that the most effective and risk-averse strategies are well understood. **It is the opinion of the Chair that broad consideration of comprehensive and multi-disciplinary climate engineer-**

[47] H. REP. NOS. 111–366 of P.L. 111–117 (2009).

[48] *See Expanding Climate Services at the National Oceanic and Atmospheric Administration (NOAA): Developing the National Climate Service Hearing Before the House of Representatives Committee on Science and Technology*, 111th Cong. (2009) (Hearing Charter).

ing research at the federal level begin as soon as possible in order to ensure scientific preparedness for future climate events.

Defining Climate Engineering

At this time, the definitional boundaries between some climate engineering strategies and traditional mitigation remain unclear. It is generally agreed that "climate engineering" or "geoengineering" implies a willful *intent* to produce meaningful impacts on the global climate.[49] In contrast, while human activities have already greatly impacted our global climate, they were not undertaken for that express purpose. However, what remains unclear is how activities should be distinguished from traditional mitigation and adaptation, and at what scale of application they amount to "climate engineering." Many of these activities are already being undertaken at smaller scales, whether or not for the express goal of reflecting solar radiation or absorbing greenhouse gases. For example, reforestation in pursuit of environmental and public goods, other than carbon management, has existed for hundreds of years. Some experts argue that CDR strategies should not be designated as climate engineering because, like traditional mitigation, they seek to manage climate change by reducing atmospheric concentrations of greenhouse gases. Still others argue that CDR does belong in the category of climate engineering as it distracts from the primary goal of mitigation through emissions reductions. As climate engineering will likely remain a controversial topic, the designation itself may provoke a negative public opinion or even inappropriately strict regulation on relatively low-risk strategies. A moratorium on all climate engineering "activities," for example, without an adequate scientific basis for what specific strategies and at what scales fall under this definition, could effectively ban low-risk and commonplace activities such as small-scale afforestation.

Furthermore, uncertainty about what research activities fall under the climate engineering umbrella may create challenges for agencies, Congress, and the Office of Management and Budget (OMB) in determining appropriate funding levels for these activities. When the United States first began to coordinate federal work on nanoscience and explore the aggregate of existing federal research, agencies were uncertain as to which activities could be classified as nanotechnology, and would often report their nano-scale research activities as materials science or basic chemistry. Only after OMB established explicit guidelines for what might fall under the umbrella of "nanotechnology" was there a clearer picture of existing capacities in the federal agencies. Certainly if climate engineering research is formally authorized by the federal government, a more certain definition will be required to help U.S. agencies, and ultimately the international community, identify their relevant research activities. The GAO's efforts to quantify existing federal efforts in its October 2010 report provide a useful foundation for this process.

[49] INNOVATIVE ENERGY STRATEGIES FOR CO_2 STABILIZATION p.412 (Robert G. Watts, ed., Cambridge University Press) (2002).

At this time, a consistent and comprehensive definition of climate engineering may not be feasible. For the purposes of organizing research, potential strategies should be considered on a case-by-case basis, accommodating the political, environmental, and social risks associated with them. Furthermore, as noted earlier and used throughout this report, the term "climate engineering" is a more appropriate tool for communicating the concept to policymakers and the public than "geoengineering." **It is the opinion of the Chair that there must ultimately be an international consensus on climate engineering terminology that will best communicate the strategies and desired effects to the scientific community, policy makers, and the public.**

In addition, there has been considerable discussion as to whether techniques designed for the purposes of altering specific weather event, rather than the larger climate, should fall under the definition of climate engineering. The express goal of weather modification techniques, such as cloud seeding, is to impact weather patterns, such as hurricane intensity and precipitation, on a geographically limited scale and with little or no lasting effectiveness. **It is the opinion of the Chair, and in agreement with the U.K. Committee,[50] that weather modification techniques such as cloud seeding should not be included within the definition of climate engineering.**

Defining a "Climate Emergency"

As previously noted, it is the opinion of the Chair that some SRM strategies such as stratospheric injections, if proven viable, should be reserved as an option of last resort to be used only in the case of a "climate emergency," and when other options have been exhausted. The majority of stakeholders appear to agree that climate engineering should not be considered an alternative to stringent emissions reductions, and, if deployed, SRM should be used only as a temporary measure. Experts predict that large-scale SRM methods, if prepared in advance, could be deployed very quickly and would exert a nearly immediate impact on global albedo. However, as the National Research Council notes in its report *America's Climate Choices: Advancing the Science of Climate Change*, if the intended strategy is to withhold SRM until a dangerous tipping point is imminent, there must be some collective understanding of what constitutes such a tipping point ahead of time. At this time there is no consensus on what events would constitute a "climate emergency," and there is much to consider about the complexity of the climate system, the potentially long timescales over which an emergency might occur, and the global tolerance of climate changes in defining the term.[51] Furthermore, because the impacts of climate engineering are not yet well-understood, it is not clear how a particular strategy might be used to offset specific impacts if a climate

[50] SCIENCE AND TECHNOLOGY COMMITTEE, UNITED KINGDOM HOUSE OF COMMONS, THE REGULATION OF GEOENGINEERING p.16 (Stationery Office Limited) (2010).

[51] DIVISION ON EARTH AND LIFE SCIENCES, NATIONAL RESEARCH COUNCIL, AMERICA'S CLIMATE CHOICES: ADVANCING THE SCIENCE OF CLIMATE CHANGE p.299 (National Academies Press) (2010).

emergency did arise.[52] **It is the opinion of the Chair that the global climate science and policy communities should work towards a consensus on what constitutes a "climate emergency" warranting deployment of SRM technologies.**

Categories of Climate Engineering

In *The Regulation of Geoengineering*,[53] the U.K. Committee recommended that because climate engineering as currently defined covers such a broad range of CDR and SRM technologies and techniques, any regulatory framework for climate engineering cannot be uniform. Similarly, the associated research needs vary greatly among the different suggested strategies. While general climate science information today could likely inform all climate engineering strategies, the anticipated ecological impacts and scientific basis for a particular strategy would require a unique and focused set of research priorities. Many CDR activities, for example, have a sizable scientific foundation from related research activities, while SRM has not been tested at any meaningful scale in the field or in a laboratory. The divergent and unique research needs for CDR and SRM must be accounted for when research activities are authorized in various federal agencies and program offices.

> *"[A] solar radiation management (SRM) R&D program should be organized separately from the air capture (AC) R&D program. Exploring SRM entails tasks that differ from those needed to explore AC. Disparate tasks demand disparate skills. Also, if research on AC were ever to be successful it might well devolve to the private sector; whereas, SRM is likely to remain under direct government control. Yoking together two such different efforts would be certain to impede the progress of both."*
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> —Mr. Lee Lane, Geoengineering: Assessing the Implications of Large-Scale Climate Intervention (responses to questions for the record) (2009).

Geographically Localized Climate Engineering

Several witnesses and outside academic experts have explored the possibility of climate engineering to address only geographically specific areas. This strategy is intended to protect specific environmental features that are particularly sensitive to climate change and/or pivotal elements of global sustainability. It has been suggested that localized climate engineering could offer more "bang for the buck," requiring a smaller, somewhat more controlled scale operation to produce appreciable positive impacts.

> ***Isolating the Ice Caps?*** *The impacts of climate change on the polar ice caps is of great concern, not only because melting will contribute to major sea level rises, threatening low-altitude coastal communities, but because the ice contains vast stores of frozen methane, a potent greenhouse gas. Melting could cause the release of huge quantities of methane, warming the climate further and encouraging dangerous feedback loops. Some scientists have suggested that SRM could be somewhat localized to help protect polar ice and to prevent such feedback loops.*

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[52] David Victor, et al., *The Geoengineering Option: A Last Resort Against Global Warming?*, March/April FOREIGN AFFAIRS p.5 (2009).

[53] SCIENCE AND TECHNOLOGY COMMITTEE, UNITED KINGDOM HOUSE OF COMMONS, THE REGULATION OF GEOENGINEERING p.16 (Stationery Office Limited) (2010).

However, as Dr. Shepherd of the Royal Society noted, "It would . . . be generally undesirable to attempt to localize SRM methods, because any localized radiative forcing would need to be proportionally larger to achieve the same global effect, and this is likely to induce modifications to normal spatial patterns of weather systems including winds, clouds, precipitation and ocean currents and upwelling patterns." [54]

At this time there is no consensus on the likelihood that geographically localized applications would work as desired and without unacceptable secondary consequences. However, models have suggested that while the global ecosystem is highly interconnected and no large-scale intervention can be isolated, the desired and unanticipated impacts of some strategies would be maximized at the location in which they are deployed.[55] **Therefore, it is the opinion of the Chair that a climate engineering research program should explore the unique range of possibilities and risks associated with geographically localized climate engineering. Furthermore, any proposed application of climate engineering to protect polar ice specifically should be reviewed by the Arctic Council, an intergovernmental forum representing the world's circumpolar nations.**

Space-Based Reflectors

One suggested climate engineering proposal entails placing large-scale sunlight deflectors in space to reduce the amount of solar energy reaching the earth. Some suggestions include a great number of reflective surfaces, mirrors, or light-colored materials, in a near-earth orbit, or a lesser number of reflectors positioned at the L–1 point, also referred to as a LaGrange point, where the gravitational attractions of the earth and sun are equal. Development and deployment costs of such strategies are projected to be extremely high, as they would require the development of new technologies likely much larger in scale and far more complex than any space program ever attempted.[56] For this reason project development and deployment is also estimated to take several decades, making it an unviable option for rapid deployment in an emergency situation. Also, solar applications represent potentially the most serious type of the "termination problem," in which the intentional or accidental termination of SRM activities could result in a rapid and potentially catastrophic increase in global temperatures unless strict, congruent controls on greenhouse gases had been undertaken while the solar applications were in effect. An international team of scientists recently reported that space-based reflectors would do little to combat rising sea levels, as sea levels respond slowly to changes

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[54] STAFF OF HOUSE OF REPRESENTATIVES COMMITTEE ON SCIENCE AND TECHNOLOGY, 111TH CONG., REPORT ON GEOENGINEERING: ASSESSING THE IMPLICATIONS OF A LARGE SCALE CLIMATE INTERVENTION HEARING (COMM. PRINT 2009).

[55] STAFF OF HOUSE OF REPRESENTATIVES COMMITTEE ON SCIENCE AND TECHNOLOGY, 111TH CONG., REPORT ON GEOENGINEERING II: THE SCIENTIFIC BASIS AND ENGINEERING CHALLENGES HEARING (COMM. PRINT 2010).

[56] *See* JOHN SHEPHERD ET AL., GEOENGINEERING THE CLIMATE: SCIENCE, GOVERNANCE AND UNCERTAINTY p.34 (THE U.K. ROYAL SOCIETY) (2009).

in the earth's atmosphere.[57] Furthermore, like all SRM strategies, space-based reflectors would do nothing to address the problem of ocean acidification.

In addition, there is considerable agreement among climate engineering experts and international policy analysts that deployment of space-based reflectors would introduce an extremely precipitous geopolitical scenario. Space-based applications would likely have considerable impacts on all earth systems, including effects on precipitation patterns and agricultural yields. However, the system would likely be controlled by a single, technologically-sophisticated group. In such a scenario a host of legal issues would arise regarding the negative environmental changes caused, or perceived to be caused, by the reflectors.[58] This scenario would complicate both public acceptance and international agreement on how such a project should be undertaken, and run counter to the U.K. and U.S. Committees' objectives of forming sufficient international consensus and giving equitable consideration to third world interests. **Therefore, it is the opinion of the Chair that due to high projected costs, technological infeasibility and unacceptable environmental and political risks, the solar radiation management (SRM) strategy of space-based mirrors should be a low priority consideration for research.**

> ***Mirrors in Space*** *"The space sunshade concept is an unappealing approach to SRM. It offers few benefits that might not be achieved at vastly lower costs with other SRM techniques, and the very large up-front infrastructure costs would simply be so much waste if the project were to be fail or be abandoned for any reason."*
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> —Dr. Lee Lane, Geoengineering: Assessing the Implications of Large-Scale Climate Intervention (responses to questions for the record) (2009).

Desert-Based Reflectors

Another proposal is to cover large spans of desert with white or reflective materials to greatly increase the local albedo, therefore decreasing the overall global solar intake. Its proponents would argue that landforms unsuited to agriculture or human inhabitance may be suitable for SRM. However, as the Royal Society noted in its report, this strategy would certainly conflict with other desirable land uses and may cause great ecological damage to the desert ecosystem. Furthermore, as the application itself would be highly localized, some of the unintended effects would also be highly localized, causing potentially severe changes in atmospheric circulation and precipitation patterns. Each of the expert witnesses appearing before the Committee that addressed this proposal expressed significant doubts about the potential merits and technological feasibility of such a policy. As Dr. Robert Jackson noted in his responses to Committee questions:

> "This suggestion [of desert-based reflectors] strikes me as a poor idea, environmentally and scientifically. Deserts are

[57] J.C. Moore et al., *Efficacy of Geoengineering to Limit 21st Century Sea-level Rise*, 10.1073/pnas.1008153107, PROCEEDINGS OF THE NATIONAL ACADEMY OF SCIENCES (published online Aug. 23, 2010). *Available at <http://www.pnas.org/content/107/36/15699>.*

[58] CLAIRE L. PARKINSON, COMING CLIMATE CRISIS? CONSIDER THE PAST, BEWARE THE BIG FIX (Rowman and Littlefield Publishers, Inc.) (2010).

unique ecosystems with a diverse array of life. They are not a wasteland to be covered over and forgotten. Based on the best science available, I believe that placing reflective shields over desert . . . is likely to be both unsustainable and harmful to native species and ecosystems. Take as one example the suggestion to use a reflective polyethylene-aluminum surface. This shield would alter almost every fundamental aspect of the native habitat, from the amount of sunlight received (by definition) to the way that rainfall reaches the ground. Implemented over the millions of acres required to make a difference to climate, such a shield could also alter cloud cover, weather, and many other important factors."[59]

Therefore it is the opinion of the Chair that due to wide array of potentially harmful impacts on ecosystems, such as water cycles and wildlife, the solar radiation management (SRM) strategy of desert-based reflectors should be a low priority consideration for research.

International Collaboration

International collaboration on climate engineering is key. The U.S. Science and Technology Committee began its consideration of climate engineering upon meeting with the then-Chair of the U.K. Science and Technology Committee, MP Phil Willis, in April 2009. Chair Willis and Chairman Gordon agreed to work together on a joint inquiry into climate engineering, and each Committee initiated public hearings to establish a public record through expert testimony on the subject. The U.K. Committee published a comprehensive report on its findings on March 18, 2010.

It is the opinion of the Chair, in agreement with U.K. Committee,[60] that further collaborative work between national legislatures on topics with international reach, such as climate engineering, should be pursued. The Chair also agrees that there are a range of measures that could be taken to streamline the process and enhance the effectiveness of collaboration.

It is the opinion of the Chair, in agreement with the U.K. Committee,[61] that the U.S. Government should press for an international database of climate engineering research to encourage and facilitate transparency and open publication of results.

It is the opinion of the Chair that others topics such as synthetic biology, nanotechnology, and strategic raw materials may be of international significance and mutual interest to the U.S. and U.K. committees, and that these topics may be appropriate for bilateral or multilateral collaboration in the future.

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[59] STAFF OF HOUSE OF REPRESENTATIVES COMMITTEE ON SCIENCE AND TECHNOLOGY, 111TH CONG., REPORT ON GEOENGINEERING II: THE SCIENTIFIC BASIS AND ENGINEERING CHALLENGES HEARING (COMM. PRINT 2010).

[60] SCIENCE AND TECHNOLOGY COMMITTEE, UNITED KINGDOM HOUSE OF COMMONS, THE REGULATION OF GEOENGINEERING p.47 (Stationery Office Limited) (2010).

[61] *Id. at* p.32.

It is the opinion of the Chair that this joint inquiry should serve as a model for future inter-Committee collaboration between the U.S. and the U.K. or other inter-Parliamentary partnerships.

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Appendix:

United States–United Kingdom Joint Agreement

United States – United Kingdom Joint Agreement
March 2010

United States House of Representatives
Committee on Science and Technology

United Kingdom House of Commons
Select Committee on Science and Technology

Collaboration and Coordination on Geoengineering

Introduction

A joint inquiry on geoengineering was initiated in 2009 by the Science and Technology committees of the U.S. House of Representatives and the U.K. House of Commons. Geoengineering is the deliberate, large-scale modification of the Earth's climate systems for the purposes of counteracting climate change. This document serves as an explanation of the committees' co-ordination and collaboration on the topic.

Background

In April 2009, the U.K. Committee with the remit for science visited Washington D.C. Its Members met with Representative Bart Gordon, Chairman of the U.S. House of Representatives Science and Technology Committee, and the chairmen of both committees—Phil Willis MP was the Chairman of the House of Commons Committee—discussed topics of mutual interest and potential collaboration. Representative Gordon suggested that there would be value in the two Committees collaborating on an emerging science and technology subject with important international implications.

The committees explored several potential topics and arrangements for coordinating activities. Geoengineering emerged as an attractive subject for the collaboration, particularly as most geoengineering projects will have international implications and require international collaboration. The two committees were at different stages of examination on the subject, with the U.K. Committee having already produced a report and the U.S. Committee initiating a series of preliminary hearings on the subject. This would allow the committees to leverage each other's experience by covering distinct aspects of subject.

Geoengineering

In its report, *Engineering: turning ideas into reality*, (HC (2008-09) 50-I, March 2009) the U.K. Committee recommends that the Government develop a publicly-funded programme of geoengineering research (para 217). Following the Committee's report the U.K. Royal Society published, on 1 September 2009, the findings of a major study into geoengineering, *Geoengineering the climate: science, governance and uncertainty*. This study provided a detailed assessment of the various methods and considered the potential efficiency and unintended consequences they might pose. The U.S. Committee is drawing on the Royal Society's report and its contributing scientists and policy experts, including Professor John Shepherd, who chaired the working group that produced the report.

The U.S. inquiry

The U.S. Committee is examining issues regarding the research and development of geoengineering proposals, focusing their inquiry on the following questions:

- Under what circumstances would the U.S. consider initiating research or the actual deployment of geoengineering?
- Which, if any, of the proposed geoengineering activities warrant further evaluation through coordinated, government-sponsored research, and which activities should be removed from consideration due to unacceptable risks or costs?
- Which U.S. Federal Agencies have either the legal jurisdiction or technical resources to address geoengineering and, of those, which should lead a coordinated U.S. effort?
- To inform international decision-making processes regarding the deployment of geoengineering activities, what level of investment in research is appropriate?
- Which existing international frameworks would govern research, development and deployment of geoengineering? And what new models for international cooperation must be developed to address the unique challenges of geoengineering deployment?
- How could these international frameworks for research and development serve to inform the regulation of deployment of geoengineering activities?

The U.S. Committee began its inquiry by convening a series of hearings and they will publish a final report as a capstone to the joint inquiry. The final report will include the include materials from all three hearings as well as the UK Commons Committee report. The hearings serve both to form the foundation for an informed and open dialogue on the science and engineering of geoengineering, and to provide a Congressional record to underpin the formation of legislation authorizing the United States to engage in geoengineering research at the Federal and international level.

The first hearing provided an introduction to the concept of geoengineering, including the science and engineering underlying various proposals, potential environmental risks and benefits, associated domestic and international governance issues, research and development needs, and economic rationales both supporting and opposing the research and deployment of geoengineering activities.

The second hearing explored the science, engineering needs, environmental impacts, price, efficacy, and permanence of solar radiation management and carbon dioxide removal strategies for geoengineering. The third and final hearing in this series will explore issues relevant to the both the domestic and international governance of geoengineering research, with Phil Willis, Chairman of the U.K. Science and Technology Committee, testifying at this hearing.

The U.K. inquiry

One area which the Royal Society's report identified as requiring examination was the need to develop adequate international mechanisms to regulate geoengineering. It noted the importance of identifying where regulatory gaps existed in relation to geoengineering methods and to establish a process for the development of mechanisms to address these gaps. Taking its cue from the Royal Society's report, the British Committee settled on the following terms of reference for an inquiry into the regulation of geoengineering:

- What UK regulatory mechanisms apply to geoengineering and what changes will need to be made for purpose of regulating geoengineering;
- Is there a need for international regulation of geoengineering and, if so, what international regulatory mechanisms need to be developed; and
- How should international regulations be developed collaboratively?

The outline timetable for the inquiry is:

Nov 2009	Call for evidence
Dec 2009	Deadline for written submissions to the Committee
Jan 2010	Hearing—experts, international organisations and the UK Government.
Mar 2010	Report published and Chairman gives testimony on Committee's report to the U.S. Committee.

Committee co-ordination

Due to procedure, the committees will not sit jointly; therefore, the committees are working together by sharing publicly available papers and the evidence and testimony that each has received. In addition, the committees are coordinating inquiry-related activities. The following arrangements have been agreed:

- All U.K. Committee memoranda and transcripts (i.e., papers) will be sent to the U.S. Committee once reported to the House of Commons;
- All U.S. Committee papers will be sent to the U.K. Committee once reported to the Committee Clerk;
- The staff of each Committee are in regular contact with one another and sharing information on geoengineering;
- The U.K. Committee's report will contain a chapter drawing on the experience of two Committees working together with, if necessary, recommendations on arrangements for future coordination; and,
- The Chairman of the U.K. Committee will testify in March 2010 on the conclusions and recommendations in the U.K. Committee report to the U.S. Committee, which will be treated as testimony to the U.S. Committee.

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