GEOENGINEERING: PARTS I, II, AND III

HEARING

BEFORE THE

COMMITTEE ON SCIENCE AND TECHNOLOGY
HOUSE OF REPRESENTATIVES

ONE HUNDRED ELEVENTH CONGRESS

FIRST SESSION
AND
SECOND SESSION

NOVEMBER 5, 2009
FEBRUARY 4, 2010
and
MARCH 18, 2010

Serial No. 111–62
Serial No. 111–75
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CONTENTS

Geoengineering: Assessing the Implications of Large-Scale Climate Intervention

November 5, 2009

Appendix 1: Answers to Post-Hearing Questions

Appendix 2: Additional Material for the Record

CONTENTS

Geoengineering II: The Scientific Basis and Engineering Challenges

February 4, 2010

Opening Statements

Page

Witnesses:

Appendix 1: Answers to Post-Hearing Questions

Appendix 2: Additional Material for the Record

Page

CONTENTS

Geoengineering III: Domestic and International Research Governance

March 18, 2010

Appendix 1: Answers to Post-Hearing Questions

Appendix 2: Additional Material for the Record

GEOENGINEERING: ASSESSING THE IMPLICATIONS OF LARGE-SCALE CLIMATE INTERVENTION

THURSDAY, NOVEMBER 5, 2009

HOUSE OF REPRESENTATIVES,
COMMITTEE ON SCIENCE AND TECHNOLOGY,
Washington, DC.

The Committee met, pursuant to call, at 10:10 a.m., in Room 2318 of the Rayburn House Office Building, Hon. Bart Gordon [Chairman of the Committee] presiding.

BART GORDON, TENNESSEE
CHAIRMAN

RALPH M. HALL, TEXAS
RANKING MEMBER

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Committee on Science and Technology

Hearing on

Geoengineering: Assessing the Implications of Large-Scale Climate Intervention

Thursday, November 5, 2009
10:00 a.m. – 12:00 p.m.
2318 Rayburn House Office Building

Witness List

Professor John Shepherd, FRS
Professional Research Fellow in Earth System Science
National Oceanography Centre
University of Southampton
Chair, Royal Society Geoengineering Report Working Group

Dr. Ken Caldeira
Professor of Environmental Science
Department of Global Ecology
The Carnegie Institution of Washington
Co-Author, Royal Society Report

Mr. Lee Lane
Co-Director
American Enterprise Institute (AEI) Geoengineering Project

Dr. Alan Robock
Professor
Department of Environmental Sciences
School of Environmental and Biological Sciences
Rutgers University

Dr. James Fleming
Professor and Director
Science, Technology and Society Department
Colby College

HEARING CHARTER

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

"Geoengineering: Assessing the Implications of Large-Scale Climate Intervention"

THURSDAY, NOVEMBER 5, 2009
10:00 A.M.
2318 RAYBURN HOUSE OFFICE BUILDING

Purpose

On Thursday, November 5, 2009, the House Committee on Science & Technology will hold a hearing entitled "***Geoengineering: Assessing the Implications of Large-Scale Climate Intervention***." Geoengineering can be described as the deliberate large-scale modification of the earth's climate systems for the purposes of counteracting climate change. Geoengineering is a controversial issue because of the high degree of uncertainty over potential environmental, economic and societal impacts, and the assertion that research and deployment of geoengineering diverts attention and resources from efforts to reduce greenhouse gas emissions. The purpose of this hearing is to provide 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. This hearing is the first in a series on the subject to be conducted by the Committee, with subsequent hearings intended to provide more detailed examination of these issues.

Witnesses

- **Professor John Shepherd, FRS** is a Professorial Research Fellow in Earth System Science at the University of Southampton, and Chair of the UK Royal Society working group that produced the report *Geoengineering the Climate. Science, Governance and Uncertainty*.
- **Dr. Ken Caldeira** is a professor of Environmental Science in the Department of Global Ecology and Director of the Caldeira Lab at the Carnegie Institution of Science at Stanford University, and a co-author of the Royal Society report.
- **Mr. Lee Lane** is a Resident Fellow and the Co-director of the Geoengineering Project at the American Enterprise Institute (AEI) and former Executive Director of the Climate Policy Center.
- **Dr. Alan Robock** is a Distinguished Professor of Climatology in the Department of Environmental Sciences at Rutgers University and Associate Director of Rutgers Center for Environmental Prediction.
- **Dr. James Fleming** is a Professor and Director of Science, Technology and Society at Colby College and the author of *Fixing the Sky: The Checkered History of Weather and Climate Control*.

Background

Climate

Global warming is caused by a change in the ratio between the amount of incoming shortwave radiation from the sun and the outgoing longwave radiation. Greenhouse gases (GHG's), such as carbon dioxide and methane, decrease the ability of longwave radiation to escape earth's atmosphere. This makes it more difficult for radiation to "escape" and therefore, causes higher radiation absorption. The trapped energy causes higher global temperatures. Proposals for geoengineering typically include activities that alter the earth's climate system by either directly reflecting solar radiation back into space or removing greenhouse gases from the atmosphere to stabilize the intake-output ratio.

In pre-industrial times, the atmospheric concentration of carbon dioxide (CO_2) remained stable at approximately 280 parts per million (ppm). Today the concentration stands at approximately 385 ppm and is steadily increasing. While some industrialized countries' emissions have remained flat in recent years—due in part to slowing economic growth and reduction of economic energy-intensity—overall global emissions are still growing more rapidly than most 1990s climate projections had anticipated,[1] currently increasing CO_2 concentrations by approximately 2 ppm per year.

Estimates on safe and plausible CO_2 concentration targets vary greatly. Climate scientists at the National Oceanic and Atmospheric Administration (NOAA) and a consensus of other scientific authorities identify 350 ppm as the long-term upper limit of atmospheric carbon concentrations that avoid significant environmental consequences. A climate panel led by NASA's Dr. Jim Hansen identified the ecological "tipping point," the level at which atmospheric carbon, without additional increases, would produce rapid climate changes outside of our control, to be 450 ppm.[2,3] The U.S. Global Change Research Program has also identified a stabilization target of 450 ppm in order to "keep the global temperature rise at or below . . . 2° F above the current average temperature, a level beyond which many concerns have been raised about dangerous human interference with the climate system."

Pending U.S. climate legislation and international initiatives under the United Nations Framework Convention on Climate Change (UNFCCC) would establish goals for reducing domestic and global greenhouse gas emissions and accelerating development of low-carbon or zero-carbon energy technologies. However, many in the international climate community hold that even the most aggressive achievable emissions reductions targets will not result in the avoidance of adverse impacts of climate change and ocean acidification. Given global economic growth trends, many consider reaching 450 ppm and temperature increases of more than 2° C to be imminent. The Intergovernmental Panel on Climate Change (IPCC) estimated in its 2007 assessment report that, under various emissions scenarios, the global temperature average will rise between 1.1 and 6.4° C by the year 2100, resulting in sea level rise of 18 to 59 cm in the same time frame.

Further complicating these projections is the possibility of non-linear, "runaway" environmental reactions to climate change. Two such reactions that would amount to climate emergencies are rapidly melting sea ice and sudden thawing of Arctic permafrost. Sea ice reflects sunlight, and as it melts it exposes more (darker) open ocean to sunlight, thus absorbing more heat and accelerating melting and sea level rise. Likewise, as Arctic permafrost thaws it releases methane, a more powerful greenhouse gas than CO_2, which then further decreases the Earth's albedo and accelerates warming.

Geoengineering

It is for these reasons that geoengineering activities are considered by some climate experts and policymakers to be potential "emergency tool" in a much broader long-term and slower acting global program of climate change mitigation and adaptation strategies. Dr. John Holdren, director of the Office of Science and Technology Policy and President Obama's lead science advisor, asserted that while geoengineering proposals are currently problematic due to potential environmental side effects and financial costs, the possibility "has got to be looked at" as an emergency approach.[4] While the deployment of geoengineering will likely remain a very controversial subject, an increasing number of experts are calling for a robust and transparent international research and development program to help determine which, if any, geoengineering proposals have potential for slowing climate change, and which carry unacceptable environmental or financial risk.

Scientific hypotheses resembling geoengineering were published as early as the mid 20th century, but serious consideration of the topic has only begun in the last few years. In 1992 the National Academies of Sciences published a brief review of

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[1] The Global Carbon Project's CO_2 emissions trends notes that CO_2 emissions from fossil fuels and industrial processes have increased from 1.1% a year from 1990–1999 to 3.0% a year from 2000–2004. This growth represents a faster rate of increase than projected by even the most fossil-intensive scenarios projected in by the IPCC in the late 1990s. Archived at *http://www.globalcarbonproject.org/global/pdf/TrendsInCO2Emissions.V15.pdf* as of October 20, 2009.

[2] Michael McCracken notes that the lowest concentration at which economic analyses [suggest] that stabilization seem even remotely possible is 450 ppm. See McCracken p. 2.

[3] Hansen, James et al. *Target Atmospheric C02: Where Should Humanity Aim?* Open Atmospheric Science Journal., **2**, 217–231, doi:10.2174/1874282300802010217.

[4] Associated Press Interview with Seth Borenstein, April 8, 2009. See also his clarifying follow up email, published by Andrew C. Revkin, *New York Times*, April 9, 2009.

climate engineering concepts[5] and provided rough cost estimates for injecting aerosols into the stratosphere to reflect sunlight.[6] The Academies will also finalize a report in early 2010 which, in part, formally addresses geoengineering. The Intergovernmental Panel on Climate Change (IPCC) plans to do the same in its 5th report, to be finalized in 2014. The U.S. Department of Energy penned a White Paper in 2001 recommending a $64 million, five-year program for research as part of the National Climate Change Technology Initiative, but it was not published. NASA held a workshop in April 2007 to discuss solar radiation management options. In May 2008, the Council on Foreign Relations held the forum *Geoengineering: Workshop on Unilateral Planetary Scale Geoengineering*. Earlier in 2009, the Defense Advanced Research Projects Agency (DARPA) began consideration of funding certain geoengineering research initiatives, and NSF has funded independent research projects on potential implications.[7] Last Friday, the Massachusetts Institute of Technology hosted a public symposium, "*Engineering a Cooler Earth: Can We Do It? Should We Try?*"

In September of this year, the United Kingdom's Royal Society—an equivalent to the U.S. National Academies—published what many consider to be the most significant report on geoengineering entitled *Geoengineering the Climate: Science, Governance and Uncertainty*, which outlines various geoengineering methods and the associated challenges in research, ethics and governance. Otherwise, in general, the body of work on geoengineering consists of a limited number of individual scientific papers exploring variations of a few potential strategies, and the body of evaluative information on specific topics remains modest and mostly theoretical. The specific ecological safety issues and ethical considerations, similarly, have been assessed by only a handful of scientists and ethicists. Cost estimations for the various strategies are generally rough. Some are inexpensive enough to be undertaken unilaterally by independent nations or even wealthy individuals, while others entail immensely expensive technologies that would likely only be carried out through international partnerships.

The Royal Society report and other studies divide geoengineering methods into two main categories: **Solar Radiation Management (SRM)** methods that reflect a portion of the sun's radiation back into space, reducing the amount of solar radiation trapped in the earth's atmosphere; and **Carbon Dioxide Removal (CDR)** methods that involve removing CO_2 from the atmosphere. SRM and CDR present fundamentally different challenges of governance, ethics, economics, and ecological impacts and experts most often assess them as wholly separate topics.

Carbon Dioxide Removal (CDR) or Air Capture (AC)

CDR purports to remove greenhouse gases from the atmosphere, either by displacement or by stimulating the pace of naturally occurring carbon-consuming chemical processes. CDR strategies have the advantage of lowering the carbon content of the atmosphere. However, several of the options would be slow to implement and may be impossible to reverse. Those strategies involving a release of chemicals could also have a significant effect on vulnerable oceanic and terrestrial ecosystems. In addition, the chemical strategies would require increased mining efforts and the transportation of needed materials, which would carry its own environmental implications. Some of the potential strategies include:

Afforestation/avoided deforestation—planting new trees on earlier deforested lands or otherwise promoting forest growth results in greater carbon absorption. In addition, old growth forests are efficient carbon consumers. Many believe a more comprehensive plan for avoiding old-forest destruction could be a useful contribution to greenhouse gas management.[8]

Biological sequestration—Because terrestrial vegetation removes atmospheric carbon, carbon sinks can sequester carbon as biomass or in soil. This biomass could

[5] National Academy of Sciences. "Chapter 28: Geoengineering." In *Policy Implications of Greenhouse Warming: Mitigation, Adaptation and the Science Base*, 422–464. National Academies Press, 1992.

[6] Council on Foreign Relations, workshop notes, May 2008.

[7] For example, Rutgers University received a research grant in May 2008 to be led by Alan Robock and Richard P. Turco to perform collaborative research on the implications of stratospheric aerosols and sun shading.

[8] The Canadian Forest Service's Forest Carbon Accounting Program educates land managers and the public on forestry's contribution to GHG management and establishes a National Forest Carbon Monitoring Accounting and Reporting System (NFCMARS). Archived online at *http://carbon.cfs.nrcan.gc.ca/CBM-CFS3_e.html* as of October 20, 2009. Scientific sources on the impact of trees on atmospheric carbon generally attribute between 15 and 20% of global GHG emissions to deforestation.

be used for fuels or sequestered permanently as biochar or other organic materials. The Committee held a hearing entitled *Biomass for Thermal Energy and Electricity: A Research and Development Portfolio for the Future* on October 21, 2009 that addressed this among other topics.

Enhanced weathering techniques—Silicate materials react with CO_2 to form carbonates, thereby reducing ambient CO_2. Silicate rocks could be mined and dispersed over agricultural soils, or released and dissolved into ocean waters (discussed below).

Carbon capture and sequestration (CCS)—Already the subject of several U.S. and international research and development initiatives for electric power plant applications,[9] in this case CCS describes the capture of ambient GHGs and storage in geologic reservoirs, such as natural cave systems and depleted oil wells. Some geoengineering papers refer to this strategy as Carbon Removal and Storage (CRS).

Oceanic upwelling and downwelling—the natural ocean circulation processes are increased and accelerated in order to transfer atmospheric GHGs to the deep sea, a kind of carbon sequestration, using vertical pipes.

Chemical ocean fertilization—The addition of iron, silicates, phosphorus, nitrogen, calcium hydroxide and/or limestone could enhance specific natural chemical processes which consume carbon, such as carbon uptake by phytoplankton.

Solar Radiation Management (SRM) or Sunlight Management

Solar Radiation strategies do not modify CO_2 levels in the atmosphere. Instead, they reflect incoming radiation to reduce the atmosphere's solar energy content and restore its natural energy balance. Proposed reductions of solar radiation absorption are usually 1–2%[10]; around 30% is already reflected naturally by the earth's surface and atmosphere.[11] The methods are space, land, or ocean-based and involve either introducing new reflective objects within or outside of the atmosphere, or an increase in the reflectivity or *albedo*[12] of existing structures and landforms. SRM could reduce increases in temperature, but it may not address the non-temperature aspects of greenhouse-induced climate changes. SRM strategies would generally take effect more quickly than CDR strategies. However, once started, some would likely require constant maintenance and/or replenishment to avoid sudden and drastic increases in temperature. Some SRM proposals include:

Stratospheric Sulfate Injections—A spray of sulfates into the second layer of earth's atmosphere[13] could reflect incoming solar radiation to reduce absorption. This process occurs naturally after a volcanic eruption, in which large quantities of sulfur dioxide are released into the stratosphere.[14]

White roofs and surfaces—Painting the roofs of urban structures and pavements of urban environments white would increase their albedo by 0.15–0.25 (15–25%). This strategy was suggested by DOE Secretary Steven Chu in May of 2009 at the St. James Palace Nobel Laureate Symposium.

Cloud brightening/Tropospheric Cloud Seeding—A fine spray of salt water or sulfuric acid is injected into the lowest level of our atmosphere to encourage greater cloud formation over the oceans, which would increase the local albedo.

Land use changes—Portions of the earth's natural land cover could be modified for more reflective growth patterns, such as light colored grasses. Also, existing agricultural crops could be genetically modified to reflect more sunlight.

Desert reflectors—Metallic or other reflective materials could be used to cover largely underused desert areas, which account for 2% of the earth's surface.

Space-based reflective surfaces—One large satellite or an array of several small satellites with mirrors or sunshades could be placed in orbit to reflect a portion of sun radiation before it reaches the earth's atmosphere. Reflectors could also be placed at the sun-earth Lagrange (L 1) point, where the gravitational pulls from each body act with equal force and therefore allow objects to "hover" in place.

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[9] For example, FutureGen and the Clean Coal Power Initiatives (CCPI) at DOE support RD&D for carbon capture and sequestration.

[10] The Royal Society report suggests a reduction of 1.8% (RS 23).

[11] Novim 8. This inherent reflectivity of the earth is often referred to as "planetary albedo."

[12] Albedo is usually presented as a number between 0 and 1, 0 representing a material in which all radiation is absorbed and 1 a material which reflects all radiation.

[13] Roughly 6 to 30 miles above the earth's surface.

[14] The naturally-occurring sulfur emissions from the 1991 eruption of a volcano in the Philippines, Mt. Pinatubo, are thought to have decreased the average global temperature by ~0.5° C for a 1–2 year period by increasing global albedo. Another example of such short term atmospheric cooling is often attributed to the eruption of El Chicón in March 1982.

Key Strategies for Levying Assessments of Geoengineering Methods

Very little applied research to demonstrate the efficacy and outside consequences of geoengineering proposals has been conducted so far; study has largely been limited to computer simulations. According to the Royal Society, outside of the existing RD&D programs for carbon sequestration and forest management, the only proposals that have undergone sustained research by the scientific community are certain types of ocean fertilization.[15] Such research will likely need to be conducted over many years. Thus, experts argue that broad, collaborative discussions of proposed geoengineering methods should happen in the near term so policymakers can be sufficiently informed of their options well in advance of potential emergency climate events.

The primary costs for program deployment can be determined with some measure of accuracy, but a program's secondary costs (ecological, political, etc) and economic benefits will be more difficult to measure. Strenuous modeling is required to identify potential ecological impacts on, among other considerations: precipitation patterns and the hydrological cycle, ozone concentrations, agricultural resources, acid rain, air quality, ambient temperatures, and species extinction. Other factors to be examined include human health impacts, the costs incurred on consumers and taxpayers, impacts on minerals markets and increased mining needs,[16] job creation or dissolution, international opinion/consensus, data collection and monitoring needs, sources of technology and infrastructure, and the energy demands incurred by large scale deployment. Many of these criteria can be quantified in relatively absolute scientific and economic terms, but others will be difficult to measure and even more difficult to weigh against one another.

Geoengineering methods with more encapsulated impacts (e.g. reforestation and white roofs) are expected to be easier to research and implement from a governance standpoint, but the evaluation of concentrated impacts on community natural resources and microeconomies remains a challenge.

The reversibility of any geoengineering proposal is also a factor. Reversibility includes both the time it takes to end the program itself (e.g. the time it takes for stratospheric sulfate injections to dissipate) and the time in which the externalities will be ended and/or remediated (e.g. the time it takes for additional sulfates in the ecosystem to recede). Identifying the party responsible for reversing a geoengineering application, should it become necessary, is also a key front end consideration.

Lastly, both the cost of carbon credits and public opinion are expected to heavily impact which strategies would be most viable. Just as a significant price on carbon would encourage the development of carbon-neutral energy sources, a higher price per ton of CO_2, paired with offsets allowances, would likely increase the economic viability of many CDR options such as reforestation and CCS. Similarly, public preference for particular strategies will affect the viability of application for different methods.

Experts in the field believe that the risks and costs associated with the various geoengineering strategies must not only be assessed in comparison to one another, but also relative to the potential costs of inaction on climate change or insufficient mitigation efforts.

Risks and Detriments

Unilateral deployment—It is possible for a non-governmental group or individual to undertake one of the higher-impact, lower-cost geoengineering initiatives unilaterally, perhaps without scientific support or any risk management strategy. As recognized in the Royal Society report, the materials for stratospheric injections, for example, would be readily available and affordable to a small group or even a wealthy individual. For this reason and others, national and global security are also key concerns with geoengineering and international governance may be needed at the front end.

Moral hazard—Another concern is that the public knowledge of widespread implementation of geoengineering represents a moral hazard, in which a person or group perceiving itself insulated from risk is more likely to engage in risky or detrimental behavior. The Royal Society suggests that there is significant risk in large-scale efforts being treated as a "get out of jail free card," in which carbon sensitive consumer decision-making for mitigation will wane. Federal funding and political mo-

[15] Royal Society 19

[16] For example, stratospheric injections and ocean fertilization would require large chemical inputs of mined materials.

mentum for mitigation could also be compromised if geoengineering is seen as a superior substitute for traditional mitigation and adaptation.

Ocean Acidification—A clear and significant disadvantage of geoengineering is that, unlike carbon mitigation strategies, most strategies do not reduce the progress of ocean acidification or destruction of coral reefs and marine life due to higher ocean temperatures. CDR methods address ambient carbon levels and could indirectly affect ocean carbon levels by slowing the rate of carbon uptake, but it is not clear that decreases in atmospheric carbon would help reverse ocean acidification. SRM methods do not address carbon levels at all.

Accidental Cessation of SRM—One critical drawback of SRM methods specifically is that, because they do not modify atmospheric carbon concentrations, a disruption of service could result in large and rapid changes in climate, i.e. a return to the unmitigated impact of increased carbon levels. If SRM methods are undertaken without congruent controls on GHG emissions, then we would be constantly at risk of dramatic climate changes if the SRM program ends. These potential rapid, potentially catastrophic impacts must be carefully considered before implementation at any scale. A concurrent charge against geoengineering is that we may not have the political power, funds, foresight or organization, either domestically or internationally, for long-term governance of projects of this scale without incurring unacceptable negative impacts.

Food and Water Security—A large-scale initiative impacting weather patterns could greatly modify the precipitation patterns in particular geographic areas, jeopardizing local food and fresh water supplies for local populations. For example, a drought incurred by unforeseen impacts of artificial cloud formation could suppress crop growth. Poor and developing nations may be particularly susceptible to such impacts.

Butterfly Effect—Ultimately, there is near certainty that some consequences of geoengineering methods cannot be anticipated and will remain unseen until full-scale deployment. Skeptics have alleged the possibility of an ecological "butterfly effect," in which the secondary effects of geoengineering are so wildly unforeseen that a large scale ecological crisis could occur. Some scientists argue that the possibility that such harmful side effects may be larger than the expected benefits should deter consideration of some or all geoengineering proposals.

Governance and International Issues

Any effective, large-scale modification of the climate will necessarily have global consequences. While the technical aspects of essentially every geoengineering method will require a great deal of additional research and examination, the legal, governmental, socio-political and ethical issues may ultimately be greater challenges to deployment. There are several fundamental questions on geoengineering governance that would need to be addressed: Who decides what methods are used? What regulatory mechanisms are there, and who establishes them? Who pays for the research, implementation, and surveillance? Who decides our ultimate goals and the pace in which we take toward achieving them? While some international treaties or agreements may be applicable to certain geoengineering applications, there are currently no regulatory frameworks in place aimed at geoengineering specifically.[17] Furthermore, several proposed geoengineering strategies may directly violate existing treaties. These frameworks may pose an additional challenge for geoengineering implementation, but they may also provide guidance on ways to address the complex issues of jurisdiction and responsibility at the international scale.

One challenge to address is the likelihood of inequitable effects on particular localities. Large-scale efforts conducted in a particular place may produce greater net impact on that region. For example, stratospheric aerosols injections in the Midwest United States might result in decreased crop outputs in the region. In addition, a weather pattern, ecosystem balance or wildlife population modified as an effect of geoengineering could yield a disproportionate effect somewhere outside the source area. This could, for example, cause erratic precipitation patterns in a non-participatory nation.

It is not clear whether one or more existing international frameworks such as the Intergovernmental Panel on Climate Change (IPCC) or the United Nations Framework Convention on Climate Change (UNFCCC) could be the appropriate managing entity of global geoengineering governance issues, or if the unique features of geoengineering would require the creation of a new international mechanism. In addition, as geoengineering is multidisciplinary, several domestic agencies at the Fed-

[17] Royal Society 5

eral level have clear jurisdiction over topics imbedded in all or some of the suggested geoengineering methods as well as their immediate research and development needs. A number of cabinet-level departments and Federal agencies may be directly pertinent to the concurrent agricultural, economic, international security, and governance issues.

Analogous Government Initiatives

The early years of nuclear weapons testing display a number of similarities to geoengineering, including the difficulties of levying cost-benefit analyses of their impacts, uncertain ecological impacts, an unknown geographic scope of impact, and potential intra- and intergovernmental liability issues. This relationship is noted by the ETC Group for the U.S. National Academies workshop on geoengineering held earlier this year.[18] Before the Limited Test Ban Treaty was signed in 1963, several nations regularly performed nuclear tests underwater and in the atmosphere without international agreement, regulation, or transparency. Of course, the consequences of nuclear radiation and the potential for creating weapons are inherently international, but domestic experimentation preceded diplomatic considerations. The global impacts on both human health and international diplomacy, incurred without international consent, were considerable.

Human-engineered weather modification shares these characteristics as well. The most commonly used strategy is cloud-seeding, in which particles[19] are sprayed into the air to stimulate condensation and cloud formation. This practice is thought to modify precipitation patterns[20] in order to enhance crop growth, manage water resources and promote human safety from natural hazards like floods and droughts. In 2003, the National Academies' National Research Council published its fourth report on weather modification, *Critical Issues in Weather Modification Research*. As of report publication there were 23 countries engaging in weather modification on a large scale, and China is the Nation most aggressively pursuing it, with an annual budget of over $40 million for hail suppression and precipitation enhancement. However, NAS concluded that "there is still no convincing scientific proof of the efficacy of intentional weather modification efforts. In some instances there are strong indications of induced changes, but this evidence has not been subjected to tests of significance and reproducibility."[21] No consensus on the cause-and-effect relationship between cloud seeding and weather patterns has been determined, but it still continues to be practiced worldwide.

Public Perception and Ethical Implications

Due to the large uncertainties associated with most geoengineering methods, the opinions of the general public and the scientific community at this time generally vary from cautiously optimistic to unequivocally opposed. While a portion of the scientific community is committed to investigating the possibilities of geoengineering, another portion is resistant because geoengineering and carbon mitigation could be seen by some as direct substitutes[22] and therefore in competition with one another, as discussed above.

The general public may have qualms with geoengineering for several reasons. A given method's efficacy and safety may not coincide with the general public's perception, which then may unduly influence momentum toward an unjustified strategy. However, negative public perceptions of geoengineering may also prove to be a powerful catalyst for emissions reductions.[23] A study by the British Market Research Bureau found that while participants were cautious or hostile toward geoengineering, "several agreed that they would actually be more motivated to undertake mitigation actions themselves" after a large-scale geoengineering application was suggested.[24]

One major ethical issue is that even in a best case scenario, some nations are expected to benefit more than others. Moreover, the effects won't necessarily reflect

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[18] *Geoengineering's Governance Vacuum: Unilateralism and the Future of the Planet*. For the National Academies workshop Geoengineering Options to Respond to Climate Change: Steps to Establish a Research Agenda. Washington, DC. June 15–16, 2009.

[19] Usually silver iodide or frozen CO_2

[20] A highly visible example of an application of weather modification occurred during the 2008 Summer Olympic Games in China, when the Beijing Weather Engineering Office used cloud seeding to delay rainfall for several hours in order to accommodate the Games' opening ceremonies.

[21] NAS 3

[22] Barrett 1

[23] Barrett 2

[24] Royal Society 43

which nations have contributed the most to the carbon problem (the debtors), nor those agent nations who devise, fund and execute the geoengineering activities. Another is the "Dr. Frankenstein" ethical concern, in which some believe deliberate human modification of the global climate is both a dangerous and inappropriate activity in the first place.

Because geoengineering threatens to alter biological processes at a large scale, many are concerned that inequitable negative impacts may occur. Undue burdens may be placed on a particular locality, even if the locality or nation neither engaged in geoengineering nor produced a disproportionate share of anthropogenic carbon emissions. Because deployment and even applied research can hold global implications, open information access and an open equitable forum for international dialogue are expected to be requisite for a responsible approach to geoengineering.

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Chairman GORDON. Good morning. I would like to welcome everyone to today's hearing of the House Committee on Science and Technology entitled Geoengineering: Assessing the Implications of Large-Scale Climate Intervention.

I believe this hearing marks the first time that a Congressional committee has undertaken a serious review of proposals for climate engineering. That is not surprising because this is a very complex, controversial subject that has had little formal debate in the United States.

Geoengineering carries with it a tremendous range of uncertainties, ethical and political concerns, and the potential for catastrophic environmental side-effects. But we are faced with the stark reality that the climate is changing, and the onset of impacts may outpace the world's political and economic ability to avoid them.

Therefore, we should accept the possibility that certain climate engineering proposals may merit consideration and, as a starting point, review research and development as appropriate. At its best geoengineering might only buy us some time. But if we want to know the answers we have to begin to ask the tough questions. Today we begin what I believe will be a long conversation.

In fact, my intention is for this hearing to serve as the introduction to the concept of climate engineering. Over the next eight months the Committee will hold two to three more hearings to explore underlying science, engineering, ethical, economic and governance concerns in fuller detail.

I am pleased to announce that this will be part of an inter-parliamentary project with our counterpart in the United Kingdom House of Commons Science and Technology Committee. When members of the Commons Committee visited us last spring, the Chairman, Phil Willis, proposed that we work together on issues of common interest. Geoengineering has decidedly global implications, and research should be considered in the context of a transparent international process.

Yesterday the Commons Committee voted to undertake a parallel effort to examine the domestic and international regulatory framework that may be applicable to geoengineering. We will be in close contact with them, sharing the findings from our own efforts. When they complete their work in the spring, the Chairman of the Committee will testify before us in a hearing on domestic and international governance issues.

But before we begin this discussion today I want to make something very clear upfront. My decision to hold this hearing should not in any way be misconstrued as an endorsement of any geoengineering activity, and the timing has nothing to do with the pending negotiations in Copenhagen. I know we will run the risk of misleading headlines.

However, this subject requires very careful examination, and will likely only be considered as a potential stopgap tool in a much wider package of climate change mitigation and adaptation strategies. It will require years of internationally coordinated research for us to better understand our options, to examine the impacts, and to know if any activity warrants deployment. In the meantime nothing should stop us from pursuing aggressive long-term domestic and global strategies for achieving deep reductions in greenhouse gas emissions.

This issue is too important for us to keep our heads in the sand. We must get ahead of geoengineering before it gets ahead of us, or worse, before we find ourselves in a climate emergency with inadequate information as to the full range of options. As Chairman of the committee of jurisdiction, I feel a responsibility to begin a public dialogue and develop a record on geoengineering.

With that, I look forward to a good, healthy discussion, and I turn it over to my distinguished Ranking Member, Mr. Hall, for his opening statement.

[The prepared statement of Chairman Gordon follows:]

PREPARED STATEMENT OF CHAIRMAN BART GORDON

Good morning. I would like to welcome everyone to today's hearing of the House Committee on Science and Technology entitled, "Geoengineering: Assessing the Implications of Large-Scale Climate Intervention."

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With that, I look forward to a healthy discussion, and I yield to the distinguished Ranking Member, Mr. Hall for his opening statement.

Mr. HALL. Mr. Chairman, I could make the shortest opening speech in the history of this committee.

Chairman GORDON. Okay.

Mr. HALL. I could say geoengineering, hello, but I won't do that. I will just say to you that I thank you for holding this hearing today, and once again, the Commerce and this Committee in our duties are taking on issues that are really the forefront of cutting-edge science, and I appreciate your leadership.

As many of my colleagues will agree, the debate about climate change is far from over, and I am sure that you have conducted and participated in that and came to the conclusion that the fact that there are still many, many opinions as to the causes, the effects and the potential solutions demonstrates how much uncertainty there is out there and how crucial it is for our Nation to continue to search for answers.

Geoengineering, or climate engineering, is the intentional modification of the earth's environment to promote—and just go to the definition and see that it is so broad that you could apply the term to almost any human changes that are made by humans and their surrounding environment, from building dams to deforestation. The actions are more local or regional in scope. The types of modifications we will be discussing are global in nature, and therefore, no matter what our preconceptions are, the implications of such technologies are far-reaching.

I understand that the hearing is to be the first of a series of hearings on this topic, further exploring the scientific basis underpinning the concept of geoengineering, and the ethical concerns and issues surrounding any future development and deployment scenarios could be extremely helpful in advancing the discussion about geoengineering.

I will reserve my full judgment on this issue until all the facts are in, but I have to admit I am a bit skeptical about this non-traditional approach. I know that our witnesses here today represent a variety of different viewpoints on geoengineering, and I am eager to listen to their thoughts about the issue. I am sure we will have plenty of questions to ask them. I really look forward to a very lively discussion, and I expect we are going to have one.

So I think I have to thank you again, Mr. Chairman. This kind of opens up, you know—Alfred Hitchcock did *The Birds*. You remember that movie? And I have been working all since that time on a movie that have the elephants, flying elephants, you know, like Hitchcock had those birds that just were going to disturb the whole world. I don't know if I can get that underway or not, but we will maybe work that in in some of this here.

I would yield back to my Chairman, James Bond, and I thank you very much for letting me talk.

[The prepared statement of Mr. Hall follows:]

PREPARED STATEMENT OF REPRESENTATIVE RALPH M. HALL

Thank you, Mr. Chairman. I would like to thank you for holding this hearing today on geoengineering. Once again, this Committee is tackling issues that are the forefront of cutting edge science, and I appreciate your leadership.

As many of my colleagues will agree, the debate about climate change is far from over. I am sure that you concluded that the fact that there are still so many opinions as to the causes, the effects and the potential solutions, demonstrates how much uncertainty is out there and how crucial it is for our nation to continue to search for answers.

Geoengineering, or climate engineering, is the intentional modification of the Earth's environment to promote habitability. The definition is so broad that you could apply the term to any changes humans make in their surrounding environment, from building dams to deforestation. These actions are more local or regional in scope. The types of modifications we will be discussing this morning are global in nature, and therefore no matter what our preconceptions are, the implications of such technologies are far reaching.

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I know that our witnesses here today represent a variety of different viewpoints on geoengineering, and I am eager to listen to their thoughts about the issue. I'm sure that we will have plenty of questions to ask them, and I look forward to a lively discussion.

So I have to thank you once again for holding this hearing, and I look forward to hearing from our distinguished witnesses.

[The prepared statement of Mr. Costello follows:]

PREPARED STATEMENT OF REPRESENTATIVE JERRY F. COSTELLO

Good Morning. Thank you, Mr. Chairman, for holding today's hearing to examine the future of geoengineering strategies for reducing greenhouse gas emissions and counteracting climate change.

This committee has met several times to discuss the implications of climate change and the best mechanisms to counter its effects. Throughout these discussions, we have emphasized the importance of working with our international partners to ensure that the global problem of climate change is addressed through a global solution.

I am pleased to welcome our colleagues from the United Kingdom with whom this committee has worked to explore the potential of geoengineering as a means of reducing greenhouse gas emissions.

I have been a strong supporter of many geoengineering techniques currently in use today, in particular the use of carbon capture and storage technology for coal, to reduce the amount of carbon released into the atmosphere. These demonstrated technologies allow us to combat climate change and continue using abundant natural resources. However, I am concerned about the unintended consequences of some geoengineering proposals. These untested techniques could have irreversible effects that may permanently change the chemical, physical and biological make-up of our oceans and land. While I recognize that these proposals are still in their earliest stages, I believe it is important to address these concerns early in the research effort.

I would like to hear from our witnesses how they will address these risks during the in-depth discussions on the potential of geoengineering. Further, as research and development projects move forward, how will these concerns be addressed and what protections will be put in place.

I welcome our panel of witnesses, and I look forward to their testimony. Thank you again, Mr. Chairman.

[The prepared statement of Ms. Johnson follows:]

PREPARED STATEMENT OF REPRESENTATIVE EDDIE BERNICE JOHNSON

Good morning, Mr. Chairman.

I would like to welcome today's panel to our hearing, focused on research and work done in the field of geoengineering.

Perhaps the greatest challenge the science community will face in the years ahead is being able to moderate climate change and global warming.

While I believe that cutting emissions of greenhouse gases is a priority in climate mitigation, we must also prepare for the possibility that our environment will continue

to degrade.

There is no simple, solution, and while geoengineering may be possible, we still face many hurdles to its implementation and success.

There are a range of methods that are currently being considered in the field of geoengineering and I look forward to hearing more about their potential today.

We need global solutions to this global problem. We cannot proceed with any approach until we thoroughly examine the potential downside and all of the legal and ethical ramifications.

There is a great deal of uncertainty in this field and as we proceed with future hearing look forward to examining all the consequences of implementing this type of science.

Today's hearing represents a commitment on behalf of this Committee and Congress to work in a global capacity to foster this type of research.

The witnesses who will join us are true subject experts. It is my hope that they can provide committee members with good information that is based on science.

It is my hope that we can move forward proactively to devise policies for a broad approach to the problem of global warming.

Thank you for hosting today's full committee hearing to learn more about geoengineering.

Chairman GORDON. Well, Professor Shepherd, welcome to America. If there are other Members who wish——

Mr. HALL. I knew that would get me in trouble.

Chairman GORDON. If there are other Members who wish to submit additional opening statements, your statements will be added to the record at this point.

And now it is my pleasure to introduce our witnesses. Professor John Shepherd is a Professional Research Fellow in Earth System Science at the University of Southampton and Chair of the Royal Society Geoengineering Working Group that produced the report *Geoengineering The Climate: Science, Governance & Uncertainty.* And it is the University of Southampton not located in New York. Dr. Ken Caldeira is a Professor of Environmental Science in the Department of Global Ecology at the Carnegie Institute of Washington and co-author of the Royal Society Report. Mr. Lee Lane is the Co-Director of the American Enterprise Institute for Public Policy Research's Geoengineering Project. Dr. Alan Robock is a Professor at the Department of Environmental Science at the School of Environmental and Biological Sciences at Rutgers University. Dr. Robock, Mr. Rothman wanted us to give you his best. He is ill today but wanted to be with you. And Dr. James Fleming is a Professor and Director of the Science, Technology and Society Program at Colby College and the author of *Fixing the Sky: The Checkered History of Weather and Climate Control.*

As our witnesses should know, we will have five minutes for your spoken testimony. Your written testimony will be included in the record for the hearing, and when you have completed your spoken testimony we will begin the questions. Each Member then will have five minutes to question the witnesses.

So we begin in the order, Dr. Caldeira.

Dr. CALDEIRA. Isn't Dr. Shepherd first?

Chairman GORDON. Well, I am reading from my report here, and so you are first in that regard but if you would like to yield to Dr. Shepherd, then we will do that. So if you will turn on your mic, we will all be better off.

STATEMENT OF DR. KEN CALDEIRA, PROFESSOR OF ENVIRONMENTAL SCIENCE, DEPARTMENT OF GLOBAL ECOLOGY, THE CARNEGIE INSTITUTION OF WASHINGTON, AND CO-AUTHOR, ROYAL SOCIETY REPORT

Dr. CALDEIRA. Chairman Gordon, Ranking Member Hall, Members of the Committee, I thank you for giving me the opportunity today to speak with you about why it makes sense for us as American taxpayers to invest some of our hard-earned dollars in exploring ways to cost-effectively reduce the environmental threats that are facing us.

I am a climate scientist working at the Carnegie Institution Department of Global Ecology. I have been studying climate and ocean acidification for over 20 years and investigating geoengineering options for more than 10 years.

Climate change poses a real risk to Americans. The surest way to reduce this risk is to reduce emissions of greenhouse gases, such as carbon dioxide. We can build a 21st-century energy system based on solar and nuclear power along with carbon capture and storage from coal-, oil- and gas-fired power plants. I believe we can and will make this transformation to the clean energy system of the future. However, even if we decide to start building our 21st-century energy system today, because of the long time lags involved, we will still face threats from climate change.

The options we are discussing today can be divided into two categories with very different characteristics, solar radiation management [SRM] approaches and carbon dioxide removal [CDR] approaches.

Solar radiation management methods, which you could also call sunlight reflection methods, seek to reduce the amount of climate change by reflecting some of the sun's warming rays back to space. We know this basically works because volcanoes have cooled the earth in this way. Preliminary research suggests that we could rapidly and relatively cheaply put tiny particles high in the stratosphere and that this would cause the earth to cool quickly.

Nobody thinks these approaches will perfectly offset the effects of carbon dioxide. For example, these methods do not address the problem of ocean acidification. However, preliminary climate model simulations indicate that these approaches could offset most climate change in most places most of the time.

While these approaches may be able to reduce overall risk, they could and likely will introduce new environmental and political risks.

In contrast, carbon dioxide removal approaches seek to reduce the amount of climate change and ocean acidification by removing carbon dioxide from the atmosphere. Essentially, these options reverse carbon dioxide emissions in the atmosphere by pulling carbon dioxide back out of the atmosphere.

There are two basic types of carbon dioxide removal methods. One is to use growing forests or other plants to store carbon in organic forms. The other is to use chemical techniques. We could build centralized carbon dioxide removal factories or perhaps spread out finely ground-up minerals that would remove carbon dioxide from the atmosphere.

With the exception of proposals to fertilize the oceans, carbon dioxide removal methods are unlikely to introduce new, unprecedented risks, so cost is likely to be the primary consideration governing deployment.

Let me mention in closing that I do not think the term "geoengineering" is very useful in informed discussions. The term has been used by so many people to refer to so many different and poorly defined grab bags of distantly related things that I do not believe the term can help us to think clearly about the decisions we need to make.

So to conclude, we need multi-agency research programs in both sunlight reflection methods and carbon dioxide removal approaches to find cost-effective ways to protect American taxpayers from unnecessary environmental risk. Because these two basic approaches, the solar radiation management approaches and the carbon dioxide removal approaches, differ in so many dimensions, it seems unwise to link these research programs closely together.

Solving our climate change problem is largely about cost-effective risk management. There are many different ways that risk might be diminished, and the most important of these is to reduce greenhouse gas emissions. However, we also need to improve our resilience so that we can better adapt to the climate change that does occur. We also need to understand whether there are ways that we can cost-effectively remove carbon dioxide and perhaps other greenhouse gases from the atmosphere. Lastly, we should try to understand whether thoughtful, intentional interventions into the climate system might be able to undo some of the damage that we are doing with our current, inadvertent intervention.

The problem is too serious to allow prejudice to take options off of the table. I thank you for your attention, and I would be happy to answer your questions.

[The prepared statement of Dr. Caldeira follows:]

PREPARED STATEMENT OF KEN CALDEIRA

1. Summary

Climate change poses a real risk to Americans. The surest way to reduce this risk is to reduce emissions of greenhouse gases.

However, other options may also be available which could in some circumstances cost-effectively contribute to risk reduction. These options can be divided into two categories with very different characteristics:

- Solar Radiation Management (SRM) approaches seek to reduce the amount of climate change by reflecting some of the sun's warming rays back to space.
    - The most promising Solar Radiation Management proposals appear to be inexpensive (at least with respect to direct costs), can be deployed rapidly, and can cause the Earth to cool quickly. They attempt symptomatic relief without addressing the root causes of our climate problem. Thus, these methods do not address the problem of ocean acidification. While these approaches may be able to reduce overall risk, there is the potential that they could introduce additional environmental and political risk. Solar Radiation Management approaches have not yet been given careful consideration in international negotiations to diminish risks of climate change. The primary consideration governing whether such systems would be deployed is our level of confidence that they would really contribute to overall risk reduction.
- Carbon Dioxide Removal (CDR) approaches seek to reduce the amount of climate change and ocean acidification by removing the greenhouse gas carbon dioxide from the atmosphere.

- ○ The most promising of the Carbon Dioxide Removal approaches appear to be expensive (relative to SRM methods, but perhaps competitive with methods to reduce emissions), slow acting, and take a long time before they could cool the Earth. However, they address the root cause of the problem—excess CO_2 in the atmosphere. There is no expectation that these methods will introduce any new unprecedented risks. Some Carbon Dioxide Removal approaches associated with forests and agricultural practices have received attention in international negotiations and in carbon offsetting schemes. The primary consideration governing whether Carbon Dioxide Removal approaches would be deployed is cost relative to options to reduce greenhouse gas emissions.

We need multi-agency research programs in both Solar Radiation Management and Carbon Dioxide Removal. (Every agency that has something to contribute should be given a seat at the table.) Because Solar Radiation Management and Carbon Dioxide Removal approaches differ in so many dimensions, it seems unwise to link them closely together. In particular, Carbon Dioxide Removal approaches have more in common with efforts to reduce CO_2 emissions than they have with Solar Radiation Management approaches.

- Solar Radiation Management research might best be led by agencies that have a strong track record in the highest quality science, with no vested interest in the outcome of such research, such as the National Science Foundation or perhaps NASA.
- Carbon Dioxide Removal research that focuses on storing carbon in reduced (organic) forms might best be led by agencies that are already involved in conventional Carbon Dioxide Removal methods involving agricultural or forestry practices. Carbon Dioxide Removal approaches which employ centralized chemical engineering methods to remove CO_2 from the atmosphere might best be led by agencies, such as DOE, already involved in carbon dioxide capture from power plants. It is less clear where research into distributed chemical approaches might fit best, although leadership by the National Science Foundation is a possibility.

2. Background

Climate change represents a real risk to Americans

It is increasingly obvious that modern industrial society is affecting climate. It is less clear how much this climate change will affect the average American. Nevertheless, it is reasonable to think that there is a significant risk that climate change will be more disruptive to our economy than a few million mortgage defaults.

Economists estimate that it might take 2% of our GDP to squeeze carbon dioxide emissions out of our energy and transportation systems. I believe that the risk is high that, if we continue to produce devices that dump carbon dioxide waste into the atmosphere, climate change will lead to problems that dwarf the subprime mortgage debacle. The recent subprime mortgage crisis, driven by defaults on several million mortgages, led to an approximately 4% reduction in worldwide GDP growth. Therefore, I believe a rational investor would invest 2% of our GDP to avoid this risk.

When I am speaking, I often ask:

> *If we already had energy and transportation systems that met our needs without using the atmosphere as a waste dump for our carbon dioxide pollution, and I told you that you could be 2% richer, but all you had to do was acidify the oceans and risk killing off coral reefs and other marine ecosystems, all you had to do was heat the planet, and risk melting the ice caps with rapid sea-level rise, risk shifting weather patterns so that food growing regions might not be able to produce adequate amounts of food, and so on, would you take all of that environmental risk, just to be 2% richer?*

Nobody I have ever spoken with has said that all of this environmental risk is worth being 2 % richer. (Some years, I have gotten a 2% raise and barely noticed it.) So, I think we have to agree that the main issue with solving the climate-carbon problem is not the cost *per se*—it is that the cost is high enough to make it difficult to generate the necessary level of cooperation needed to solve the problem.

I do not know how much climate change will affect the average American. While I cannot with confidence predict great damage, I can predict great risk.

The carbon-climate problem is about risk management—and the best, surest, and clearest way to reduce environmental risk associated with greenhouse gas emissions is to reduce greenhouse gas emissions.

If you take the risk of climate damage seriously, you want to take action to diminish risk by reducing greenhouse gas emissions, but you would not want to limit yourself to only one risk-reduction approach.

There may be novel approaches that could also help us manage risk associated with greenhouse gas emissions. However, these novel approaches are poorly understood and have been inadequately evaluated. There has been a paucity of the kind of research and development that would let us understand the positive and negative properties of these approaches. These novel approaches are not alternatives to reducing greenhouse gas emissions; they are supplementary measures that might help us reduce the risk of climate-related damage. Some of them are approaches that America might need in a time of crisis.

3. Introduction to the concept of "geoengineering"

"Geoengineering" is a catch-all term, used to refer to a broad collection of strategies to diminish the amount of climate change resulting from greenhouse gas emissions. The term "geoengineering" is used in different ways by different authors and there is no generally agreed-upon definition, although features common to strategies referred to by the word "geoengineering" generally include:

(1) Intent to affect climate

(2) Affecting climate at a regional to global scale

(3) Novelty or lack of familiarity

Emitting CO_2 by driving a car is not generally considered geoengineering because, while it affects global climate, there is no intent to alter climate. Planting a shade tree to provide a cooler local environment is not generally considered geoengineering because, while there is intent to alter climate, it is not at a sufficiently large scale. Promoting the growth of forests as a climate mitigation strategy involves an intent to affect climate at global scales; however, we are familiar with forest management, so this approach does not have the novelty that would cause most people to use the word "geoengineering" to refer to it.

The term "geoengineering" also has another meaning related to the engineering of tunnels and other structures involving the solid Earth. Furthermore, the term "geoengineering" has been applied to large scale efforts to alter geophysical systems, such as the old Soviet plan to reroute northward flowing rivers so that they would instead flow south towards central Asia.

Because "geoengineering" has been used by different people to refer to many different types of activities, and there is no single universally agreed definition, it is my opinion that the term "geoengineering" no longer has much use in informed discussions. More than that, use of the term "geoengineering" can have a negative influence on the ability to conduct an informed discussion, since there is little that can be said generally about such an ill-defined and heterogeneous set of proposals.

4. An introduction to the major "geoengineering" strategies

"Geoengineering" strategies can be divided into two broad categories:

(1) Solar Radiation Management (SRM) and related strategies that seek to directly intervene in the climate system, without directly affecting atmospheric greenhouse gas concentrations.

(2) Carbon Dioxide Removal (CDR) and related strategies that seek to diminish atmospheric greenhouse gas concentrations, after the gases have already been released to the atmosphere.

These two broad classes of strategy are so different, that they should be treated as being independent of each other. Solar Radiation Management approaches (SRM—can also be thought of as Sunlight Reflection Methods) attempt to limit damage from elevated greenhouse gas concentrations—these methods are designed to provide symptomatic relief. In contrast, Carbon Dioxide Removal strategies try to remove the atmospheric drivers of climate change—these methods are designed to address the root causes of our climate problem.

Solar Radiation Management proposals will inherently involve actions by governments, because the primary issues driving deployment of such approaches will involve questions of environmental risk reduction, equity, governance, and so on. (Of course, a clear scientific and technical basis needs to be developed to act as a foundation for these policy discussions.)

In contrast, Carbon Dioxide Removal proposals would likely be driven by actions of private corporations, because the primary factor driving deployment is likely to be a price on carbon emissions. If it is more cost-effective to remove carbon dioxide from the atmosphere than to prevent an emission to the atmosphere, and local environmental issues have been adequately addressed, then there will be an economic driver to remove carbon dioxide from the atmosphere.

Because the issues around Solar Radiation Management (and related approaches) differ so greatly from issues around Carbon Dioxide Removal (and related approaches), it is best to address these two classes of possible activities separately.

4.1 Solar Radiation Management (SRM) and related strategies

4.1.1. Overview of Solar Radiation Management

While proposals to intentionally alter climate go back a half century or more, relatively little research has been done on these strategies. Therefore, everything said about these approaches must be regarded as provisional and preliminary. The recent report on Geoengineering by the U.K. Royal Society provides a good summary of this preliminary research.

The sun warms the Earth. Greenhouse gases make it harder for heat to leave the Earth. With additional greenhouse gases warming the Earth, one way to cool things back down is to prevent the Earth from absorbing so much sunlight.

There are two classes of proposal that appear to be able to address a significant part, if not all, of globally averaged mean warming: (1) placing small particles high in the atmosphere to reflect sunlight to space or (2) seeding clouds over the ocean to whiten them so that they reflect more sunlight to space.

The leading proposal for reflecting large amounts of sunlight back to space is the emplacement of many small particles in the stratosphere. We have good reason to believe that such an approach will fundamentally work because volcanoes have performed natural experiments for us. It is thought that the rate of particle injection needed to offset a doubling of atmospheric CO_2 content is small enough that it could be carried in a single fire hose. The determination of whether we would ever want to deploy such a system would not depend on cost of the deployment, but rather on an assessment of whether it was really able to contribute to overall risk reduction, taking both environmental and political factors into consideration.

In 1991, the Mt. Pinatubo volcano erupted in the Philippines, introducing a large amount of tiny particles into the stratosphere. This caused the Earth to cool by around 1 degree Fahrenheit. Within a year or two, most of this material left the stratosphere. Had we replenished this material, the total amount of cooling would have been more than enough to offset the average amount of warming from a doubling of atmospheric CO_2 concentration.

There are questions about how good a short term eruption is as an analogue for a continuous injection of material into the stratosphere. Nevertheless, the natural experiment of volcanic eruptions give us confidence that the approach will basically work, and while there might be negative consequences, the world will not come instantly to an end, and that after stopping a short-term deployment, the world is likely to return to its previous trajectory within years.

Nobody should think that any Solar Radiation Management strategy will work perfectly. Sunlight and greenhouse gases act differently on the atmosphere. Sunlight strikes the surface of the Earth where it can both warm the surface and help to evaporate water. Greenhouse gases for the most part absorb radiation in the middle of the atmosphere. So, changes in sunlight can never exactly compensate for changes in greenhouse gases.

However, preliminary simulations indicate that it should be possible to offset most of the climate change in most of the world most of the time. Climate model simulations show that deflecting some sunlight away from the Earth can make a high CO_2 world more similar to a low CO_2 world at most times and at most places. However, the climate might deteriorate in some places. This raises important governance issues in that Solar Radiation Management approaches (or Solar Reflection Methods) have the potential to cause harm at some times in some places, even if they are able to reduce overall environmental damage and environmental risk.

4.1.2. Concerns relating to Solar Radiation Management

While there is some expectation that Solar Radiation Management approaches can diminish most of the climate change in most of the world most of the time, it is possible that there could be bad effects that would render this offsetting undesirable. These bad effects could be environmental, or they could be socio-political.

With regard to environmental negatives, it is possible there could be adverse shifts in rainfall, or damage to the ozone layer, or unintended impacts on natural ecosystems. These unintended consequences should be a major focus of a Solar Radiation Management research program. Furthermore, we must bear in mind that

Solar Radiation Management proposals do not solve problems associated with ocean acidification (but they do not significantly affect ocean acidification).

With regard to socio-political negatives, some countries might actually prefer their warmer high CO_2 climate or perhaps they might be (or believe they are) negatively impacted by a Solar Radiation Management scheme—or perhaps countries might differ in the amount or type of Solar Radiation Management to be deployed. These sorts of issues could cause political tension.

It is also possible that the perceptions that there is a technical fix could lull people into complacency, and diminish pressure for emissions reductions. However, when the U.K. Royal Society conducted a preliminary focus group, they found that people were even more willing to put effort into emissions reduction after hearing the extreme measures scientists are considering to reduce climate risk. Just because we wear seatbelts, that does not mean we will drive more recklessly. Seat belts can remind us that driving is a dangerous activity.

4.1.3. Governance, regulation, and when to deploy

4.1.3.1. Gradual deployments

Often, in discussions of Solar Radiation Management, there is an assumption that we are speaking about large scale deployments and some system of global governance is necessary. While discussions of governance and regulation of both experiments and deployments are necessary, it is not clear at this time what form that governance or those regulations should take.

For example, it is thought that sulfur emissions from power plants might today be reflecting about 1 W/m2 back to space that would have otherwise been absorbed by Earth. This could be causing the Earth to be about 1 degree Fahrenheit cooler than it would otherwise be. In other words, if we cleaned up all of the sulfur emitted by power plants worldwide, the Earth might heat up another degree.

Because sulfur lasts a year or more in the stratosphere but generally less than a week in the lower atmosphere, if we were to emit just a few per cent of the sulfur now emitted in the lower atmosphere into the upper atmosphere instead, we would get the same average cooling effect with a more than 95% reduction in overall pollution. What if China were to say, "For each power plant that we fit with sulfur scrubbers, we will inject a few percent of that sulfur in the stratosphere—and we will get the same average cooling effect with a greater than 95% reduction in our sulfur emissions."?

Today, ships at sea burn high sulfur oil. These ships can leave white contrails in their wake, reflecting sunlight to space. The International Maritime Organization has requested that these sulfur emissions be curtailed for reasons related to pollution and health—and the expected outcome is additional global warming. What if these ships were retrofitted with cloud seeding devices that would produce these same contrails, but without releasing any pollution? (It has suggested that a seawater spray would do the job.)

It is not clear whether these things would be good things to do or bad things to do. It is not clear what kind of governance or regulatory structures should be built around such activities. One reason why we need a research program and discussions about governance and regulation is so that we can make informed decisions about such issues.

4.1.3.2. Emergency deployments

While such gradual deployments might be one path to implement Solar Radiation Management schemes, there is another possibility.

In every emissions scenario considered by the Intergovernmental Panel on Climate Change, temperatures continue to increase throughout this century. Because of lags in the climate system and the long time scales involved in transforming our energy and transportation systems, the Earth is likely to continue warming throughout this century, despite our best efforts to reduce emissions. Our actions to diminish emissions can reduce the rate of warming and reduce the damage from warming, but it is probably already too late for us to see the Earth start to cool this century, unless we engage in solar radiation management (or related climate system interventions).

What if we were to find out that parts of Greenland were sliding into the sea, and that sea-level might rise 10 feet by mid-century? (Such rapid sea level rises apparently happened in the geologic past, even without the kind of rapid shock we are now applying to our climate system.) What if rainfall patterns shifted in a way that caused massive famines? What if our agricultural heartland turned into a perpetual dustbowl? And what if research told us that an appropriate placement of tiny particles in the stratosphere could reverse all or some of these effects?

That was a lot of "what if's", but nevertheless there is potential that direct intervention in the climate system could someday save lives and reduce human suffering. Moreover, direct intervention in the climate system might someday save lives and reduce suffering of American citizens. I do not know what the probabilities of such outcomes are, but I believe that if we take the risks associated with climate change seriously, we must investigate our options carefully and without prejudice.

We do not want our seat belts to be tested for the first time when we are in an automobile accident. If the seat belts are not going to work, it would be good to know that now. If there is something really wrong with thoughtfully intervening in the climate system, we should try to find that out now, so that if a crisis occurs, policy makers are not put in the decision of having to decide whether to let people die or try to save their lives by deploying, at full scale, an untested system.

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.

4.1.3.3. Building governance and regulatory structures

We should proceed cautiously in developing governance and regulatory structures that could address Solar Radiation Management approaches both in the deployment phase and in the research phase.

At this point we know very lithe. It is very easy to sound as if you are taking the moral high ground by saying, "It is wrong to intentionally intervene in the climate system, so it should be disallowed." However, every simulation of a Solar Radiation Management method that used a "reasonable" amount of solar offsetting has found that there is potential to offset most of the climate change in most places most of the time. If we really believe that climate change has the potential to cause loss of life and suffering, and we believe that Solar Radiation Management approaches may have the potential to cost-effectively reduce that loss of life and suffering, it could be immoral not to research and develop these options.

Information on Solar Radiation Management approaches is at this point highly preliminary and has not been widely disseminated. Pushing too early for formal agreements may lock political entities into hard positions that will be difficult to modify later. Therefore, what is needed now for governance is a period of discussion, careful consideration, and learning.

With respect to experiments, no additional regulation is needed for small scale field experiments designed to improve process understanding where there is no expectation of any detectable lasting effects and no detectable trans-boundary effects.

Discussions need to begin about how to develop norms that might govern larger experiments where there is potential for detectable climate effects or where significant trans-boundary issues must be addressed.

Since these larger experiments and deployments could affect people in many countries, it is important that these discussions occur both internationally and domestically. Initially, it is probably best if these discussions proceed informally, perhaps with the facilitation of scientific unions or professional organizations.

In short, we need to do the informal groundwork now, so that we can develop the shared understanding that is necessary for the development of good governance and regulatory structures.

4.1.4. Additional Solar Radiation Management strategies

While this discussion has focused on introducing small particles high in the atmosphere, a number of other approaches have been proposed that attempt to reduce the amount of climate change caused by increased greenhouse gas concentrations in the atmosphere. These include proposals to whiten clouds over the ocean, to mix heat deeper into the ocean, to whiten roofs and roads, to put giant satellites in space, and so on.

For a number of reasons, I believe that placing small particles high in the atmosphere is the most promising category of Solar Radiation Management approaches. However, approaches to whiten clouds over the ocean or mix heat downward into the deep ocean, both appear feasible and may be able to be scaled up to offset a large fraction of century-scale warming. Of these two options, whitening marine clouds seems more benign, but neither of these approaches has been subject to sufficient scrutiny.

Most other proposed Solar Radiation Management (and related) approaches, either cannot be scaled up sufficiently (e.g., proposals to whiten roofs and roads) to be a "game changer", or cannot be cost-effectively scaled up quickly enough (e.g., massive satellites placed between the Earth and Sun) to make a difference this century.

4.1.4. Institutional arrangements for research

Within the United States, agencies such as National Science Foundation or NASA might be in the best position to lead research into Solar Radiation Management, although DOE, NOAA, and other agencies also may have important roles to play.

It is important that this research be internationalized and conducted in as open and transparent a way as possible.

While laboratory and small scale process studies in the field need no additional regulation at this time, larger scale field studies will require some form of norms, governance, or regulation. Discussions need to take place, both domestically and internationally, to better understand how to strike the best balance between allowing the advancement of science and technology while safeguarding our environment.

4.2 Carbon Dioxide Removal (CDR) and related strategies

We emit greenhouse gases to the atmosphere, causing the Earth to warm. Is there potential to actively remove these gases from the atmosphere?

The answer is, 'yes, we are confident that there are ways to remove substantial amounts of carbon dioxide from the atmosphere.' By addressing the root cause of the climate change problem (high greenhouse gas concentrations in the atmosphere), Carbon Dioxide Removal strategies diminish climate risk. They also reduce ocean acidification. Carbon dioxide removal methods do not introduce significant new governance or regulatory issues.

I would suggest that within the domain of Carbon Dioxide Removal there are at least two, and possibly three or more, relatively independent research programs.

Because Carbon Dioxide Removal approaches represent a miscellaneous collection of approaches, there is no one taxonomy that would uniquely classify all of these proposals. Nevertheless, Carbon Dioxide Removal approaches can be divided into two categories:

- Strategies that use *biological approaches* (i.e., photosynthesis) to remove carbon dioxide from the atmosphere and store carbon in a reduced (organic) form.
- Strategies that use chemical approaches to remove CO_2 from the atmosphere.

Biological approaches may be subdivided in several different ways, but one way is to divide them into land-based and ocean-based approaches. Proposed land-based biological approaches include planting forests, changing agricultural practices to result in more carbon storage, and burying farm waste. All of these methods are limited by the low efficiency of photosynthesis, and thus require significant land area, although in some cases this land can be multi-use. Many of these approaches are already the subject of considerable study and are already being considered in discussions about how to limit climate change. Current research indicates that biologically-mediated carbon storage in the ocean is problematic in several dimensions, and is not likely to represent a significant contributor to solving our climate change problems.

Chemical approaches may be divided into two categories: centralized approaches and distributed approaches. Centralized approaches seek to build industrial chemical processing facilities to remove carbon dioxide from the atmosphere and store it in a form that cannot interact with the atmosphere. The most promising avenue appears to be to store the carbon dioxide underground in compressed form, as with conventional carbon capture and storage. Distributed approaches seek to spread chemicals over large areas of the land or ocean, where they can react with carbon dioxide and cause the carbon dioxide to be removed from the atmosphere.

There are additional hybrid approaches that do not fit easily into this taxonomy. For example, it has been suggested that plants could be grown and then burned in power stations to generate electricity, and then the CO_2 could be captured from the power stations and stored underground.

More thought needs to be put into finding institutional homes for these research elements. While all of these research efforts are likely to require multi-agency input, it is likely that research into biologically based methods might best be led by agencies that have strong track records in the biological sciences or experience with agriculture and forestry issues. Research into the centralized chemical approaches might best be led by DOE, but this is uncertain.

5. Closing comments

Solving our climate change problem is largely about cost-effective risk management. There are many different ways that risk might be diminished. The most important of these is to diminish greenhouse gas emissions. However, we also need to improve our resilience so that we can better adapt to the climate change that does occur. We also need to understand whether there are ways that we can cost-effectively remove carbon dioxide and perhaps other greenhouse gases from the atmosphere. Lastly, we should try to understand whether a thoughtful intentional intervention in the climate system might be able to undo some of the damage of a thoughtless unintentional intervention in the climate system. This problem is too serious to allow prejudice to take options off the table.

Geoengineering to Shade Earth

Ken Caldeira

In June 1991, Mount Pinatubo in the Philippines erupted explosively—the biggest eruption of the twentieth century. The volcano created a column of ash and debris extending upward 40 kilometers (about 25 miles). The eruption ejected around 20 million tons of sulfur dioxide into the stratosphere, where it oxidized to form sulfate dust particles. The stratosphere is the part of the atmosphere that is higher than where jets normally fly.[1]

As a result, about 2 percent of the sunlight passing down through the stratosphere was deflected upward and back into space. The dust particles were big enough to scatter sunlight away from Earth but small enough to allow Earth's radiant heat energy to escape into space. Earth cooled about half a degree Celsius (almost 1 degree Fahrenheit) the following year, despite the continued increase in greenhouse gas concentrations. This raises an obvious question: Could we similarly put dust into the stratosphere to offset climate change?[2]

Earth is heated by sunlight and cooled by the escape of radiant heat into space. Earth's atmosphere is relatively transparent in the wavelengths that make up sunlight but somewhat opaque in the wavelengths that make up escaping radiant heat energy. As greenhouse gases accumulate, the atmosphere becomes more opaque to outgoing radiant heat. With greater amounts of radiant heat trapped in the lower atmosphere, Earth's surface warms.[3]

The most obvious approach to keeping Earth cool is to reduce greenhouse gas concentrations in the atmosphere, so that heat energy can escape more easily into space. But another strategy involves reducing the amount of sunlight absorbed by Earth. If greenhouse gases accumulating in the atmosphere are like closing the windows of a greenhouse and trapping heat inside, then "geoengineering" approaches seek to keep Earth cool by putting the greenhouse partially in the shade. They try to reverse warming by preventing sunlight from being absorbed by Earth.[4]

A number of modeling and theoretical studies have looked into such climate engineering schemes. The consensus appears to be that these will not perfectly reverse the climate effects of increased greenhouse gases but that it might be technically feasible to use geoengineering to reduce the overall amount of climate change. Obviously, however, these schemes would not reverse the chemical effects of increased carbon dioxide (CO_2) in the environment, such as ocean acidification or the CO_2-fertilization of land plants.[5]

Several approaches have been suggested for deflecting sunlight away from Earth. The most science-fiction scheme would be to place sunlight-blocking satellites between Earth and the sun. But in order to compen-

Ken Caldeira is a climate scientist at the Department of Global Ecology at the Carnegie Institution for Science in Stanford, California.

sate for the current rate of increases of greenhouse gases in the atmosphere, governments would need to build and put in place more than a square mile (about 3 square kilometers) of satellite every hour. Most people would probably agree that such an enormous effort would be better applied to reducing greenhouse gas emissions.[6]

The placement of sulfur dust particles in the stratosphere appears to be the leading candidate for most easily engineering Earth's climate. (Numerous other approaches have been suggested, including some designed to increase the whiteness of clouds over the ocean with sea salt particles formed by spraying seawater in the lower atmosphere.) Tiny particles have a lot of surface area, so a lot of sunlight can be scattered with a relatively small amount of dust. The full amount of sulfur from Mount Pinatubo, if it had remained in the stratosphere for a long time, would have been more than enough to offset the warming (at least, on a global average) from a doubling of atmospheric carbon dioxide content. The actual short-lived cooling from the Mount Pinatubo eruption turned out to be much less because the oceans helped keep Earth warm despite the reduction in the amount of absorbed sunlight.[7]

The sulfur from Mount Pinatubo remained in the stratosphere only for a year or two. To maintain a dust shield in the stratosphere for the long term would require continual dust injection. It is thought that a small fleet of planes, or perhaps a single fire hose to the sky suspended by balloons, would be enough to keep the dust shield in place. Costs are uncertain, but it might total less than a few billion dollars a year. The amount of sulfur required would be a few percent of what is currently emitted from power plants and so would contribute somewhat to the acid raid problem.[8]

Why might policymakers want to deploy

Karin Jackson, U.S. Air Force

Mount Pinatubo erupting on June 12, 1991, as seen from Clark Air Force base eight miles away

climate engineering systems? The main reason is to reduce climate damage and the risk of further damage from greenhouse gases. Some commentators deny the reality of human-caused greenhouse warming but think it worth developing climate engineering systems as an insurance policy—just in case events prove them wrong. Others accept human-induced climate change but think reducing emissions will be either too costly or too difficult to achieve, so they favor climate engineering as an alternative approach. Some people fear that a climate crisis may be imminent or already unfolding and that these systems are needed right away to reduce negative climate impacts such as the loss of Arctic ecosystems while the world works to reduce greenhouse gas emissions in the longer term. Still others think climate engineering is needed as an emergency response system in case an unexpected climate emergency occurs while greenhouse gases are being reduced.[9]

There are also many reasons not to develop climate engineering, some of them having to do with climate science and some having to do with social systems. These schemes will not work perfectly, for example, and there is some chance that unanticipated consequences will prove even more environmentally damaging than the problems they are designed to solve. Concerns include possible effects on the ozone layer or patterns of precipitation and evaporation. Climate engineering would not solve the ocean acidification problem, although it would not directly make it worse either.[10]

Some observers fear that the mere perception that there is an engineering fix to the climate problem will reduce the amount of effort placed on emissions reduction. Climate engineering could lull people into complacency and produce even greater emissions and ultimately greater climate damage. (On the other hand, such schemes also could frighten people into redoubling efforts to reduce greenhouse gas emissions.) And it might work well at first, with negative consequences manifesting themselves strongly only as greenhouse gas concentrations and the offsetting climate engineering effort both continued to grow.[11]

Climate engineering will affect everyone on the planet, but there is no clear way to develop an international consensus on whether it should be attempted and, if so, how and when. It would likely produce winners and losers and therefore has the potential to generate both political friction and legal liability. Conflict over deployment could produce political strife and social turmoil. (On the other hand, any success at reducing climate damage could lessen strife and turmoil.)

From the perspective of physical science and technology, it appears that climate engineering schemes have the potential to lower but not eliminate the risk of climate damage from greenhouse gas emissions, yet unanticipated effects and difficult-to-predict political and social responses could mean increased risk. Thus the bottom line is that climate engineering schemes have the potential to make things better, but they could also make things worse.

Chairman GORDON. Thank you, Dr. Caldeira. And Professor Shepherd, you are recognized.

STATEMENT OF PROFESSOR JOHN SHEPHERD, FRS, PROFESSIONAL RESEARCH FELLOW IN EARTH SYSTEM SCIENCE, NATIONAL OCEANOGRAPHY CENTRE, UNIVERSITY OF SOUTHAMPTON, AND CHAIR, ROYAL SOCIETY GEOENGINEERING REPORT WORKING GROUP

Professor SHEPHERD. Good morning, Mr. Chairman, Ranking Member, members of the Committee, ladies and gentlemen, thank you very much for the invitation to come and testify to you this morning. It is a privilege to have that opportunity, and my testimony will be largely based on the Royal Society study that you mentioned, Mr. Chairman, which was undertaken over the past year and which I chaired. The report of this study was published in September, and it is available on the Royal Society's website, and printed copies have been made available to the Committee.

The aim of this study was really to try and produce an authoritative and wide-ranging review to reduce the confusion and misinformation which exists in some quarters about this rather controversial and novel issue in order to enable a well-informed debate on the subject, and so it is a great pleasure for me to be here at the beginning of such a debate, and I hope that our work will be useful.

The Working Group was composed of 12 members, mainly scientists and engineers from the U.K., but also included a sociologist, a lawyer and an economist and one member from the U.S.A., Dr. Caldeira on my left, and one from Canada. And the members of the group were not proponents of geoengineering; they reflected a very wide range of opinions on the subject, and all recognize that the primary goal is to make the transition to the low-carbon economy that Dr. Caldeira has already mentioned which we shall need to do eventually irrespective of climate change simply because fossil fuels are a finite resource.

So our terms of reference were to consider and as far as possible to evaluate proposed schemes for geoengineering, which we took to mean the deliberate, large-scale intervention in the earth's climate system primarily in order to moderate the global warming. Our study was based primarily on a review of the literature but also by a call for submissions of evidence, of which we received some 75.

Since time is short, I would like to move directly to summarize the key messages of our study and first among these is that geoengineering is not a magic bullet. None of the methods that have been proposed provide an easy or immediate solution to the problems of climate change. There is a great deal of uncertainty about various aspects of virtually all the schemes that are being discussed. So at present, this technology, in whatever form it takes, is not an alternative to emissions reductions which remain the safest and most predictable method of moderating climate change, and in our view cutting global emissions of greenhouse gases must remain our highest priority.

However, we all recognize that this is proving to be difficult, and in the future, given adequate research, geoengineering may be useful to support the efforts to mitigate climate change by conventional means.

We concluded that geoengineering is very likely to be technically possible, but there are major uncertainties and risks with all methods concerning not only their effectiveness but also their costs, their unintended environmental impacts, and the social consequences and mechanisms needed to manage them.

So in our view, this is not a technology which is ready for deployment in the immediate future. It is, however, a technology that may be useful at some point in the future if we find that we have need of it. But it will not be available unless we undertake the necessary research, not only on the technology but particularly also on the environmental and social impacts of such proposals. And to do that we need to have a widespread public debate and widespread public engagement and especially to develop an acceptable system of governance. Geoengineering by intention will affect everybody on the planet because it is an intentional moderation of the environment, and consequently everybody has an interest in the outcome. And we need to find a way to engage the opinions of a very diverse group of people on the planet in order that this can be done in an orderly and acceptable manner.

Dr. Caldeira has reviewed the major differences between some of the methods, which I support entirely. And I would say finally, too little is known about the technologies at this stage to pick a winner. What we need is research on a small portfolio of promising techniques of both major types in order that our Plan B will be well prepared, should we ever need it.

Mr. Chairman, thank you very much.

[The prepared statement of Professor Shepherd follows:]

PREPARED STATEMENT OF JOHN SHEPHERD

Preamble

This testimony is based extensively on the results of the U.K. Royal Society study undertaken during 2008 and 2009, which I chaired, entitled **"Geoengineering the Climate: Science, Governance & Uncertainty".** The report of this study was published in September 2009. It is available at on-line at *http://royalsociety.org/document.asp?tip=0&id=8770,* and printed copies of it have also been made available to the Committee. For the study we considered Geoengineering to be **the deliberate largescale intervention in the Earth's climate system,** in order to moderate global warming. The study was based primarily on a review of the available literature (concentrating so far as possible on published papers which have been peer reviewed) but also supplemented by a call for submissions of evidence (of which ~75 were received).

Key Messages

- **Geoengineering is not a magic bullet:** none of the methods proposed provides an easy or immediate solution to the problems of climate change, and it is not an alternative to emissions reductions.
- **Cutting global emissions of greenhouse gases must remain our highest priority.** However, this is proving to be difficult, and geoengineering may in the future prove to be useful to support mitigation efforts.
- **Geoengineering is very likely to be technically possible.** However, **there are major uncertainties and thus potential risks with all methods,** concerning their effectiveness, costs, and social & environmental impacts.
- **Much more research is needed** before geoengineering methods could realistically be considered for deployment, especially on their possible environmental impacts (as well as on technological and economic aspects).

- **Widespread public engagement and debate is also needed,** especially to develop an acceptable **system of governance & regulation** (for both eventual deployment and for some research activities)

Other major issues

Geoengineering comprises a very wide range of methods which vary in many ways. This includes:

- **Methods that remove greenhouse gases from atmosphere** (e.g. engineered air capture).
  - These address the root cause of problem and would be generally preferred, but they only **act slowly** and are likely to **be costly.**
- **Methods that reflect a little sunlight** (e.g. small particles in the upper atmosphere)
  - **These act quickly,** and are **relatively cheap,** but have to be maintained so they **may not be sustainable** in the long term (there is a major problem if you stop) and they do nothing for ocean acidification (the "other CO_2 problem").

We do not yet have enough information, so it is too soon to pick winners, and if geoengineering is ever deployed we may need a combination of both types of method. We therefore **need to commence serious research and development** on several of the promising methods, as soon as possible.

1) Introduction

It is not yet clear whether, and if so when, it may become necessary to consider deployment of geoengineering to augment conventional efforts to moderate climate change by mitigation, and to adapt to its effects. However, global efforts to reduce emissions have not yet been sufficiently successful to provide confidence that the reductions needed to avoid dangerous climate change will be achieved. There is a serious risk that sufficient mitigation actions will not be introduced in time, despite the fact that the technologies required are both available and affordable. It is likely that global warming will exceed 2° C this century unless global CO_2 emissions are cut by at least 50% by 2050, and by more thereafter. There is no credible emissions scenario under which global mean temperature would peak and then start to decline by 2100. Unless future efforts to reduce greenhouse gas emissions are much more successful then they have been so far, additional action such as geoengineering may be required should it become necessary to cool the Earth this century.

Proposals for geoengineering for climate intervention are numerous and diverse, and for our study we deliberately adopted a broad scope in order to provide a wide-ranging review. There has been much discussion in the media and elsewhere about possible methods of geoengineering, and there is much misunderstanding about their feasibility and potential effectiveness and other impacts. The overall aim of study was therefore **to reduce confusion & misinformation, and so to enable a well-informed debate** among scientists & engineers, policy-makers and the wider public on this subject.

The working group which undertook the study was composed of 12 members (listed below). These were mainly scientists & engineers, but also included a sociologist, a lawyer and an economist. The members were mainly from U.K. but included one member from the U.S.A. and one from Canada, and the study itself had an international remit. The WG members were not advocates of geoengineering, and held a wide range of opinions on the subject, ranging from cautious approval to serious scepticism.

The **terms of reference** for the study were **to consider, and so far as possible evaluate,** proposed schemes for moderating climate change by means of geoengineering techniques, and specifically:

1) to consider **what is known, and what is not known,** about the **expected effects, advantages and disadvantages** of such schemes
2) to assess their **feasibility, efficacy, likely environmental impacts,** and any **possible unintended consequences**
3) to identify **further research requirements,** and any specific **policy and legal implications.**

The scope adopted included any methods intended to moderate climate change by deliberate large-scale intervention in the working of the Earth's natural climate system, but excluded:

a) Low-carbon energy sources & methods for reducing emissions of greenhouse gases (because these are methods for conventional mitigation, not geoengineering)
b) carbon capture & storage (CCS) at the point of emission, and
c) conventional afforestation and avoided deforestation schemes (because these are also not *geoengineering per se* and have been extensively considered elsewhere)

2) General issues

The methods considered fall into two main classes, which differ greatly in many respects, including their modes of action, the timescales over which they are effective, their effects on temperature and on other aspects of climate, so that they are generally best considered separately. These classes are:

1) **Carbon dioxide removal (CDR)** techniques which address the root cause of climate change by removing greenhouse gases from the atmosphere;
2) **Solar Radiation Management (SRM)** techniques that attempt to offset the effects of increased greenhouse gas concentrations by reflecting a small percentage of the sun's light and heat back into space.

Carbon Dioxide Removal methods reviewed in the study include:

- Land use management to protect or enhance land carbon sinks;
- The use of biomass for carbon sequestration as well as a carbon neutral energy source ;
- Acceleration of natural weathering processes to remove CO_2 from the atmosphere;
- Direct engineered capture of CO_2 from ambient air;
- The enhancement of oceanic uptake of CO_2, for example by fertilisation of the oceans with naturally scarce nutrients, or by increasing upwelling processes.

Solar Radiation Management techniques would take only a few years to have an effect on climate once they had been deployed, and could be useful if a rapid response is needed, for example to avoid reaching a climate threshold. Methods considered in the study include:

- Increasing the surface reflectivity of the planet, by brightening human structures (e.g. by painting them white), planting of crops with a high reflectivity, or covering deserts with reflective material;
- Enhancement of marine cloud reflectivity;
- Mimicking the effects of volcanic eruptions by injecting sulphate aerosols into the lower stratosphere;
- Placing shields or deflectors hi space to reduce the amount of solar energy reaching the Earth.

The scale of the impact required is global, and its magnitude is large. To have a significant effect on man-made global warming by an SRM method one would need to achieve a negative radiative forcing of a few WIm2, and for an effective CDR method one would need to remove several billion tons of carbon per year from the atmosphere for many decades. We did not consider in any detail any methods which were not capable of achieving effects approaching this magnitude.

There are many criteria by which geoengineering proposals need to be evaluated, and some of these are not easily quantified. We undertook a preliminary and semi-quantitative evaluation of the more promising methods according to our judgement of several technical criteria only, namely their effectiveness, affordability, safety and timeliness. The cost estimates available are extremely uncertain, and it would be premature to attempt detailed cost-benefit analysis at this time.

3) Technical Aspects: feasibility, cost, environmental impacts and side-effects

Our study concluded that geoengineering of the Earth's climate is very likely to be technically possible. However, the technology to do so is barely formed, and there are major uncertainties regarding its effectiveness, costs, and environmental impacts. If these uncertainties can be reduced, geoengineering methods could in the future potentially be useful in future to augment continuing efforts to mitigate climate change by reducing emissions. Given these uncertainties, it would be appropriate to adopt a precautionary approach: to enable potential risks to be assessed and avoided requires more and better information. Potentially useful methods should therefore be the subject of more detailed research and analysis, especially on their possible environmental impacts (as well as on technological and economic aspects).

In most respects Carbon Dioxide Removal methods would be preferable to Solar Radiation Management methods, because they effectively return the climate system to a state closer to its natural state, and so involve fewer uncertainties and risks. Of the Carbon Dioxide Removal methods assessed, none has yet been demonstrated to be effective at an affordable cost, with acceptable side effects. In addition, removal of CO_2 from the atmosphere only works very slowly to reduce global temperatures (over many decades). If safe and low cost methods can be deployed at an appropriate scale they could make an important contribution to reducing CO_2 concentrations and could provide a useful complement to conventional emissions reductions. It is possible that they could even allow future reductions of atmospheric CO_2 concentrations (negative emissions) and so address the ocean acidification problem.

Carbon Dioxide Removal methods that remove CO_2 from the atmosphere without perturbing natural systems, and without large-scale land-use change requirements, such as CO_2 capture from air and possibly also enhanced weathering are likely to have fewer side effects. Techniques that sequester carbon but have land-use implications (such as biochar and soil based enhanced weathering) may be useful contributors on a small-scale although the circumstances under which they are economically viable and socially and ecologically sustainable remain to be determined. The extent to which methods involving large-scale manipulation of Earth systems (such as ocean fertilisation), can sequester carbon affordably and reliably without unacceptable environmental side-effects, is not yet clear.

Solar Radiation Management techniques are expected to be relatively cheap and would take only a few years to have an effect on the climate once deployed. However there are considerable uncertainties about their consequences and additional risks. It is possible that in time, assuming that these uncertainties and risks can be reduced, that Solar Radiation Management methods could be used to augment conventional mitigation. However, the large-scale adoption of Solar Radiation Management methods would create an artificial, approximate, and potentially delicate balance between increased gas concentrations and reduced solar radiation, which would have to be maintained, potentially for many centuries. It is doubtful that such a balance would really be sustainable for such long periods of time, particularly if emissions of greenhouse gases were allowed to continue or even increase. The implementation of any large-scale Solar Radiation Management method would introduce additional risks and so should only be undertaken for a limited period and in parallel with conventional mitigation and/or Carbon Dioxide Removal methods.

Of the Solar Radiation Management techniques considered, stratospheric aerosol methods have the most potential because they should be capable of producing large and rapid global temperature reductions, because their effects would be more uniformly distributed than for most other methods, and they could be readily implemented. However, potentially there are significant side-effects and risks associated with these methods that would require detailed investigation before large-scale experiments are undertaken. Cloud brightening methods are likely to be less effective and would produce primarily localised temperature reductions, but they may prove to be readily implementable, and should be testable at small scale with fewer governance issues than other SRM methods. Space based SRM methods would provide a more uniform cooling effect than surface or cloud based methods, and if long-term geoengineering is required, may be a more cost-effective option than the other SRM methods although development of the necessary technology is likely to take decades.

4) The Human Dimension (Public Attitudes, Legal, Social & Ethical issues)

The acceptability of geoengineering will be determined as much by social, legal and political issues as by scientific and technical factors. There are serious and complex governance issues which need to be resolved if geoengineering is ever to become an acceptable method for moderating climate change. Some geoengineering methods could probably be implemented by just one nation acting independently, and some maybe even by corporations or individuals, but the consequences would affect all nations and all people, so their deployment should be subject to robust governance mechanisms. There are no existing international treaties or bodies whose remit covers all the potential methods, but most can probably be handled by the extension of existing treaties, rather than creating wholly new ones. The most appropriate way to create effective governance mechanisms needs to be determined, and a review of existing bodies, treaties and mechanisms should be initiated as a high priority. It would be highly undesirable for geoengineering methods which involve activities or effects that extend beyond national boundaries (other than simply the removal of greenhouse gases from the atmosphere), to be deployed before appropriate governance mechanisms are in place.

Overall Conclusion

The safest and most predictable method of moderating climate change is to take early and effective action to reduce emissions of greenhouse gases. No geoengineering method can provide an easy or readily acceptable alternative solution to the problem of climate change.

Key recommendations:

- Parties to the UNFCCC **should make increased efforts towards mitigating and adapting to climate change,** and in particular to agreeing to global emissions reductions of at least 50% by 2050 and more thereafter. **Nothing now known about geoengineering options gives any reason to diminish these efforts.**
- **Further research and development of geoengineering options should be undertaken** to investigate whether low risk methods can be made available if it becomes necessary to reduce the rate of warming this century. This should include **appropriate observations, the development and use of climate models, and carefully planned and executed experiments.** We suggested an expenditure of around £10M per year for ten years as an appropriate initial level for a U.K. contribution to an international programme, to which we would hope that the U.S.A. would also contribute a substantially larger amount.

Members of the working group

Chair
Professor John Shepherd, University of Southampton, U.K.

Members
Professor Ken Caldeira, Carnegie Institution, U.S.A.
Professor Peter Cox, University of Exeter, U.K.,
Professor Joanna Haigh, Imperial College, London, U.K.
Professor David Keith, University of Calgary, Canada.
Professor Brian Launder, University of Manchester, U.K.
Professor Georgina Mace, Imperial College, London, U.K.
Professor Gordon MacKerron, University of Sussex, U.K.
Professor John Pyle, University of Cambridge, U.K.
Professor Steve Rayner, University of Oxford, U.K.

BIOGRAPHY FOR JOHN SHEPHERD

Professor John Shepherd MA Ph.D. CMath FLMA FRS is a Professorial Research Fellow in Earth System Science in the School of Ocean and Earth Science, National Oceanography Centre, University of Southampton, U.K. He is a physicist by training, and has worked on the transport of pollutants in the atmospheric boundary layer, the dispersion of tracers in the deep ocean, the assessment & control of radioactive waste disposal in the sea, on the assessment and management of marine fish stocks, and most recently on Earth System Modelling and climate change. His current research interests include the natural variability of the climate system on long time-scales, and the development of intermediate complexity models of the Earth climate system for the interpretation of the palaeo-climate record. He graduated {first degree in 1967 and Ph.D. in 1971) from the University of Cambridge. From 1989–94 he was Deputy Director of the MAFF Fisheries Laboratory at Lowestoft, and the principal scientific adviser to the U.K. government on fisheries management. From 1994–99 he was the first Director of the Southampton Oceanography Centre. He has extensive experience of international scientific assessments and advice in the controversial areas of fisheries management, radioactive waste disposal, and climate change, and has recently taken a particular interest in the interaction between science and public policy. He is Deputy Director of the Tyndall Centre for Climate Change Research, and a Fellow of the Institute of Mathematics and its Applications. He was elected a Fellow of the Royal Society in 1999, participated in the Royal Society study on Ocean Acidification published in 2005, and chaired that on Geoengineering the Climate published in 2009.

Chairman GORDON. Thank you, Professor Shepherd. And now, Mr. Lane, you are recognized.

STATEMENT OF MR. LEE LANE, CO-DIRECTOR, AMERICAN ENTERPRISE INSTITUTE (AEI) GEOENGINEERING PROJECT

Mr. LANE. Chairman Gordon, Ranking Member Hall, other Members of the Committee, thank you very much for the opportunity to appear here this morning.

I am Lee Lane. I am a Resident Fellow and head of the AEI Geoengineering Project. The American Enterprise Institute is a non-profit, non-partisan organization that engages in research and education on issues of public policy. AEI does not take organizational stances on the issues that it studies, and the views that I am going to express here this morning are entirely my own.

I want to begin by warmly commending the Committee for convening this hearing, and my statement fundamentally urges that you treat this session as a first step toward embarking upon a serious, sustained and systematic exploration by the U.S. Government of research and development into solar radiation management in particular, one of the two approaches to climate engineering discussed by Dr. Caldeira and Dr. Shepherd.

Solar radiation management, or SRM, as the Committee has heard, envisions offsetting manmade global warming by slightly raising the amount of sunlight that the earth reflects back into space. In a recent study, a panel of five highly acclaimed economists, including three Nobel laureates, rated R&D for two solar radiation management concepts as the first- and third-most productive kinds of investment that can be made in dealing with climate change. Now, the panel that did those rankings was well aware of the large uncertainties that continue to surround solar radiation management, and they were also aware of the fact that, in the long run, at least solar radiation management cannot replace the need for greenhouse gas emissions reductions. But at the same time, the panel was clearly very much aware of the vast potential that solar radiation management has.

One preliminary assessment is that SRM, if deployed, might well produce savings in terms of reduce damages from climate change, in terms of $200 to $700 billion a year. So we have potentially a good deal of upside with this technology.

The cost of an R&D effort into solar radiation management is likely to be miniscule in comparison with these potential benefits. SRM research is needed in part because for many nations, steep reductions in greenhouse gas emissions cost more than the perceived value of the benefits of making those reductions. The record of the last 20 years of climate talks amply demonstrates that the prospects for steep emissions reductions on a global scale are poor, and they are likely to remain so for an extended period of time. Yet, without such emissions reductions, and perhaps even with them, some risk exists that quite harmful climate change might occur. An SRM system might greatly reduce the potential for harm. SRM, it is true, carries some hazards of its own. An R&D program, though, provides the best chance of gaining the information that might be needed, both to assess the prospects of SRM in a more knowledgeable way and also perhaps to find ways of minimizing those risks in the future.

At this point, the top priority should be to gain added knowledge about SRM. Eventually, the United States may wish to address questions of international governance, but at this point, our first goal should be to learn more about solar radiation management as a tool.

I guess the single most important caution that I would like to leave with the Committee is that the governance arrangements for any research program, including one on solar radiation management, can either serve to nurture R&D success or they can serve to stifle it. And I think it is awfully important as we go forward in considering how we want to manage research and development into SRM that we keep in mind the need to balance the risks and the benefits of how we structure our R&D efforts.

Thank you very much.

[The prepared statement of Mr. Lane follows:]

PREPARED STATEMENT OF LEE LANE

1 Introduction

1.1 Summary

Chairman Gordon, ranking member Hall, other members of the Committee, thank you for the opportunity to appear before you today. I am Lee Lane, a Resident Fellow at the American Enterprise Institute, where I am also co-director of AEI's geoengineering project. AEI is a nonpartisan, non-profit organization conducting research and education on public policy issues. AEI does not adopt organizational positions on the issues that it studies, and the views that I express here are solely my own.

The Committee is to be commended for its decision to address the issue of geoengineering as a possible response to climate change. Climate change is an extremely difficult issue. It poses multiple threats that are likely to evolve over time. Too often, climate policy discussions have been locked into an excessively narrow range of possible responses.

My statement this morning urges that the committee treat this hearing as a first step in what should grow into a serious, sustained, and systematic effort by the U.S. government to conduct research and development (R&D) on solar radiation management (SRM). SRM, as the committee has heard, envisions offsetting man-made global warming by slightly raising the amount of sunlight that the Earth reflects back into space.

In a recent study, a panel of five highly acclaimed economists, including three Nobel laureates, rated fifteen possible concepts for coping with climate change. The rankings were based on the panel's assessments of the ratio of benefits to costs of each approach. Research on the two SRM technologies discussed below ranked first and third among these concepts. The expert panel was aware that many doubts continue to surround SRM, but its members were also clearly impressed with SRM's vast potential as one tool among several for holding down the cost of climate change.

Research into SRM is needed in part because, for many nations, a steep decline in greenhouse gas (GHG) emissions may well cost more than the perceived value of its benefits (Nordhaus, 2008; Tol, 2009; Posner and Sunstein, 2008). The record of the last twenty years of climate negotiations amply demonstrates that steep emission reductions are unlikely, and will probably remain so for a long time to come. Yet, without such controls, and even with them, some risk exists that quite harmful climate change might occur.

A successful SRM system could greatly reduce the risk of these harmful effects. SRM, it is true, carries some risks of its own. An R&D program may, however, provide additional information with which to assess these risks and, perhaps, to devise means to limit them. The potential net benefits of SRM are very large indeed. One recent study found that the difference between the costs of deploying SRM and the savings it could reap amount to $200 billion to $700 billion (Bickel and Lane, 2009).

The costs of an R&D effort appear to be minuscule compared with these possible gains.

1.2 Main SRM concepts

SRM aims to offset the warming caused by the build-up of man-made greenhouse gases in the atmosphere by reducing the amount of solar energy absorbed by the Earth. GHGs in the atmosphere absorb long-wave radiation (thermal infrared or heat) and then radiate it in all directions-including a fraction back to Earth's surface, raising global temperature. SRM does not attack the higher GHG concentrations. Rather, it seeks to reflect into space a small part of the sun's incoming short-wave radiation. In this way, temperatures are lowered even though GHG levels are elevated. At least some of the risks of global warming can thereby be counteracted (Lenton and Vaughan, 2009).

Reflecting into space only one to two percent of the sunlight that strikes the Earth would cool the planet by an amount roughly equal to the warming that is likely from doubling the pre-industrial levels of greenhouse gases (Lepton and Vaughan, 2009). Scattering this amount of sunlight appears to be possible.

Several SRM concepts have been proposed. They differ importantly in the extent of their promise and in the range of their possible use. At least two such concepts appear to be promising at a global scale: marine cloud whitening and stratospheric aerosols.

1.2.1 Marine Cloud Whitening

One current proposal envisions producing an extremely fine mist of seawater droplets. These droplets would be lofted upwards and would form a moist sea salt aerosol. The particles within the aerosol would be less than one micron in diameter. These particles would provide sites for cloud droplets to form within the marine cloud layer. The up-lofted droplets would add to the effects of natural sea salt and other small particles, which are called, collectively, cloud condensation nuclei (Latham *et al.,* 2008). The basic concept was succinctly described by one of its developers:

> Wind-driven spray vessels will sail back and forth perpendicular to the local prevailing wind and release micronsized drops of seawater into the turbulent boundary layer beneath marine stratocumulus clouds. The combination of wind and vessel movements will treat a large area of sky. When residues left after drop evaporation reach cloud level they will provide many new cloud condensation nuclei giving more but smaller drops and so will increase the cloud albedo to reflect solar energy back out to space." (Salter *et al.,* 2008)

The long, white clouds that form in the trails of exhaust from ship engines illustrate this concept. Sulfates in the ships' fuel provide extra condensation nuclei for clouds. Satellite images provide clear evidence that these emissions brighten the clouds along the ships' wakes.

Currently, the widely discussed option for implementing this approach envisions an innovative integration of several advanced technologies. The system calls for wind-powered, remotely controlled ships (Salter *et al.,* 2008). However, other more conventional deployment systems may also be possible (Royal Society, 2009).

Analyses using the general circulation model of the Hadley Center of the U.K. Meteorological Office suggest that the marine clouds of the type considered by this approach contribute to cooling. They show that augmenting this effect could, in theory, cool the planet enough to offset the warming caused by doubling atmospheric GHG levels. A relatively low percentage of the total marine cloud cover would have to be enhanced in order to achieve the desired result. A British effort is developing hardware with which to test the feasibility of this concept (Bower *et al.,* 2006).

1.2.2 Stratospheric Aerosols

Tnserting aerosols into the stratosphere is another approach. The record of several volcanic eruptions offers a close and suggestive analogy. The global cooling from the large Pinatubo eruption (about .5 degrees Celsius) that occurred in 1991 was especially well-documented (Robock and Mao, 1995). Such eruptions loft particles into the atmosphere. There, the particles scatter back into space some of the sunlight that would otherwise have warmed the surface. As more sunlight is scattered, the planet cools.

Injecting sub-micron-sized particles into the stratosphere might mimic the cooling effects of these natural experiments. Compared to volcanic ash, the particles would be much smaller in size. Particle size is important because small particles appear to be the most effective form for climate engineering (Lepton and Vaughan, 2009). Eventually, the particles would descend into the lower atmosphere. Once there, they would precipitate out. "The total mass of such particles would amount to the equivalent of a few percent of today's sulfur emissions from power plants" (Lane *et al.,* 2007). If adverse effects appeared, most of these effects would be expected to dissipate once the particles were removed from the stratosphere.

Sulfur dioxide (SO_2), as a precursor of sulfate aerosols, is a widely discussed candidate for the material to be injected. Other candidates include hydrogen sulfide (H_2S) and soot (Crutzen, 2006). A fairly broad range of materials might be used as stratospheric scatterers (Caldeira and Wood, 2008). It might also be possible to develop engineered particles. Such particles might improve on the reflective properties and residence times now envisioned (Teller *et al.,* 2003).

The volumes of material needed annually do not appear to be prohibitively large. One estimate is that, with appropriately sized particles, material with a combined volume of about 800,000 m3 would be sufficient. This volume roughly corresponds to that of a cube of material of only about 90 meters on a side (Lane *et al.,* 2007). The use of engineered particles could, in comparison with the use of sulfate aerosols, potentially reduce the mass of the particles by orders of magnitude (Teller *et al.,* 2003).

Several proposed delivery techniques may be feasible (NAS, 1992). The choice of the delivery system may depend on the intended purpose of the SRM program. In one concept, SRM could be deployed primarily to cool the Arctic. With an Arctic deployment, large cargo planes or aerial tankers would be an adequate delivery system (Caldeira and Wood, pers. comm., 2009). A global system would require particles to be injected at higher altitudes. Fighter aircraft, or planes resembling them, seem like plausible candidates. Another option entails combining fighter aircraft and aerial tankers, and some thought has been given to balloons (Robock *et al.,* 2009).

1.3 Air capture of CO_2 (AC)

Air capture (AC) of carbon dioxide (CO_2) is the second family of climate engineering concepts. AC focuses on removing CO_2 from the atmosphere and securing it in land- or sea-based sinks.

> "Air capture may be viewed as a hybrid of two related mitigation technologies. Like carbon sequestration in ecosystems, air capture removes CO_2 from the atmosphere, but it is based on large-scale industrial processes rather than on changes in land use, and it offers the possibility of near-permanent sequestration of carbon." (Keith *et al.,* 2005).

Like carbon capture and storage (CCS), air capture involves long-term storage of CO_2, but air capture removes the CO_2 directly from the atmosphere rather than from the exhaust streams of power plants and other stationary sources (Bickel and Lane, 2009).

Were technological progress to greatly lower the costs of AC, this approach might offer a number of advantages. However, even with costs far below those that are now possible, large-scale AC appears to face huge cost penalties vis-à-vis SRM. For instance, compare the cost of using AC to achieve the cooling possible with one W m^{-22} of SRM. The present value cost of achieving this goal (over a 200-year period) with AC is (very optimistically) $5.6 trillion. The direct cost of SRM might well be less than $0.5 trillion (Bickel and Lane, 2009).

Proponents of AC may argue that even this low level of SRM might entail some costs from unwanted side effects. AC, they may also note, conveys some added benefits with regard to ocean acidification. These points are well-taken; yet it is far from clear that, when taken together, these benefits would be worth anything even remotely near $5 trillion. It seems safe to conclude that, compared with SRM, when economics is accounted for, AC should be a distinctly lower priority target for R&D. Thus, the rest of my remarks this morning will focus on SRM.

2 Deploying SRM might yield large net benefits

2.1 Initial estimates of benefits and direct costs

Expert opinion suggests that SRM is very likely to be a feasible and effective means of cooling the planet (Royal Society, 2009). Indeed, this concept may have more upside potential than does any other climate policy option. At the same time, SRM, like all other options, entails risks, and these will be discussed below.

As noted earlier, recent study found that the benefits of SRM exceeded the costs of operating the system by an amount that would translate into $200 billion to $700 billion per year (Bickel and Lane, 2009). Some of these benefits stem from lowering the economic harm expected from climate change. SRM, by lowering the risk of rapid climate change, would also allow a more gradual path toward GHG control—lowering the total costs of controls.

It is quite true that these benefit estimates are preliminary and subject to many limitations. They do not, for instance, account for the indirect costs implied by possible unwanted side effects of SRM. These indirect costs could be substantial, and the next section of my statement will discuss them. At the same time, the estimate excludes several factors that would be likely to increase the estimated benefits.

2.2 Abrupt climate change might increase the value of SRM

For example, some grounds exist for fearing that many of the current models understate the risks of extremely harmful climate change (Weitzman, 2008). Emission controls, even if they could be implemented effectively, *i.e.* globally, require more than a century before actually cooling the planet (IPCC, 2007). SRM, however, might stand a much better chance of preventing the worst should such a nightmare scenario begin to unfold. Once developed, either of the two techniques discussed above could be deployed very rapidly. The low costs of SRM mean that a few nations working together, or even a single advanced state, could act to halt warming, and it could do so quickly (Barrett, 2009).

Merely developing the capacity to deploy SRM, therefore, is like providing society with a climate change parachute. And like a real parachute, having it may be valuable even if it is not actually deployed. In general, the more one credits the risk of rapid, highly destructive climate change, the greater is the potential value of SRM.

2.3 Suboptimal controls will raise the value of SRM

Less-than-optimal GHG emission controls, or no controls, would decrease global economic welfare, but these flawed policies would actually increase the positive contribution of SRM. This fact is important because actual GHG controls are certain to be far from the broad, uniform, price-based incentives that economic analysis calls for. In fact, few, if any, countries are likely to implement controls of this kind (Lane and Montgomery, 2009).

Excess GHG emissions are an example of a fairly common kind of market failure, which can arise when property rights allow open access to a valuable resource. Instances include open access to grazing land, fishing grounds, or to oil and gas reservoirs. Open access can cause under-investment in maintaining the resource and too much consumption of it (Eggertsson, 2003). In the case of climate, the open access resource is the atmosphere's capacity to absorb GHG discharges.

In principle, collective action could solve the problem by limiting access. In practice, efforts to limit open access property rights often founder. For example, wild ocean fish stocks are being seriously depleted. Curbs on the over-pumping of oil and gas resources have sometimes worked, but often they have only done so after a great deal of economic waste had already occurred (Libecap, 2008). So far, GHG control has been another instance of this pattern of frequent failure.

Further, GHG control has many of the features that make an effective global solution more difficult to attain. In such transactions, the more diverse are the interests of the parties, the poorer are the prospects for success (Libecap, 2008). Contrasting value judgments often cause conflict (Alston and Mueller, 2008). With GHG controls, the differing interests of richer and poorer nations have emerged as especially problematic (Bial *et al.,* 2001).

Thus, for China and India, economic development offers better protection from harmful climate change than do GHG limits. This choice makes sense. Industrialization can boost the ability to adapt to climate change— Of course, it can also relieve many other more acute problems. For these countries, slowing growth in the name of GHG control may simply be a bad investment (Schelling, 2002). To put the matter bluntly, for China and India, there seem to be good reasons for thinking that taking any but the lowest cost steps to control GHG emissions is just not worth the cost.

As a result, China and India have largely limited their GHG control steps to those that in the U.S. context have been called "no regrets" measures. These are steps that would make sense absent concern about climate change. Such measures will have at best marginal impacts on the growth of emissions. Yet unless far steeper GHG cuts are implemented, widely cited goals for 2050 and 2100 are simply unattainable (Jacoby *et al.,* 2008).

The most logical inference from this situation is that those goals will not, in fact, be met. If they are not, climate change damages will exceed those projected to occur with an optimal control regime, as will the risks of abrupt, high-impact climate change. This prospect suggests that SRM is likely to be more valuable than the recent Bickel/Lane analysis indicates.

3 Important uncertainties remain

SRM could, then, offer important help in reducing some of the risks of climate change, but it poses some risks as well.

3.1 Concerns about possible indirect costs

Some of the risks that have been ascribed to SRM are somewhat poorly defined (Smith, 2009). Others, however, are clear enough, at least in concept. One such risk is the possible lessening of rainfall. The strength of the Indian or African monsoons is a particular worry. Other concerns also exist. For example, until chlorine concentrations return to levels present in the 1980s, sulfate aerosols added to the stratosphere may retard the ozone layer's recovery (Tilmes *et al.,* 2008).

Concerns have also arisen over acid precipitation if SO_2 were injected into the stratosphere. In addition, stratospheric aerosol injections would whiten skies, interfere with terrestrial astronomy, and reduce the efficiency of some kinds of solar power (Robock, 2008). Finally, some analysis suggests the possibility of "rebound warming" should SRM be deployed for a long time period and then halted abruptly (Goes *et al.,* 2009).

3.2 Viewing indirect costs in a larger perspective

Several points about the above concerns warrant attention.

None of the possible ill-effects of SRM has been monetized. Therefore, how they compare with SRM's apparently large potential benefits is unclear. In fact, the scale of the effects of these unintended consequences is highly speculative. With regard to the Indian monsoon, for example, the underlying climate science is too uncertain to assess the scale of the changes with confidence (Zickfeld *et al.,* 2005). Thus, Rasch et al. (2008), on which Robock is an author, observe:

> "Robock et al. (2008) have emphasised that the perturbations that remain in the monsoon regions after geoengineering are considerable and expressed concern that these perturbations would influence the lives of billions of people. This would certainly be true. However, it is important to keep in mind that: (i) the perturbations after geoengineering are smaller than those without geoengineering; (ii) the remaining perturbations are less than or equal to 0.5 mm d^{-1} in an area where seasonal precipitation rates reach 6–15 mm d^{-1}; (iii) the signals differ between the NCAR and Rutgers simulations in these regions; and (iv) monsoons are a notoriously difficult phenomenon to model [Annamalai *et al.,* 2007] [emphasis in original].

Ozone depletion may be a problem, but it is likely to grow less severe with the passage of time. Acid deposition seems to be a considerably less serious problem, as a recent study concluded that ". . . the additional sulfate deposition that would result from geoengineering will not be sufficient to negatively impact most ecosystems, even under the assumption that all deposited sulfate will be in the form of sulfuric acid" (Kravitz *et al.,* 2009).

On rebound warming, the significance of the problem is, again, unclear. For the effect to be large, the SRM regime would have to remain in place for at least several decades. Also, during this period, adaptation and GHG control efforts would have to be held to low levels (Bickel and Lane, 2009). Ex ante, such a course of events may be possible, but it hardly seems inevitable or, perhaps, even likely.

All of these concerns may warrant study. Nonetheless, to take a step back from the details, a few broader factors should also be kept in mind. *Most importantly, it is worth noting that the relevant choice before us is not between a climate-engineered world and a world without climate change; rather, it is between the former and the world that would prevail without climate engineering.* SRM may, indeed, do some harm. Society may, however, have to choose between accepting this harm on the one hand and running the risk of a planetary emergency on the other (Bickel and Lane 2009).

Finally, in assessing SRM, it is important to keep in mind that all climate policy options entail side-effects. GHG controls, for instance, may imply greater reliance on biofuels or nuclear power. Border tax adjustments may unleash a global trade war (Barrett, 2007). In weighing the relative priority of SRM and GHG control, these factors are no less relevant than SRM's impacts on rainfall or ozone. The key to climate policy is fording the mix of responses that minimizes total costs more than it is about either/or choices.

4 Approaches to limiting the risks of SRM

Since the risks of unintended consequences are the major barriers preventing the exploitation of this option, it is important to ford means of lowering those risks. A number of options might serve this purpose.

4.1 R&D as a risk reduction strategy

Currently, we lack much of the information that would be needed to weigh all of the potential risks of SRM against its possible benefits. Only an R&D program can buy this information, and the potential benefits of SRM appear to be very large compared to the costs of such an R&D effort. A vigorous, but careful, R&D program may offer the means of reducing the risks of SRM. It may identify faulty concepts and ford new means of avoiding risks. Progress in climate science can also increase the expected benefits of SRM (Goes *et al.,* 2009).

Such an R&D program would begin with modeling and paper studies, move to laboratory testing, and eventually, embark on field trials. The latter would start small and increase in scale by increments. As R&D progresses, spending would increase from tens of millions of dollars in early years to the low billions of dollars later. Total spending may fall in the range of $10–15 billion (Bickel and Lane, 2009). The work would stress defensive research i.e. research designed to identify and limit possible risks. A recent report has defined this type of research agenda for stratospheric aerosols (Blackstock *et al.,* 2009).

Research cannot entirely eliminate risk (Smith, 2009). Yet the risk of deploying a system under emergency conditions and without full testing are likely greatly to exceed those entailed by deploying a more fully tried and better understood system. Again, none of the options for dealing with climate change is free of risk.

4.2 Delayed deployment as a risk management strategy

The passing of time seems likely to diminish the risks of deploying SRM. One option, therefore, might be to delay deployment. This approach offers two advantages.

First, delay is likely to make it easier for the nations wishing to deploy SRM to gain international acquiescence for their plans. Today, some nations may still benefit from additional warming. Such states might strenuously object to near-term efforts to halt warming. Russia, one of the nations that might adopt this view, is a great power. It could probably apply enough pressure to prevent any other nation from deploying SRM. However, as decades pass, climate change is increasingly likely to threaten even Russia with net costs. As this happens, Russian and other objections to SRM are also likely to fade.

Second, the ozone depletion problem will also diminish with time. The stock of ozone-depleting chemicals in the atmosphere is shrinking. Before mid-century, levels will return to those that prevailed pre-1980. At that point, the impact of stratospheric aerosols on UV radiation also loses significance (Wigley, 2006).

Delayed deployment, of course, would also lower the difference between SRM's total benefits and its direct costs. Even so, large net benefits remain. This result obtains for both SRM concepts. Thus, if marine cloud whitening were deployed in 2055, the estimated present discounted value of the benefits exceeds that of the direct costs by at least $3.9 trillion, and perhaps by as much as $9.5 trillion (in 2005 dollars). If stratospheric aerosols were deployed in 2055, the gap between total benefits and total costs would range between $3.8 trillion and $9.3 trillion (Bickel and Lane, 2009).

5 Proposals for international governance require caution

For some people, creating an international governance regime is the preferred choice for controlling the risks of SRM. A number of proposals for establishing systems of international governance of SRM seem suddenly to have sprouted up. Many of them seem to be couched in somewhat alarming tones about future conflicts, and most seem to be accompanied by expressions of great urgency (Victor *et al.,* 2009). In responding to them, caution is in order.

5.1 Proposals for regulation require balancing of risks

To start with, it is important to recognize that a regime of controls can and often does produce counter-productive results. An overly restrictive system can raise the costs of undertaking R&D. Higher costs may narrow the field of active researchers. Since competition spurs technological progress, a regulatory regime that adds to research costs may slow the pace of progress (Arrow, 1962; Cohen and Noll, 1991; NRC 1999; Sarewitz and Cohen, 2009). If so, lowering the risks of unintended harm from SRM might be purchased at the costs of higher risks from abrupt, high-impact climate change. This trade-off may be worthwhile, or it may not be, depending on how one rates the relative risks.

5.2 U.S. interests may differ from those of other states

A second caution pertains to nations' different weights in world politics. A few nations command much more heft than do others. The U.S., China, and Russia are clearly in this category; others may be in the process of joining it. These states have a disproportionate ability either to carry an SRM regime into effect or to impede another state from doing so. If any of these states were to conclude that SRM was necessary to protect its vital interests, a system of international restraints would be most unlikely to constrain them.

For the U.S., the question of whether to foster the development of an international body with the authority to regulate SRM entails accepting possible future constraints on its own freedom of action, as well as constraints on other states that might be acting in accord with U.S. preferences. In exchange, the U.S. would gain possible added support were it is seeking to halt or change SRM activity by another power.

In considering this trade-off, it may be worth pondering that at least two other great powers, China and Russia, are autocracies. It is at least possible that these states are far less constrained by global public opinion than is the United States. In this case, in consenting to the creation of a global regime for governing SRM, the U.S. might be accepting a more binding limit on its own actions than that which it gains on the actions of the other great powers.

5.3 Who should consider SRM regulation?

SRM regulation is a matter of U.S. foreign policy. In this matter, U.S. interests may be congruent with those of some countries and clash with those of others. In addition to distinctions in wealth, power, and climate, states may differ in risk averseness. The strength of the contrasting U.S. and E.U. reactions to genetically modified organisms suggest that in at least some specific instances, such differences may be large.

Technical and scientific expertise is certainly important to the issue of how (or whether) SRM should be subject to international control. Yet the more basic question lies in the definition of national interests. This question is not technical; it is political. And how it is answered may well affect any nation's choices among international control regimes. For this reason, recommendations made by panels of scientists or lawyers may miss central aspects of the issues and yield misleading results. Such advice may still provide useful insights, but it should be handled with care.

6 SRM as part of a broader context

6.1 Multiple responses are needed to cope with climate change

Multiple tools are available for coping with climate change. Adaptation to change is likely to be the primary response for many decades. Weak and patchy greenhouse gas (GHG) controls are in place, but these measures fall far, far short of those that would be needed to actually halt climate change. And they are likely to continue to do so. Solar radiation management (SRM) offers great upside potential.

Still, it remains in the concept stage and is surrounded by uncertainties. Eventually, even air capture of CO_2 may become appealing, although its economic feasibility remains speculative.

In any case, a mix of climate policies is better than placing too much stress on any one response. GHG emissions pose multiple threats, and multiple responses are likely needed to respond to them. Further, at some point all responses are likely to encounter diminishing marginal returns. Excessive reliance on any one policy option is likely to raise net costs.

6.2 New knowledge as a key to climate policy success

With the current state of science and technology, the costs of coping with climate change are likely to be high. New knowledge may, however, drastically lower those costs. As just discussed, R&D on SRM may allow a better assessment of this option as well as offer ways of limiting its risks and controlling its costs. Better climate science is likely to enable more cost-effective adaption to climate change. R&D on new energy sources or on capturing and storing CO_2 might lower the cost and raise the political acceptability of GHG controls. Each of the six climate policy options selected by the above-mentioned economists' panel as being the most promising centered on the search for one or another form of new knowledge. Clearly, in the economists' opinions, research is a powerful strategy for dealing with climate change.

The quest for new knowledge may not, though, be easy. First, its results are inherently uncertain. Diversified risks and hedging are important. Second, research can take time. Electrification of the global economy, for example, has been going on for over a century and is still far from complete. Third, the right kind of rules and structures can make the difference between success and failure. This Committee is very well positioned to raise questions about the kinds of arrangements likely to maximize the chances of R&D success. I hope that this hearing may prove to be an important step forward in that inquiry.

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BIOGRAPHY FOR LEE LANE

Lee Lane is a Resident Fellow at the American Enterprise Institute for Public Policy Research. He is Co-Director of AEI's Geoengineering Project. Lane recently co-authored "An Analysis of Climate Engineering as a Response to Climate Change," a benefit/cost analysis published by the Copenhagen Consensus Center. He has also recently written "Institutions for Developing New Climate Solutions". This paper is soon to be published in a book by the Geneva, Switzerland-based World Federation of Scientists. In 2008, Lane co-authored "Political Institutions and Greenhouse Gas Controls." Mr. Lane was the lead author of NASA's April 2007 report on geoengineering. He is also the author of *Strategic Options for Bush Administration Climate Policy* (AEI Press, November 2006). Lane has testified before Congress, and has been a consultant to the U.S. Department of Energy, the U.S. Department of Transportation, the State Department, NASA, and Japan's Ministry of Economics, Trade, and Industry, as well as with CRA International, an international economics and management consulting firm. Before joining AEI, Lane served for seven years as the Executive Director of the Climate Policy Center, a policy research organization in Washington DC.

Chairman GORDON. Thank you, Mr. Lane. I also thank you for being an early supporter of ARPA–E. We hope that some of the research that will come out of ARPA–E will mean that this potential review will be moot.

Mr. LANE. I hope so, too.

Chairman GORDON. Dr. Robock, we welcome your discussion.

STATEMENT OF DR. ALAN ROBOCK, PROFESSOR, DEPARTMENT OF ENVIRONMENTAL SCIENCES, SCHOOL OF ENVIRONMENTAL AND BIOLOGICAL SCIENCES, RUTGERS UNIVERSITY

Dr. ROBOCK. Mr. Chairman, Mr. Hall, Members of the Committee, thank you for inviting me. First I would like to agree with Ken Caldeira, that global warming is a serious problem and that mitigation, reduction of emissions, should be our primary response. We also need to do adaptation and learn to live with some of the climate change which is going to happen no matter what.

Using geoengineering should only be in the event of a planetary emergency and only for a temporary period of time, and it is not a solution to global warming.

Could I have the first slide?

[The information follows:]

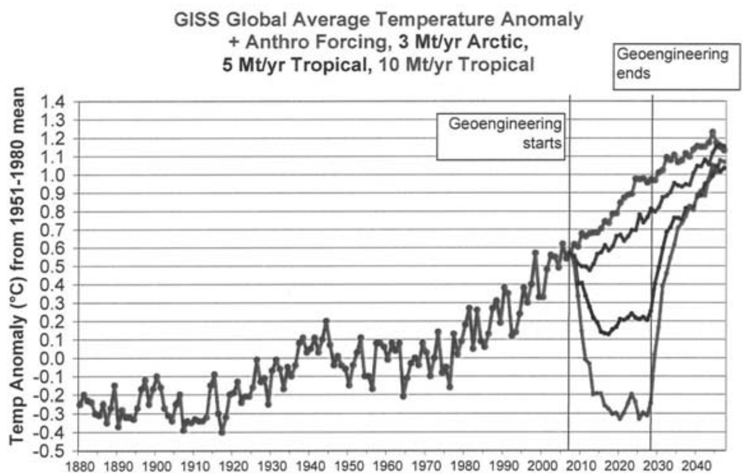

Figure 1. Global average surface air temperature change from the A1B anthropogenic forcing run (red), Arctic 3 Mt/yr SO_2 (blue), Tropical SO_2 5 Mt/yr (black), and Tropical 10 Mt/yr SO_2 (brown) cases in the context of the climate change of the past 125 years. Observations (green) are from the National Aeronautics and Space Administration Goddard Institute for Space Studies analysis [*Hansen et al.*, 1996, updated at http://data.giss.nasa.gov/gistemp/2007/].

I am a climatologist. I have done climate research and effects of volcanic eruptions for 35 years. We did a climate model simulation of what would happen if we put in the equivalent of one Mount Pinatubo volcanic eruption every four years. The green line is the global warming temperatures that we have seen up until now. The black line is one Pinatubo every four years. The brown line is one Pinatubo every two years, assuming that you could do it.

This brings up several questions. What temperature do we want the planet to be? Do we want it to stay constant? Do we want it to be at 1980 levels, do we want it at 1880 levels? And who decides? What if Russia and Canada want it a little bit warmer and India wants it a little bit cooler?

If we stopped after 20 years, we would have rapid warming, as you can see. We did it for 20 years. And this rapid climate change would be much more dangerous than the gradual change we would get without doing anything. So this is a couple of the reasons why I am concerned about it, but we certainly need more research.

Now, how do we get the aerosols—I am talking about the solar radiation management. How do we get the aerosols into the stratosphere? There is no way to do it today. Ideas of artillery or balloons or airplanes need a lot of research. Ken said it would be easy and cheap, but there is no demonstration of that. It might not be that expensive, but such equipment just doesn't exist today.

So I have made a list of seven reasons why it—benefits for stratospheric geoengineering and 17 reasons why it might be a bad idea.

Now, volcanic eruptions produce drought in Africa and Asia. They produce ozone depletion, no more blue skies, less solar power, and each of these needs to be quantified so you policymakers can make a decision about whether or not to implement it. We don't have quantification of any of these yet.

I disagree with the economic analysis because they just ignored many of the risks and didn't even count what the possible dangers might be. But I agree with everybody that we need a research program so that we can quantify each of these so policymakers can tell if—is there a Plan B in your pocket, or is it empty? We really need to know that, and we don't know the answer to that yet.

If we were going to test putting particles in the stratosphere, we don't have a system to observe them. The United States used to have a series of satellites called SAGE which looked at particles in the stratosphere. It was very useful for monitoring volcanic eruptions. And they stopped working, and there is no plan to put them up there. So we need the system anyway to monitor the stratosphere for the next volcanic eruption and to monitor it if we ever do experimentation.

If we wanted to do experimentation, it is not possible to do just a small-scale test, to put a little bit of particles in and see what would happen. We could do that, but we couldn't measure their effects because there are a lot of weather variability, a lot of weather noise. And so we would really have to put a lot of material in for a substantial period of time to see whether we are having an effect. And that would essentially be doing geoengineering itself. You can't do it on a small scale.

You could fly a plane up there and dump some gas out and see what would happen at the nozzle. But to do a full-scale experiment, we couldn't do it. For example, if there is already a cloud there and we want to put gases in and see if we get more particles, you can't do that if there are not particles there already. We may just make the particles bigger. And so it is problematic whether we could actually ever do an experiment in the stratosphere without actually doing geoengineering.

So I would like to urge you to support a research program into the climatic response with climate models, into the technology to see if it is possible to develop different systems so that you can make an informed decision in the future.

Thanks.

[The prepared statement of Dr. Robock follows:]

PREPARED STATEMENT OF ALAN ROBOCK

Introduction

In the October 28, 2009, letter from Chairman Gordon inviting me to testify at the House Committee on Science and Technology Hearing, "Geoengineering: Assessing the Implications of Large-Scale Climate Intervention," I was asked to address a number of specific issues, which I do below. But first I would like to give a brief statement of the framework within which we consider the issue of geoengineering.

I agree with the October 21, 2009, statement from the leaders of 17 U.S. scientific societies to the U.S. Senate (Supplementary Material 1), partially based on my own research, that, "Observations throughout the world make it clear that climate change is occurring, and rigorous scientific research demonstrates that the greenhouse gases emitted by human activities are the primary driver." I also agree with their statement that "Moreover, there is strong evidence that ongoing climate change will have broad impacts on society, including the global economy and on the environment." Therefore, it is incumbent on us to address the threat of climate change.

I also agree with the recent policy statement of the American Meteorological Society on geoengineering (Supplementary Material 2). I was a member of the committee that wrote this statement. As the statement explains, "Three proactive strategies could reduce the risks of climate change: 1) *mitigation:* reducing emissions; 2) *adaptation:* moderating climate impacts by increasing our capacity to cope with them; and 3) *geoengineering:* deliberately manipulating physical, chemical, or biological aspects of the Earth system."

Before discussing geoengineering it is necessary to define it. As the American Meteorological Society statement says, "Geoengineering proposals fall into at least three broad categories: 1) reducing the levels of atmospheric greenhouse gases through large-scale manipulations (e.g., ocean fertilization or afforestation using non-native species); 2) exerting a cooling influence on Earth by reflecting sunlight (e.g., putting reflective particles into the atmosphere, putting mirrors in space, increasing surface reflectivity, or altering the amount or characteristics of clouds); and 3) other large-scale manipulations designed to diminish climate change or its impacts (e.g., constructing vertical pipes in the ocean that would increase downward heat transport)."

My expertise is in category 2, sometimes called "solar radiation management." In particular, my work has focused on the idea of emulating explosive volcanic eruptions, by attempting to produce a stratospheric cloud that would reflect some incoming sunlight, to shade and cool the planet to counteract global warming. In this testimony, except where indicated, I will confine my remarks to this specific idea, and use the term "geoengineering" to refer to only it. I do this because it is the suggestion that has gotten the most attention recently, and because it is the one that I have addressed in my work.

My personal view is that we need aggressive mitigation to lessen the impacts of global warming. We will also have to devote significant resources to adaptation to deal with the adverse climate changes that are already beginning. If geoengineering is ever used, it should be as a short-term emergency measure, as a supplement to, and not as a substitute for, mitigation and adaptation. And we are not ready to implement geoengineering now.

The question of whether geoengineering could ever help to address global warming cannot be answered at this time. In our most recent paper (Supplementary Material 9) we have identified six potential benefits and 17 potential risks of stratospheric geoengineering, but a vigorous research program is needed to quantify each of these items, so that policy makers will be able to make an informed decision, by weighing the benefits and risks of different policy options.

Furthermore, there has been no demonstration that geoengineering is even possible. No technology to do geoengineering currently exists. The research program needs to also evaluate various suggested schemes for producing stratospheric particles, to see whether it is practical to maintain a stratospheric cloud that would be effective at blocking sunlight.

Introduce the key scientific, regulatory, ethical, legal and economic challenges of geoengineering.

In Robock (2008a; Supplementary Material 4) I identified 20 reasons why geoengineering may be a bad idea. Subsequent work, summarized in Robock et al. (2009; Supplementary Material 9), eliminated three of these reasons, determined that one is still not well understood, but added one more reason, so I still have identified 17 potential risks of geoengineering. Furthermore, there is no current technology to implement or monitor geoengineering, should it be tested or implemented. Robock (2008b; Supplementary Material 5) described some of these effects, particularly on ozone.

Key challenges of geoengineering related to the side effects on the climate system are that it could produce drought in Asia and Africa, threatening the food and water supply for billions of people, that it would not halt continued ocean acidification from CO_2, and that it would deplete ozone and increase dangerous ultraviolet radiation. Furthermore, the reduction of direct solar radiation and the increase in diffuse radiation would make the sky less blue and produce much less solar power from systems using focused sunlight. Any system to inject particles or their precursors into the stratosphere at the needed rate would have large local environmental impacts. If society lost the will or means to continue geoengineering, there would be rapid warming, much more rapid than would occur without geoengineering. If a series of volcanic eruptions produced unwanted cooling, geoengineering could not be stopped rapidly to compensate. In addition, astronomers spend billions of dollars to build mountain-top observatories to get above pollution in the lower troposphere. Geoengineering would put permanent pollution above these telescopes.

Another category of challenges is unexpected consequences. No matter how much analysis is done ahead of time, there will be surprises. Some will make the effects less damaging, but some will be more damaging. Furthermore, human error is likely to produce problems with any sophisticated technical system.

Ethical challenges include what is called a moral hazard—if geoengineering is perceived to be a solution for global warming, it will lessen the current gathering consensus to address climate change with mitigation. There is also the question of moral authority—do humans have the right to control the climate of the entire planet to benefit them, without consideration of all other species? Another ethical issue is the potential military use of any geoengineering technology. One of the cheapest approaches may even be to use existing military airplanes for geoengineering (Robock et al., 2009; Supplementary Material 9). Could techniques developed to control global climate forever be limited to peaceful uses? Other ethical considerations might arise if geoengineering would improve the climate for most, but harm some.

Legal and regulatory challenges are closely linked to ethical ones. Who would end up controlling geoengineering systems? Governments? Private companies holding patents on proprietary technology? And whose benefit would they have at heart? Stockholders or the general public welfare? Eighty-five countries, including the United States, have signed the U.N. Convention on the Prohibition of Military or Any Other Hostile Use of Environmental

Modification Techniques. It will have to be modified to allow geoengineering that would harm any of the signatories. And whose hand would be on the thermostat? How would the world decide on what level of geoengineering to apply? What if Canada or Russia wanted the climate to be a little warmer, while tropical countries and small island states wanted it cooler? Certainly new governance mechanisms would be needed.

As far as economic challenges go, even if our estimate (Robock et al., 2009; Supplementary Material 9) is off by a factor of 10, the costs of actually implementing geoengineering would not be a limiting factor. Rather, the economic issues associated with the potential damages of geoengineering would be more important.

Major strategies for evaluating different geoengineering methods.

Evaluation of geoengineering strategies requires determination of their costs, benefits, and risks. Furthermore, geoengineering requires ongoing monitoring. As discussed below, a robust research program including computer modeling and engineering studies, as well as study of historical, ethical, legal, and social implications of geoengineering and governance issues is needed. Monitoring will require the reestablishment of the capability of measuring the location, properties and vertical distribution of particles and ozone in the stratosphere using satellites.

Broadly evaluate the geoengineering strategies you believe could be most viable based on these criteria.

I know of no viable geoengineering strategies. None have been shown to work to control the climate. None have been shown to be safe. However, the ones that have the most potential, and which need further research, would include stratospheric aerosols and brightening of marine tropospheric clouds, as well as carbon capture and sequestration. Carbon capture has been demonstrated on a very small scale. Whether it can be conducted on a large enough scale to have a measurable impact on atmospheric CO_2 concentrations, and whether the CO_2 can be sequestered efficiently and safely for a long period of time, are areas that need to be researched.

Identify the climate circumstances under which the U.S. or international community should undertake geoengineering.

For a decision to actually implement geoengineering, it needs to be demonstrated that the benefits of geoengineering outweigh the risks. We need a better understanding of the evolution of future climate both with and without geoengineering. We need to know the costs of implementation of geoengineering and compare them to the costs of not doing geoengineering. Geoengineering should only be implemented in response to a planetary emergency. However, there are no governance mechanisms today that would allow such a determination. Governance would also have to establish criteria to determine the end of the emergency and the ramping down of geoengineering.

Examples of climate circumstances that would be candidates for the declaration of a planetary emergency would include rapid melting of the Greenland or Antarctic ice sheets, with attendant rapid sea level rise, or a catastrophic increase in severe hurricanes and typhoons. Even so, stratospheric geoengineering should only be implemented if it could be determined that it would address these specific emergencies without causing worse problems. And there may be local means to deal with these specific issues that would not produce the risks of global geoengineering. For example, sea level rise could be addressed by pumping sea water into a new lake in the Sahara or onto the cold Antarctic ice sheet where it would freeze. There may be techniques to cool the water ahead of approaching hurricanes by mixing cold water from below up to the surface. Of course, each of these techniques may have its own unwelcome side effects.

Right now there are no circumstances that would warrant geoengineering. This is because we lack the knowledge to evaluate the benefits, risks, and costs of geoengineering. We also lack the requisite governance mechanisms. Our policy right now needs to be to focus on mitigation, while funding research that will produce the knowledge to make such decisions about geoengineering in five or ten years.

Recommendations for first steps, if any, to begin a geoengineering research and/or governance effort.

In 2001, the U.S. Department of Energy issued a white paper (Supplementary Material 3) that called for a $64,000,000 research program over five years to look into a variety of suggested methods to control the climate. Such a coordinated program was never implemented, but there are now a few research efforts using climate models of which I am aware. In addition to my grant from the National Science Foundation, discussed below, I know of one grant from NASA to Brian Toon for geoengineering research and some work by scientists at the National Center for Atmospheric Research, funded by the Federal Government. In addition, there have been some climate modeling studies conducted at the United Kingdom Hadley Centre, and there is a new three-year project, started in July 2009, funded by the European Union for €1,000,000 ($1,500,000) for three years called "IMPLICC—Implications and risks of engineering solar radiation to limit climate change," involving the cooperation of 5 higher educational and research institutions in France, Germany and Norway.

In light of the importance of this issue, as outlined in Robock (2008b; Supplementary Material 5), I recommend that the U.S., in collaboration with other countries, embark on a well-funded research program to "consider geoengineering's potential benefits, to understand its limitations, and to avoid ill-considered deployment" (as the American Meteorological Society says in Supplementary Material 2). In particular the American Meteorological Society recommends:

1) Enhanced research on the scientific and technological potential for geoengineering the climate system, including research on intended and unintended environmental responses.
2) Coordinated study of historical, ethical, legal, and social implications of geoengineering that integrates international, interdisciplinary, and intergenerational issues and perspectives and includes lessons from past efforts to modify weather and climate.
3) Development and analysis of policy options to promote transparency and international cooperation in exploring geoengineering options along with restrictions on reckless efforts to manipulate the climate system.

I support all these recommendations. Research under item 1) would involve state-of-the-art climate models, which have been validated by previous success at simulating past climate change, including the effects of volcanic eruptions. They would consider different suggested scenarios for injection of gases or particles designed to produce a stratospheric cloud, and evaluate the positive and negative aspects of the climate response— So far, the small number of studies that have been conducted have all used different scenarios, and it is difficult to compare the results to see which are robust. One such example is given in the paper by Rasch et al. (2008; Supplementary Material 7). Therefore, I am in the process of organizing a coordinated experiment among the different climate modeling groups that are performing runs for the Coupled Model Intercomparison Project, Phase 5, which will inform the next Intergovernmental Panel on Climate Change report. Once we agree on a set of standard scenarios, participation will depend on these different groups from around the world volunteering their computer and analysis time to conduct the experiments. Financial support from a national research program, in cooperation with other nations, will produce more rapid and more comprehensive results.

Another area of research that needs to be supported under topic 1) is the technology of producing a stratospheric aerosol cloud. Robock et al. (2009; Supplementary Material 9) calculated that it would cost several billion dollars per year to just inject enough sulfur gas into the stratosphere to produce a cloud that would cool the planet using existing military airplanes. Others have suggested that it would be quite a bit more expensive. However, even if SO_2 (sulfur dioxide) or H_2S (hydrogen sulfide) could be injected into the stratosphere, there is no assurance that nozzles and injection strategies could be designed to produce a cloud with the right size droplets that would be effective at scattering sunlight. Our preliminary theoretical work on this problem is discussed by Rasch et al. (2008; Supplementary Material 7). However, the research program will also need to fund engineers to actually build prototypes based on modification of existing aircraft or new designs, and to once again examine other potential mechanisms including balloons, artillery, and towers. They will also have to look into engineered particles, and not just assume that we would produce sulfate clouds that mimic volcanic eruptions.

At some point, given the results of climate models and engineering, there may be a desire to test such a system in the real world. But this is not possible without full-scale deployment, and that decision would have to be made without a full evaluation of the possible risks. Certainly individual aircraft or balloons could be launched into the stratosphere to release sulfur gases. Nozzles can be tested. But whether such a system would produce the desired cloud could not be tested unless it was deployed into an existing cloud that is being maintained in the stratosphere. While small sub-micron particles would be most effective at scattering sunlight and producing cooling, current theory tells us that continued emission of sulfur gases would cause existing particles to grow to larger sizes, larger than volcanic eruptions typically produce, and they would be less effective at cooling Earth, requiring even more emissions. Such effects could not be tested, except at full-scale.

Furthermore, the climatic response to an engineered stratospheric cloud could not be tested, except at full-scale. The weather is too variable, so that it is not possible to attribute responses of the climate system to the effects of a stratospheric cloud without a very large effect of the cloud. Volcanic eruptions serve as an excellent natural example of this. In 1991, the Mt. Pinatubo volcano in the Philippines injected 20 Mt (megatons) of SO_2 (sulfur dioxide) into the stratosphere. The planet cooled by about 0.5° C (1° F) in 1992, and then warmed back up as the volcanic cloud fell out of the atmosphere over the next year or so. There was a large reduction of the Asian monsoon in the summer of 1992 and a measurable ozone depletion in the stratosphere. Climate model simulations suggest that the equivalent of one Pinatubo every four years or so would be required to counteract global warming for the next few decades, because if the cloud were maintained in the stratosphere, it would give the climate system time to cool in response, unlike for the Pinatubo case, when the cloud fell out of the atmosphere before the climate system could react fully. To see, for example, what the effects of such a geoengineered cloud would be on precipitation patterns and ozone, we would have to actually do the experiment. The effects of smaller amounts of volcanic clouds on climate can simply not be detected, and a diffuse cloud produced by an experiment would not provide the correct environment for continued emissions of sulfur gases. The recent fairly large eruptions of the Kasatochi volcano in 2008 (1.5 Mt SO_2) and Sarychev in 2009 (2 Mt SO_2) did not produce a climate response that could be measured against the noise of chaotic weather variability.

Some have suggested that we test stratospheric geoengineering in the Arctic, where the cloud would be confined and even if there were negative effects, they would be limited in scope. But our experiments (Robock et al., 2008; Supplementary Material 6) found that clouds injected into the Arctic stratosphere would be blown by winds into the midlatitudes and would affect the Asian summer monsoon. Observations from all the large high latitude volcanic eruptions of the past 1500 years, Eldgjá in 939, Laid in 1783, and Katmai in 1912, support those results.

Topics 2) and 3) should also be part of any research program, with topic 3) dealing with governance issues. This is not my area of expertise, but as I understand it, the U.N. Convention on the Prohibition of Military or Any Other Hostile Use of Environmental Modification Techniques prohibits geoengineering if it will have negative effects on any of the 85 signatories to the convention (which include the U.S.). International governance mechanisms, probably through the United Nations, would have to be established to set the rules for testing, deployment, and halting of any geoengineering. Given the different interests in the world, and the current difficulty of negotiating mitigation, it is not clear to me how easy this would be. And any abrogation of such agreements would produce the potential for conflict.

How much would a geoengineering research program cost? Given the continued threat to the planet from climate change, it is important that in the next decade policy makers be provided with enough information to be able to decide whether geoengineering can be considered as an emergency response to dangerous climate change, given its potential benefits, costs, and risks. If the program is not well-funded, such answers will be long in coming. The climate modeling community is ready to conduct such experiments, given an increase in funding for people and computers. Funding should include support for students studying climate change as well as to existing scientists, and would not be that expensive. It should certainly be in, the range of millions of dollars per year for a 5–10 year period. I am less knowledgeable of what the costs would be for engineering studies or for topics 2) and 3).

A geoengineering research program should not be at the expense of existing research into climate change, and into mitigation and adaptation. Our first goal should be rapid mitigation, and we need to continue the current increase in support for green alternatives to fossil fuels. We also need to continue to better understand regional climate change, to help us to implement mitigation and adapt to the climate change that will surely come in the next decades no matter what our actions today. But a small increment to current funding to support geoengineering will allow us to determine whether geoengineering deserves serious consideration as a policy option.

Describe your NSF-funded research activities at Rutgers University.

I am supported to conduct geoengineering research by the following grant:

National Science Foundation, ATM–0730452, "Collaborative Research in Evaluation of Suggestions to Geoengineer the Climate System Using Stratospheric Aerosols and Sun Shading," February 1, 2008—January 31, 2011, $554,429. (Includes $5000 Research Experience for Undergraduates supplement.)

I conduct research with Professors Georgiy Stenchikov and Martin Bunzl and students Ben Kravitz and Allison Marquardt at Rutgers, in collaboration with Prof. Richard Turco at UCLA, who is funded on a collaborative grant by NSF with separate funding. We conduct climate model simulations of the response to various scenarios of production of a cloud of particles in the stratosphere. We use a NASA climate model on NASA computers to conduct our simulations. We also have investigated the potential cost of injecting gases into the stratosphere that would react with water vapor to produce a cloud of sulfuric acid droplets. We calculated how much additional acid rain and snow would result when the sulfuric acid eventually falls out of the atmosphere. Prof. Turco focuses on the detailed mechanisms in the stratosphere whereby gases convert to particles. Prof. Bunzl is a philosopher. Together we are also examining the ethical dimensions of geoengineering proposals.

We have published five peer-reviewed journal articles on our research so far, attached as Supplementary Material items 5–9, and Prof. Bunzl has published one additional peer-reviewed paper supported by this grant.

Delineate the precautionary steps that might be needed in the event of large scale testing or deployment.

First of all, there is little difference between large-scale testing and deployment. To be able to measure the climate response to a stratospheric cloud above the noise of chaotic weather variations, the injection of stratospheric particles would have to so large as that it would be indistinguishable from deployment of geoengineering. And it would have to last long enough to produce a measurable climate response, at least for five years. One of the potential risks of this strategy is that if it is perceived to be working, the enterprise will develop a constituency that will push for it to continue, just like other government programs, with the argument that jobs and business need to be protected.

The world will have to develop a governance structure that can decide on whether or not to do such an experiment, with detailed rules as to how it will be evaluated and how the program will be ended. The current U.N. Convention on the Prohibition of Military or Any Other Hostile Use of Environmental Modification Techniques will have to be modified.

Any large-scale testing or deployment would need to be first be evaluated thoroughly with climate model simulations. Climate models have been validated by simulating past climate change, including the effects of large volcanic eruptions. They will allow scientists to test different patterns of aerosol injection and different types of aerosols, and to thoroughly study the resulting spatial patterns of temperature, precipitation, soil moisture, and other climate responses. This information will allow the governance structure to make informed decisions about whether to proceed—

Any field testing of geoengineering would need to be monitored so that it can be evaluated. 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 Stratospheric Aerosol and Gas Experiment II (SAGE II) instrument on the Earth Radiation Budget Satellite 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. Right now, the only limb-scanner in orbit is the Optical Spectrograph and InfraRed Imaging System (OSIRIS), a Canadian instrument on Odin, a Swedish satellite. SAGE III flew from 2002 to 2006, and there are no plans for a follow on mission. A spare SAGE III sits on a shelf at a NASA lab, and could be used now. There is one Canadian satellite in orbit now with a laser, but it is not expected to last long enough to monitor future geoengineering, and there is no system to use it to produce the required observations of stratospheric particles. Certainly, a dedicated observational program would be needed as an integral part of any geoengineering implementation.

These current and past successes can be used as a model to develop a robust stratospheric observing system, which we need anyway to be able to measure the effects of episodic volcanic eruptions. The recent fairly large eruptions of the Kasatochi volcano in 2008 and Sarychev in 2009 produced stratospheric aerosol clouds, but the detailed structure and location of the resulting clouds is poorly known, because of a lack of an observing system.

Identify the aspects of geoengineering you believe present the greatest risks.

Our recent article (see box at right) lists 17 potential risks, but without further research to evaluate the magnitude of each, my answer will just be a subjective judgment.

Nevertheless, I would say that the potential weakening of the Asian and African summer monsoon, with a reduction in precipitation and threat to the food and water supply for more than two billion people, should be at the top of the list. So far different climate model experiments give different amounts of precipitation change, and even if precipitation changes, reduced evapotranspiration, enhanced growth from diffuse radiation and increased CO_2 may compensate. This is an area of research that deserves detailed study with many different climate models.

Other important potential risks include continued ocean acidification and ozone depletion (with enhanced ultraviolet radiation). And if society ever lost the will or means to continue geoengineering, rapid warming would be more dangerous than the gradual warming we are now experiencing.

Even if governance issues were completely addressed before any geoengineering takes place, international conflict could result if there are perceived negative consequences for some nations, and geoengineering continues due to the perceived advantages for those conducting the geoengineering.

Risks
1. Drought in Africa and Asia
2. Continued ocean acidification from CO_2
3. Ozone depletion
4. No more blue skies
5. Less solar power
6. Environmental impact of implementation
7. Rapid warming if stopped
8. Cannot stop effects quickly
9. Human error
10. Unexpected consequences
11. Commercial control
12. Military use of technology
13. Conflicts with current treaties
14. Whose hand on the thermostat?
15. Ruin terrestrial optical astronomy
16. Moral hazard – the prospect of it working would reduce drive for mitigation
17. Moral authority – do we have the right to do this?

Potential risks of geoengineering [Table 1 from Robock et al., 2009; Supplementary Material 9]

With regard to another suggested geoengineering technique, brightening of marine clouds, there is also a threat to precipitation in other locations, such as the Amazon, and a possible large impact on the oceanic food chain due to less solar energy needed for plankton at the base of the food chain to grow. Again, these potential risks need to be evaluated.

Biography for Alan Robock

Dr. Alan Robock is a Professor II (Distinguished Professor) of climatology in the Department of Environmental Sciences at Rutgers University and the associate director of its Center for Environmental Prediction. He also directs the Rutgers Undergraduate Meteorology Program. He graduated from the University of Wisconsin, Madison, in 1970 with a B.A. in Meteorology, and from the Massachusetts Institute of Technology with an S.M. in 1974 and Ph.D. in 1977, both in Meteorology. Before graduate school, he served as a Peace Corps Volunteer in the Philippines. He was a professor at the University of Maryland, 1977–1997, and the State Climatologist of Maryland, 1991–1997, before moving to Rutgers in 1998.

Prof. Robock has published more than 250 articles on his research in the area of climate change, including more than 150 peer-reviewed papers. His areas of expertise include geoengineering, the effects of volcanic eruptions on climate, the impacts of climate change on human activities, detection and attribution of human effects on the climate system, regional atmosphere-hydrology modeling, soil moisture, and the climatic effects of nuclear weapons.

Professor Robock is currently supported by the National Science Foundation to do research on geoengineering. He has published five peer-reviewed journal articles on geoengineering, in 2008 and 2009. He was a member of the committee that drafted the July 2009 American Meteorological Society Policy Statement on Geoengineering the Climate System. He has convened sessions on geoengineering at two past American. Geophysical Union Fall Meetings, and is the convener of sessions on geoengineering to be held at meetings of the American Association for the Advancement of Science and European Geosciences Union in 2010.

His honors include being a Fellow of the American Meteorological Society, a Fellow of the American Association for the Advancement of Science (AAAS), and a participant in the Intergovernmental Panel on Climate Change, which was awarded the Nobel Peace Prize in 2007. He was the American Meteorological Society/Sigma Xi Distinguished Lecturer for the academic year 2008–2009.

Prof. Robock was Editor of the *Journal of Geophysical Research—Atmospheres* from April 2000 through March 2005 and of the *Journal of Climate and Applied Meteorology* from January 1985 through December 1987. He was Associate Editor of the Journal of Geophysical Research -Atmospheres from November 1998 to April 2000 and of Reviews of Geophysics from September 1994 to December 2000, and is once again serving as Associate Editor of Reviews of Geophysics, since February, 2006.

Prof. Robock serves as President of the Atmospheric Sciences Section of the American Geophysical Union and Chair-Elect of the Atmospheric and Hydrospheric Sciences Section of the American Association for the Advancement of Science. He has been a Member Representative for Rutgers to the University Corporation for Atmospheric Research since 2001, and serves on its President's Advisory Committee on University Relations. Prof Robock was a AAAS Congressional Science Fellow in 1986–1987, serving as a Legislative Assistant to Congressman Bill Green (R–NY) and as a Research Fellow at the Environmental and Energy Study Conference.

Robock Supplement, p. S45

Vol. 64, No. 2, p. 14-18, 59
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20 reasons why geoengineering may be a bad idea

Carbon dioxide emissions are rising so fast that some scientists are seriously considering putting Earth on life support as a last resort. But is this cure worse than the disease?

BY ALAN ROBOCK

THE STATED OBJECTIVE OF THE 1992 U.N. Framework Convention on Climate Change is to stabilize greenhouse gas concentrations in the atmosphere "at a level that would prevent dangerous anthropogenic interference with the climate system." Though the framework convention did not define "dangerous," that level is now generally considered to be about 450 parts per million (ppm) of carbon dioxide in the atmosphere; the current concentration is about 385 ppm, up from 280 ppm before the Industrial Revolution.

In light of society's failure to act concertedly to deal with global warming in spite of the framework convention agreement, two prominent atmospheric scientists recently suggested that humans consider geoengineering—in this case, deliberate modification of the climate to achieve specific effects such as cooling—to address global warming. Nobel laureate Paul Crutzen, who is well regarded for his work on ozone damage and nuclear winter, spearheaded a special August 2006 issue of *Climatic Change* with a controversial editorial about injecting sulfate aerosols into the stratosphere as a means to block sunlight and cool Earth. Another respected climate scientist, Tom Wigley, followed up with a feasibility study in *Science* that advocated the same approach in combination with emissions reduction.[1]

The idea of geoengineering traces its genesis to military strategy during the early years of the Cold War, when scientists in the United States and the Soviet Union devoted considerable funds and research efforts to controlling the weather. Some early geoengineering theories involved damming the Strait of Gibraltar and the Bering Strait as a way to *warm* the Arctic, making Siberia more habitable.[2] Since scientists became aware of rising concentrations of atmospheric carbon dioxide, however, some have proposed artificially altering climate and weather patterns to reverse or mask the effects of global warming.

Some geoengineering schemes aim to remove carbon dioxide from the atmosphere, through natural or mechanical means. Ocean fertilization, where iron dust is dumped into the open ocean to trigger algal blooms; genetic modification of crops to increase biotic carbon uptake; carbon capture and storage techniques such as those proposed to outfit coal plants; and planting forests are such examples. Other schemes involve blocking or reflecting incoming solar radiation, for example by spraying seawater hundreds of meters into the air to seed the formation of stratocumulus clouds over the subtropical ocean.[3]

Two strategies to reduce incoming solar radiation—stratospheric aerosol injection as proposed by Crutzen and space-based sun shields (i.e., mirrors or shades placed in orbit between the sun and Earth)—are among the most widely discussed geoengineering schemes in scientific circles. While these schemes (if they could be built) would cool Earth, they might also have adverse consequences. Several papers in the August 2006 *Climatic Change* discussed some of these issues, but here I present a fairly comprehensive list of reasons why geoengineering might be a bad idea, first written down during a two-day NASA-

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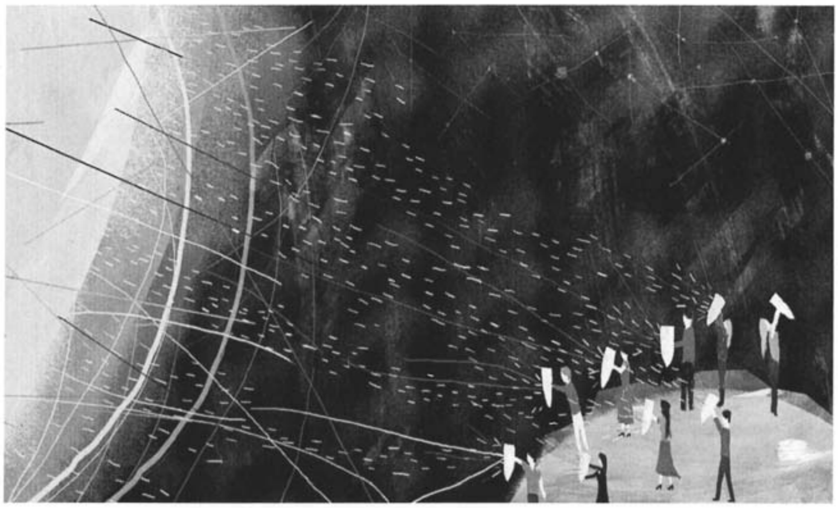

sponsored conference on Managing Solar Radiation (a rather audacious title) in November 2006.[4] These concerns address unknowns in climate system response; effects on human quality of life; and the political, ethical, and moral issues raised.

1. Effects on regional climate. Geoengineering proponents often suggest that volcanic eruptions are an innocuous natural analog for stratospheric injection of sulfate aerosols. The 1991 eruption of Mount Pinatubo on the Philippine island of Luzon, which injected 20 megatons of sulfur dioxide gas into the stratosphere, produced a sulfate aerosol cloud that is said to have caused global cooling for a couple of years without adverse effects. However, researchers at the National Center for Atmospheric Research showed in 2007 that the Pinatubo eruption caused large hydrological responses, including reduced precipitation, soil moisture, and river flow in many regions.[5] Simulations of the climate response to volcanic eruptions have also shown large impacts on regional climate, but whether these are good analogs for the geoengineering response requires further investigation.

Scientists have also seen volcanic eruptions in the tropics produce changes in atmospheric circulation, causing winter warming over continents in the Northern Hemisphere, as well as eruptions at high latitudes weaken the Asian and African monsoons, causing reduced precipitation.[6] In fact, the eight-month-long eruption of the Laki fissure in Iceland in 1783–1784 contributed to famine in Africa, India, and Japan.

If scientists and engineers were able to inject smaller amounts of stratospheric aerosols than result from volcanic eruptions, how would they affect summer wind and precipitation patterns? Could attempts to geoengineer isolated regions (say, the Arctic) be confined there? Scientists need to investigate these scenarios. At the fall 2007 American Geophysical Union meeting, researchers presented preliminary findings from several different climate models that simulated geoengineering schemes and found that they reduced precipitation over wide regions, condemning hundreds of millions of people to drought.

2. Continued ocean acidification. If humans adopted geoengineering as a solution to global warming, with no restriction on continued carbon emissions, the ocean would continue to become more acidic, because about half of all excess carbon dioxide in the atmosphere is removed by ocean uptake. The ocean is already 30 percent more acidic than it was before the Industrial Revolution, and continued acidification threatens the entire oceanic biological chain, from coral reefs right up to humans.[7]

3. Ozone depletion. Aerosol particles in the stratosphere serve as surfaces for chemical reactions that destroy ozone in the same way that water and nitric acid aerosols in polar stratospheric clouds produce the seasonal Antarctic ozone hole.[8] For the next four decades or so, when the concentration of anthropogenic ozone-depleting substances will still be large enough in the stratosphere to produce this effect, additional aerosols from geoengineering would destroy even more ozone and increase damaging ultraviolet flux to Earth's surface.

4. Effects on plants. Sunlight scatters as it passes through stratospheric aerosols, reducing direct solar radiation and increasing diffuse radiation, with important biological consequences. Some studies, including one that measured this effect in trees following the Mount Pinatubo eruption, suggest that diffuse radiation allows plant canopies to photosynthesize more efficiently, thus increasing their capacity as a carbon sink.[9] At the same time, inserting aerosols or reflective disks into the atmosphere would reduce the total sunlight to reach Earth's surface. Scientists need to assess the impacts on crops and natural vegetation of reductions in total, diffuse, and direct solar radiation.

5. More acid deposition. If sulfate is injected regularly into the stratosphere, no matter where on Earth, acid deposition will increase as the material passes through the troposphere—the atmospheric layer closest to Earth's surface. In 1977, Russian climatologist Mikhail Budyko calculated that the additional acidity caused by sulfate injections would be negligibly greater than levels that resulted from air pollution.[10] But the relevant quantity is the *total* amount of acid that reaches the ground, including both wet (acid rain, snow, and fog) and dry deposition (acidic gases and particles). Any additional acid deposition would harm the ecosystem, and it will be important to understand the consequences of exceeding different biological thresholds. Furthermore, more acidic particles in the troposphere would affect public health. The effect may not be large compared to the impact of pollution in urban areas, but in pristine areas it could be significant.

6. Effects of cirrus clouds. As aerosol particles injected into the stratosphere fall to Earth, they may seed cirrus cloud formations in the troposphere.[11] Cirrus clouds affect Earth's radiative balance of incoming and outgoing heat, although the amplitude and even direction of the effects are not well understood. While evidence exists that some volcanic aerosols form cirrus clouds, the global effect has not been quantified.[12]

7. Whitening of the sky (but nice sunsets). Atmospheric aerosols close to the size of the wavelength of light produce a white, cloudy appearance to the sky. They also contribute to colorful sunsets, similar to those that occur after volcanic eruptions. The red and yellow sky in *The Scream* by Edvard Munch was inspired by the brilliant sunsets he witnessed over Oslo in 1883, following the eruption of Krakatau in Indonesia.[13] Both the disappearance of blue skies and the appearance of red sunsets could have strong psychological impacts on humanity.

8. Less sun for solar power. Scientists estimate that as little as a 1.8 percent reduction in incoming solar radiation would compensate for a doubling of atmospheric carbon dioxide. Even this small reduction would significantly affect the radiation available for solar power systems—one of the prime alternate methods of generating clean energy—as the response of different solar power systems to total available sunlight is not linear. This is especially true for some of the most efficiently designed systems that reflect or focus direct solar radiation on one location for direct heating.[14] Following the Mount Pinatubo eruption and the 1982 eruption of El Chichón in Mexico, scientists observed a direct solar radiation decrease of 25–35 percent.[15]

9. Environmental impacts of implementation. Any system that could inject aerosols into the stratosphere, i.e., commercial jetliners with sulfur mixed into their fuel, 16-inch naval rifles firing 1-ton shells of dust vertically into the air, or hoses suspended from stratospheric balloons, would cause enormous environmental damage. The same could be said for systems that would deploy sun

CAPITALIZING ON CARBON

Without market incentives, geoengineering schemes to reflect solar heat are still largely confined to creative thought and artists' renderings. But a few ambitious entrepreneurs have begun to experiment with privatizing climate mitigation through carbon sequestration. Here are a few companies in the market to offset your carbon footprint:

California-based technology startups Planktos and Climos are perhaps the most prominent groups offering to sell carbon offsets in exchange for performing ocean iron fertilization, which induces blooms of carbon-eating phytoplankton. Funding for Planktos dried up in early 2008 as scientists grew increasingly skeptical about the technique, but Climos has managed to press on, securing $3.5 million in funding from Braemar Energy Ventures as of February.

Also in the research and development phase is Sydney, Australia–based Ocean Nourishment Corporation, which similarly aims to induce oceanic photosynthesis, only it fertilizes with nitrogen-rich urea instead of iron. Atmocean, based in Santa Fe, New Mexico, takes a slightly different tack: It's developed a 200-meter deep, wave-powered pump that brings colder, more biota-rich water up to the surface where lifeforms such as tiny, tube-like salps sequester carbon as they feed on algae.

Related in mission if not in name, stationary carbon-capture technologies, which generally aren't considered geoengineering, are nonetheless equally inventive: Skyonic, a Texas-based startup, captures carbon dioxide at power plants (a relatively well-proven technology) and mixes it with sodium hydroxide to render high-grade baking soda. A pilot version of the system is operating at the Brown Stream Electric Station in Fairfield, Texas. To the west in Tucson, Arizona, Global Research Technologies, the only company in the world dedicated to carbon capture from ambient air, recently demonstrated a working "air extraction" prototype—a kind of carbon dioxide vacuum that stands upright and is about the size of a phone booth. Meanwhile, GreenFuel Technologies Corporation, in collaboration with Arizona Public Service Company, is recycling carbon dioxide emissions from power plants by using it to grow biofuel stock in the form of—what else?—algae.

KIRSTEN JERCH

shields. University of Arizona astronomer Roger P. Angel has proposed putting a fleet of 2-foot-wide reflective disks in a stable orbit between Earth and the sun that would bend sunlight away from Earth.[16] But to get the needed *trillions* of disks into space, engineers would need 20 electromagnetic launchers to fire missiles with stacks of 800,000 disks every five minutes for twenty years. What would be the atmospheric effects of the resulting sound and gravity waves? Who would want to live nearby?

10. Rapid warming if deployment stops. A technological, societal, or political crisis could halt a project of stratospheric aerosol injection in mid-deployment. Such an abrupt shift would result in rapid climate warming, which would produce much more stress on society and ecosystems than gradual global warming.[17]

11. There's no going back. We don't know how quickly scientists and engineers could shut down a geoengineering system—or stem its effects—in the event of excessive climate cooling from large volcanic eruptions or other causes. Once we put aerosols into the atmosphere, we cannot remove them.

12. Human error. Complex mechanical systems never work perfectly. Humans can make mistakes in the design, manufacturing, and operation of such systems. (Think of Chernobyl, the *Exxon Valdez*, airplane crashes, and friendly fire on the battlefield.) Should we stake the future of Earth on a much more complicated arrangement than these, built by the lowest bidder?

13. Undermining emissions mitigation. If humans perceive an easy technological fix to global warming that allows for "business as usual," gathering the national (particularly in the United States and China) and international will to change consumption patterns and energy infrastructure will be even more difficult.[18] This is the oldest and most persistent argument against geoengineering.

14. Cost. Advocates casually claim that it would not be too expensive to implement geoengineering solutions, but there have been no definitive cost studies, and estimates of large-scale government projects are almost always too low. (Boston's "Big Dig" to reroute an interstate highway under the coastal city, one of humankind's greatest engineering feats, is only one example that was years overdue and billions over budget.) Angel estimates that his scheme to launch reflective disks into orbit would cost "a few trillion dollars." British economist Nicholas Stern's calculation of the cost of climate change as a percentage of global GDP (roughly $9 trillion) is in the same ballpark; Angel's estimate is also orders of magnitude greater than current global investment in renewable energy technology. Wouldn't it be a safer and wiser investment for society to instead put that money in solar power, wind power, energy efficiency, and carbon sequestration?

15. Commercial control of technology. Who would end up controlling geoengineering systems? Governments? Private companies holding patents on proprietary technology? And whose benefit would they have at heart? These systems could pose issues analogous to those raised by pharmaceutical companies and energy conglomerates whose products ostensibly serve the public, but who often value shareholder profits over the public good.

16. Military use of the technology. The United States has a long history of trying to modify weather for military purposes, including inducing rain during the Vietnam War to swamp North Vietnamese supply lines and disrupt antiwar protests by Buddhist monks.[19] Eighty-five countries, including the United States, have signed the U.N. Convention on the Prohibition of Military or Any Other Hostile Use of Environmental Modification Techniques (ENMOD), but could techniques developed to control global climate forever be limited to peaceful uses?

17. Conflicts with current treaties. The terms of ENMOD explicitly prohibit "military or any other hostile use of environmental modification techniques having widespread, long-lasting or severe effects as the means of destruction, damage, or injury to any other State Party." Any geoengineering scheme that adversely affects regional climate, for example, producing warming or drought, would therefore violate ENMOD.

18. Control of the thermostat. Even if scientists could predict the behavior and environmental effects of a given geoengineering project, and political leaders could muster the public support and funding to implement it, how would the world agree on the optimal climate? What if Russia wants it a couple of degrees warmer, and India a couple of degrees cooler? Should global climate be reset to preindustrial temperature or kept constant at today's reading? Would it be possible to tailor the climate of each region of the planet independently without affecting the others? If we proceed with geoengineering, will we provoke future climate wars?

19. Questions of moral authority. Ongoing global warming is the result of inadvertent climate modification. Humans emit carbon dioxide and other greenhouse gases to heat and cool their homes; to grow, transport, and cook their food; to run their factories; and to travel—not intentionally, but as a by-product of fossil fuel combustion. But now that humans are aware of their effect on climate, do they have a moral right to continue emitting greenhouse gases? Similarly, since scientists know that stratospheric aerosol injection, for example, might impact the ecosphere, do humans have a right to plow ahead regardless? There's no global agency to require an environmental impact statement for geoengineering. So, how should humans judge how much climate control they may try?

20. Unexpected consequences. Scientists cannot possibly account for all of the complex climate interactions or predict all of the impacts of geoengineering. Climate models are improving, but scientists are discovering that climate is changing more rapidly than they predicted, for example, the surprising and unprecedented extent to which Arctic sea ice melted during the summer of 2007. Scientists may never have enough confidence that their theories will predict how well geoengineering systems can work. With so much at stake, there is reason to worry about what we don't know.

THE REASONS WHY GEOENGINEERING may be a bad idea are manifold, though a moderate investment in *theoretical* geoengineering research might help scientists to determine whether or not it *is* a bad idea. Still, it's a slippery slope: I wouldn't advocate actual small-scale stratospheric experiments unless comprehensive climate modeling results could first show that we could avoid at least all of the potential consequences we *know* about. Due to the inherent natural variability of the climate system, this task is not trivial. After that there are still the unknowns, such as the long-term effects of short-term experiments—stratospheric aerosols have an atmospheric lifetime of a couple years.

Solving global warming is not a difficult technical problem. As Stephen Pacala and Robert Socolow detail with their popular wedge model, a combination of several specific actions can stabilize the world's greenhouse gas emissions—although I disagree with their proposal to use nuclear power as one of their "wedges."[20] Instead, the crux of addressing global warming is political. The U.S. government gives multibillion-dollar subsidies to the coal, oil, gas, and nuclear industries, and gives little support to alternative energy sources like solar and wind power that could contribute to a solution. Similarly, the federal government is squashing attempts by states to mandate emissions reductions. If global warming is a political problem more than it is a technical problem, it follows that we don't need geoengineering to solve it.

The U.N. Framework Convention on Climate Change defines "dangerous anthropogenic interference" as *inadvertent* climate effects. However, states must also carefully consider geoengineering in their pledge to prevent dangerous anthropogenic interference with the climate system. ■

FOR NOTES, PLEASE SEE P. 59.

Alan Robock is director of the meteorology undergraduate program and associate director of the Center for Environmental Prediction in the Department of Environmental Sciences at Rutgers University. *This work is supported by the National Science Foundation.*

AN ETHICAL ASSESSMENT OF GEOENGINEERING

While there are many questions about the feasibility, cost, and effectiveness of geoengineering plans, my colleague Alan Robock has been the most systematic and persistent of a number of scientists in raising ethical quandaries about the enterprise. But just how serious are these ethical quandaries?

Most science poses risks of unintended consequences, and lots of science raises issues of commercial and military control. At issue here is whether there is any reason to believe *ex ante* that these are special or unusually large risks. Merely asserting them does not ground an objection *per se*.

Not all of Robock's concerns involve ethics, but of those that do, some involve issues of procedural justice (such as who decides) while others involve matters of distributive justice (such as uneven benefit and harm). To simplify things, let's assume that injecting aerosols into the stratosphere successfully cooled Earth without any untoward effects and with evenly distributed benefits. One might still object that there are issues of procedural justice involved—who decides and who controls. But such concerns don't get much traction when everyone benefits.

Let's pull back from this idealization to imagine an outcome that involves untoward consequences and an uneven distribution of benefits. We deal with consequences by balancing them against the benefits of our interventions. The issue is whether or not we can obtain reliable estimates of both risks and benefits without full-scale implementation of the planned intervention. We already know from modeling that the impact of any such intervention will be uneven, but again, without knowing what the distribution of benefit and harm would be, it's hard to estimate how much this matters. Let's differentiate two circumstances under which going ahead with the intervention might be judged: One is where everyone benefits, while the other is a circumstance in which something less is the case. A conservative conclusion would be to say that beyond modeling and controlled, low-level tests (if the modeling justifies it), we shouldn't sanction any large-scale interventions unless they are in everyone's interest. A slightly eased condition, proposed by the philosopher Dale Jamieson, would be that at least nobody is worse off. That may not be as farfetched a condition as one might think, since, in the end, we are considering this intervention as a means to balance a risk we all face—global warming.

But suppose there are isolated livelihoods that only suffer negative effects of geoengineering. Then numbers begin to matter. In the case that a geoengineering scheme were to harm the few, we should have the foresight to be able to compensate, even if doing so requires something as drastic as relocating populations. I don't mean to oversimplify a complicated issue, but objection to any negative consequences whatsoever isn't a strong enough argument to end discussion.

More trenchant is the worry that the mere possibility of geoengineering would undermine other efforts to decrease our carbon output. Such moral hazard is a familiar worry, and we don't let it stop us in other areas: Antilock braking systems and airbags may cause some to drive more recklessly, but few would let that argument outweigh the overwhelming benefits of such safety features.

As Robock correctly asserts, the crux of addressing global warming may be a political—not a scientific—problem, but it doesn't follow that we may not need geoengineering to solve it. If it is a political problem, it is a *global* political problem, and getting global agreement to curb greenhouse gases is easier said than done.

With geoengineering, in principle, one nation or agent could act, but a challenge arises if the intervention is certain to have uneven impacts among nations. At this early stage, there is no cost associated with improving our ability to quantify and describe what those inequalities would look like. Once we have those answers in hand, then we can engage in serious ethical consideration over whether or not to act. MARTIN BUNZL

Martin Bunzl is a professor of philosophy at Rutgers University.

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NOTES

20 reasons why geoengineering may be a bad idea

CONTINUED FROM P. 18

1. Paul Crutzen, "Albedo Enhancement by Stratospheric Sulfur Injections: A Contribution to Solve a Policy Dilemma?" *Climatic Change*, vol. 77, pp. 211–19 (2006); Tom M. L. Wigley, "A Combined Mitigation/Geoengineering Approach to Climate Stabilization," *Science*, vol. 314, pp. 452–54 (2006).

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Climate change and security

CONTINUED FROM P. 24

1. Climate Change 2007: Summary for Policy Makers. Contribution of Working Group II to the Fourth Assessment Report of the

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Benefits, risks, and costs of stratospheric geoengineering

Alan Robock,[1] Allison Marquardt,[1] Ben Kravitz,[1] and Georgiy Stenchikov[1,2]

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[1] Injecting sulfate aerosol precursors into the stratosphere has been suggested as a means of geoengineering to cool the planet and reduce global warming. The decision to implement such a scheme would require a comparison of its benefits, dangers, and costs to those of other responses to global warming, including doing nothing. Here we evaluate those factors for stratospheric geoengineering with sulfate aerosols. Using existing U.S. military fighter and tanker planes, the annual costs of injecting aerosol precursors into the lower stratosphere would be several billion dollars. Using artillery or balloons to loft the gas would be much more expensive. We do not have enough information to evaluate more exotic techniques, such as pumping the gas up through a hose attached to a tower or balloon system. Anthropogenic stratospheric aerosol injection would cool the planet, stop the melting of sea ice and land-based glaciers, slow sea level rise, and increase the terrestrial carbon sink, but produce regional drought, ozone depletion, less sunlight for solar power, and make skies less blue. Furthermore it would hamper Earth-based optical astronomy, do nothing to stop ocean acidification, and present many ethical and moral issues. Further work is needed to quantify many of these factors to allow informed decision-making. **Citation:** Robock, A., A. Marquardt, B. Kravitz, and G. Stenchikov (2009), Benefits, risks, and costs of stratospheric geoengineering, *Geophys. Res. Lett.*, *36*, L19703, doi:10.1029/2009GL039209.

1. Introduction

[2] Global warming will continue for decades due to anthropogenic emissions of greenhouse gases and aerosols [*Intergovernmental Panel on Climate Change* (*IPCC*), 2007a], with many negative consequences for society [*IPCC*, 2007b]. Although currently impossible, as there are no means of injecting aerosols or their precursors into the stratosphere, the possibility of geoengineering the climate is now being discussed in addition to the conventional potential responses of mitigation (reducing emissions) and adaptation [*IPCC*, 2007c]. While originally suggested by *Budyko* [1974, 1977], *Dickinson* [1996], and many others (see *Robock et al.* [2008] and *Rasch et al.* [2008a] for a comprehensive list), *Crutzen* [2006] and *Wigley* [2006] rekindled interest in stratospheric geoengineering using sulfate aerosols. This proposal for "solar radiation management," to reduce insolation with an anthropogenic stratospheric aerosol cloud in the same manner as episodic explosive volcanic eruptions, will be called "geoengineering" here, recognizing that others have a more inclusive definition of geoengineering that can include tropospheric cloud modification, carbon capture and sequestration, and other proposed techniques.

[3] The decision to implement geoengineering will require a comparison of its benefits, dangers, and costs to those of other responses to global warming. Here we present a brief review of these factors for geoengineering. It should be noted that in the three years since *Crutzen* [2006] and *Wigley* [2006] suggested that, in light of no progress toward mitigation, geoengineering may be necessary to reduce the most severe impacts of global warming, there has still been no global progress on mitigation. In fact, Mauna Loa data show that the rate of CO_2 increase in the atmosphere is actually rising. However, the change of U.S. administration in 2009 has completely changed the U.S. policy on global warming. In the past eight years, the U.S. has stood in the way of international progress on this issue, but now President Obama is planning to lead a global effort toward a mitigation agreement in Copenhagen in December 2009. If geoengineering is seen as a potential low-cost and easy "solution" to the problem, the public backing toward a mitigation agreement, which will require some short-term dislocations, may be eroded. This paper, therefore, is intended to serve as useful information for that process.

[4] *Crutzen* [2006], *Wigley* [2006], and others who have suggested that geoengineering be considered as a response to global warming have emphasized that mitigation is the preferable response and that geoengineering should only be considered should the planet face a climate change emergency. However, there are no international governance mechanisms or standards that would allow the determination of such an emergency. Furthermore, should geoengineering begin, it would have to continue for decades, and the decision to stop would be even more difficult, what with commercial and employment interests in continuing the project as well as concerns for the additional warming that would result.

[5] *Robock* [2008a] presented 20 reasons why geoengineering may be a bad idea. Those reasons are updated here. However, there would also be benefits of geoengineering, against which the risks must be weighed. So first we discuss those benefits, then the risks, and finally the costs. As the closest natural analog, examples from the effects of volcanic eruptions are used to illustrate the benefits and costs.

2. Benefits

[6] The benefits of stratospheric geoengineering are listed in Table 1. Both observations of the response of climate to large explosive volcanic eruptions [*Robock*, 2000] and all modeling studies conducted so far [e.g., *Teller et al.*, 1997, 1999, 2002; *Govindasamy and Caldeira*, 2000; *Govindasamy*

[1]Department of Environmental Sciences, Rutgers University, New Brunswick, New Jersey, USA.
[2]Now at Department of Environmental Science, King Abdullah University of Science and Technology, Thuwal, Saudi Arabia.

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Table 1. Benefits and Risks of Stratospheric Geoengineering[a]

Benefits	Risks
1. Cool planet	1. Drought in Africa and Asia
2. Reduce or reverse sea ice melting	2. Continued ocean acidification from CO_2
3. Reduce or reverse land ice sheet melting	3. Ozone depletion
4. Reduce or reverse sea level rise	4. No more blue skies
5. Increase plant productivity	5. Less solar power
6. Increase terrestrial CO_2 sink	6. Environmental impact of implementation
	7. Rapid warming if stopped
	8. Cannot stop effects quickly
	9. Human error
	10. Unexpected consequences
	11. Commercial control
	12. Military use of technology
	13. Conflicts with current treaties
	14. Whose hand on the thermostat?
	15. Ruin terrestrial optical astronomy
	16. Moral hazard – the prospect of it working would reduce drive for mitigation
	17. Moral authority – do we have the right to do this?

[a]The right column is an update of *Robock* [2008a].

et al., 2002, 2003; *Wigley*, 2006; *Rasch et al.*, 2008a, 2008b; *Robock et al.*, 2008; *Lenton and Vaughan*, 2009] show that with sufficient stratospheric sulfate aerosol loading, backscattered insolation will cool Earth. The amount of cooling depends on the amount of aerosols and how long the aerosol cloud is maintained in the stratosphere. Many negative impacts of global warming are strongly correlated with global average surface air temperature, so it would in theory be possible to stop the rise of global-average temperature or even lower it, thus ameliorating these impacts. For example, reduced temperature would slow or reverse the current downward trend in Arctic sea ice, the melting of land glaciers, including Greenland, and the rise of sea level.

[7] Observations after large volcanic eruptions show that stratospheric sulfate aerosols drastically change the partitioning of downward solar flux into direct and diffuse [*Robock*, 2000]. After the 1982 El Chichón eruption, observations at the Mauna Loa Observatory in Hawaii on mornings with clear skies, at a solar zenith angle of 60° equivalent to two relative air masses, showed a peak change of downward direct insolation, from 515 W m^{-2} to 340 W m^{-2}, while diffuse radiation increased from 40 W m^{-2} to 180 W m^{-2} [*Robock*, 2000]. A similar effect was observed after the 1991 Mt. Pinatubo eruption. While the change of net radiation after El Chichón was a reduction of 35 W m^{-2}, this shift to an increase of the diffuse portion actually produced an increase of the growth of terrestrial vegetation, and an increase in the terrestrial CO_2 sink. *Gu et al.* [1999, 2002, 2003], *Roderick et al.* [2001], and *Farquhar and Roderick* [2003] suggested that increased diffuse radiation allows plant canopies to photosynthesize more efficiently, increasing the CO_2 sink. *Gu et al.* [2003] actually measured this effect in trees following the 1991 Pinatubo eruption. While some of the global increase in CO_2 sinks following volcanic eruptions may have been due to the direct temperature effects of the eruptions, *Mercado et al.* [2009] showed that the diffuse radiation effect produced an increase sink of about 1 Pg C a^{-1} for about one year following the Pinatubo eruption. The effect of a permanent geoengineering aerosol cloud would depend on the optical depth of the cloud, and these observed effects of episodic eruptions may not produce a permanent vegetative response as the vegetation adjusts to this changed insolation. Nevertheless, this example shows that stratospheric geoengineering may provide a substantial increased CO_2 sink to counter anthropogenic emissions. This increase in plant productivity could also have a positive effect on agriculture.

3. Risks

[8] The potential benefits of stratospheric geoengineering must be evaluated in light of a large number of potential negative effects [*Robock*, 2008a]. While most of those concerns are still valid, three of them can now be removed. As discussed above, the effects of the change in diffuse and direct radiation on plants would in general be positive. *Kravitz et al.* [2009] have shown that the excess sulfate acid deposition would not be enough to disrupt ecosystems. And below we show that there are potentially airplane-based injection systems that would not be overly costly as compared to the cost of mitigation. But there still remains a long list of negative effects (Table 1).

[9] Two of the reasons in the list have been strengthened by recent work. *Tilmes et al.* [2008] used a climate model to show that indeed stratospheric geoengineering would produce substantial ozone depletion, prolonging the end of the Antarctic ozone hole by several decades and producing ozone holes in the Arctic in springs with a cold lower stratosphere. *Murphy* [2009] used observations of direct solar energy generation in California after the 1991 Pinatubo eruption and showed that generation went from 90% of peak capacity in non-volcanic conditions to 70% in summer 1991 and to less than 60% in summer 1992.

[10] One additional problem with stratospheric geoengineering has also become evident. There would be a major impact on terrestrial optical astronomy. Astronomers spend billions of dollars to build mountain-top observatories to get above pollution in the lower troposphere. Geoengineering would put permanent pollution above these telescopes.

4. Costs

[11] *Robock* [2008a] suggested that the construction and operation of a system to inject aerosol precursors into the stratosphere might be very expensive. Here we analyze the costs of three suggested methods of placing the aerosol precursors into the stratosphere: airplanes, artillery shells, and stratospheric balloons (Figure 1 and Table 2). Because such systems do not currently exist, the estimates presented here are rough but provide quantitative starting points for further discussions of the practicality of geoengineering. Even if sulfate aerosol precursors could be injected into the stratosphere, it is not clear that aerosols could be created of a size range with an effective radius of about 0.5 μm, like volcanic aerosols, that would be effective at cooling the planet. Some of these issues were discussed by *Rasch et al.* [2008a]. Can injectors be designed to give appropriate initial aerosol sizes? If injected into an existing sulfate cloud, would the existing aerosols just grow at the expense

Figure 1. Proposed methods of stratospheric aerosol injection. A mountain top location would require less energy for lofting to stratosphere. Drawing by Brian West.

of smaller ones? These important topics are currently being investigated by us, and here we limit the discussion to just getting the precursor gases into the stratosphere.

[12] Figure 1 is drawn with the injection systems on a mountain and with the supplies arriving up the mountain by train. If the injection systems were placed on a mountain top, the time and energy needed to get the material from the surface to the stratosphere would be less than from sea level. Gunnbjorn Mountain, Greenland, is the highest point in the Arctic, reaching an altitude of 3700 m. In the tropics, there are multiple high altitude locations in the Andes.

[13] The 1991 Mt. Pinatubo eruption injected 20 Tg SO_2 into the tropical lower stratosphere [*Bluth et al.*, 1992], which formed sulfate aerosols and cooled the climate for about two years. As discussed by *Robock et al.* [2008], the equivalent of one Pinatubo every 4–8 years would be

Table 2. Costs for Different Methods of Injecting 1 Tg of a Sulfur Gas Per Year Into the Stratosphere[a]

Method	Payload (tons)	Ceiling (km)	Number of Units	Purchase Price (2008 Dollars)	Annual Cost
F-15C Eagle	8	20	167 with 3 flights/day	$6,613,000,000	$4,175,000,000[b]
KC-135 Tanker	91	15	15 with 3 flights/day	$784,000,000	$375,000,000
KC-10 Extender	160	13	9 with 3 flights/day	$1,050,000,000	$225,000,000[b]
Naval Rifles	0.5		8,000 shots per day	included in annual cost	$30,000,000,000
Stratospheric Balloons	4		37,000 per day	included in annual cost	$21,000,000,000–$30,000,000,000

[a]Airplane data from Air Combat Command (2008), Air Mobility Command (2008a, 2008b). See text for sources of data for airplanes. Costs in last two lines from *COSEPUP* [1992]. Conversion from 1992 and 1998 dollars to 2008 dollars (latest data available) using the Consumer Price Index (http://www.measuringworth.com/uscompare/).

[b]If operation costs were the same per plane as for the KC-135.

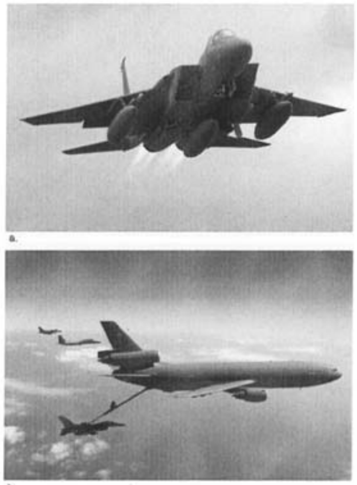

Figure 2. U.S. military planes that could be used for geoengineering. (a) F-15C Eagle (http://www.af.mil/shared/media/photodb/photos/060614-F-8260H-310.JPG), (b) KC-10 Extender (http://www.af.mil/shared/media/factsheet/kc_10.jpg).

required to stop global warming or even reduce global temperature in spite of continued greenhouse gas emissions.

[14] While volcanic eruptions inject mostly SO_2 into the stratosphere, the relevant quantity is the amount of sulfur. If H_2S were injected instead, it would oxidize quickly to form SO_2, which would then react with water to form H_2SO_4 droplets. Because of the relative molecular weights, only 2.66 Tg of H_2S (molecular weight 34 g mol^{-1}) would be required to produce the same amount of sulfate aerosols as 5 Tg of SO_2 (molecular weight 64 g mol^{-1}). Since there are choices for the desired sulfate aerosol precursor, our calculations will be in terms of stratospheric injection of any gas. H_2S, however, is more corrosive than SO_2 [e.g., *Kleber et al.*, 2008] and is very dangerous, so it would probably not be the gas of choice. Exposure to 50 ppm of H_2S can be fatal [*Kilburn and Warshaw*, 1995]. H_2S was even used for a time as a chemical warfare agent in World War I [*Croddy et al.*, 2001]. However, 100 ppm of SO_2 is also considered "immediately dangerous to life and health" [*Agency for Toxic Substances and Disease Registry*, 1998].

[15] If the decision were ever made to implement geoengineering, the amount of gas to loft, the timing and location of injections, and how to produce aerosols, would have to be considered, and these are issues we address in other work [*Rasch et al.*, 2008a]. Here we just examine the question of the cost of lofting 1 Tg of a sulfur gas per year into the stratosphere. Other more speculative geoengineering suggestions, such as engineered aerosols [e.g., *Teller et al.*, 1997], are not considered here.

[16] Our work is an update and expansion of the first quantitative estimates by *Committee on Science Engineering and Public Policy* (*COSEPUP*) [1992]. While they listed "Stratospheric Bubbles; Place billions of aluminized, hydrogen-filled balloons in the stratosphere to provide a reflective screen; Low Stratospheric Dust; Use aircraft to maintain a cloud of dust in the low stratosphere to reflect sunlight; Low Stratospheric Soot; Decrease efficiency of burning in engines of aircraft flying in the low stratosphere to maintain a thin cloud of soot to intercept sunlight" among the possibilities for geoengineering, they did not evaluate the costs of aircraft or stratospheric bubble systems.

[17] Rather than cooling the entire planet, it has been suggested that we only try to modify the Arctic to prevent a sea ice-free Arctic summer and to preserve the ice sheets in Greenland while mitigation is implemented [*Lane et al.*, 2007; *Caldeira and Wood*, 2008]. A disadvantage of Arctic injection is that the aerosols would only last a few months rather than a couple years for tropical injection [*Robock et al.*, 2008]. An advantage is that they would only need to be injected in spring, so their strongest effects would occur over the summer. They would have no effect in the dark winter. One important difference between tropical and Arctic injections is the height of the tropopause, which is about 16 km in the tropics but only about 8 km in the Arctic. These different heights affect the capability of different injection schemes to reach the lower stratosphere, and we consider both cases here.

[18] In addition to these costs would be the cost of the production and transport to the deployment point of the sulfur gas. *COSEPUP* [1992] estimated the price of SO_2 to be $50,000,000 per Tg in 1992 dollars, and H_2S would be much cheaper, as it is currently removed from oil as a pollutant, so the price of the gases themselves would be a minor part of the total. The current bulk price for liquid SO_2 is $230/ton or $230,000,000 per Tg [*Chemical Profiles*, 2009].

4.1. Airplanes

[19] Existing small jet fighter planes, like the F-15C Eagle (Figure 2a), are capable of flying into the lower stratosphere in the tropics, while in the Arctic, larger planes, such as the KC-135 Stratotanker or KC-10 Extender (Figure 2b), are capable of reaching the required altitude. Specialized research aircraft such as the American Lockheed ER-2 and the Russian M55 Geophysica, both based on Cold War spy planes, can also reach 20 km, but neither has a very large payload or could be operated continuously to deliver gases to the stratosphere. The Northrop Grumman RQ-4 Global Hawk can reach 20 km without a pilot but costs twice as much as an F-15C. Current designs have a payload of 1–1.5 tons. Clearly it is possible to design an autonomous specialized aircraft to loft sulfuric acid precursors into the lower stratosphere, but the current analysis focuses on existing aircraft.

[20] Options for dispersing gases from planes include the addition of sulfur to the fuel, which would release the

aerosol through the exhaust system of the plane, or the attachment of a nozzle to release the sulfur from its own tank within the plane, which would be the better option. Putting sulfur in the fuel would have the problem that if the sulfur concentration were too high in the fuel, it would be corrosive and affect combustion. Also, it would be necessary to have separate fuel tanks for use in the stratosphere and in the troposphere to avoid sulfate aerosol pollution in the troposphere.

[21] The military has already manufactured more planes than would be required for this geoengineering scenario, potentially reducing the costs of this method. Since climate change is an important national security issue [*Schwartz and Randall*, 2003], the military could be directed to carry out this mission with existing aircraft at minimal additional cost. Furthermore, the KC-135 fleet will be retired in the next few decades as a new generation of aerial tankers replaces it, even if the military continues to need the in-flight refueling capability for other missions.

[22] Unlike the small jet fighter planes, the KC-135 and KC-10 are used to refuel planes mid-flight and already have a nozzle installed. In the tropics, one option might be for the tanker to fly to the upper troposphere, and then fighter planes would ferry the sulfur gas up into the stratosphere (Figure 2b). It may also be possible to have a tanker tow a glider with a hose to loft the exit nozzle into the stratosphere.

[23] In addition to the issues of how to emit the gas as a function of space and time to produce the desired aerosols, another concern is the maximum concentration of sulfate aerosols through which airplanes can safely fly. In the past, noticeable damage has occurred to airplanes that fly through plumes of volcanic ash containing SO_2. In June, 1982, after the eruption of Galunggung volcano in Java, Indonesia, two passenger planes flew through a volcanic cloud. In one case the windows were pitted, volcanic ash entered the engines and thrust was lost in all four engines. In the other case, the same thing happened, with the plane descending 7.5 km before the engines could be restarted [*McClelland et al.*, 1989]. While the concentration of sulfate in the stratosphere would be less than in a plume like this, and there would be no ash, there could still be sulfuric acid damage to airplanes. In the year after the 1991 Pinatubo eruption, airplanes reported acid damage to windows and other parts. An engineering study would be needed to ascertain whether regular flight into a stratospheric acid cloud would be safe, and how much harm it would do to airplanes.

[24] The calculations for airplanes are summarized in Table 2. We assume that the sulfur gas will be carried in the cargo space of the airplane, completely separate from the fuel tank. The cost of each plane comes from Air Combat Command (F-15 Eagle, Air Force Link Factsheets, 2008, available at http://www.af.mil/information/factsheets/factsheet.asp?id=101) for the F-15C ($29.9 million), Air Mobility Command (KC-10 Extender, Air Force Link Factsheets, 2008, available at http://www.af.mil/information/factsheets/factsheet.asp?id=109) for the KC-10 ($88.4 million), and Air Mobility Command (KC-135 Stratotanker, Air Force Link Factsheets, 2008, available at http://www.af.mil/information/factsheets/factsheet.asp?id=110) for the KC-135 ($39.6 million), in 1998 dollars, and in Table 2 is then converted to 2008 dollars (latest data available) by multiplying by a factor of 1.32 using the Consumer Price Index (S. H. Williamson, Six ways to compute the relative value of a U.S. dollar amount, 1774 to present, MeasuringWorth, 2008, available at http://www.measuringworth.com/uscompare/). If existing aircraft were converted to geoengineering use, the cost would be much less and would only be for retrofitting of the airplanes to carry a sulfur gas and installation of the proper nozzles. The annual cost per aircraft for personnel, fuel, maintenance, modifications, and spare parts for the older E model of the KC-135 is $4.6 million, while it is about $3.7 million for the newer R model, based on an average of 300 flying hours per year [*Curtin*, 2003].

[25] We postulate a schedule of three flights per day, 250 days per year, for each plane. If each flight were 2 hours, this would be 1500 hours per year. As a rough estimate, we take $5 million per 300 hours times 5, or $25 million per year in operational costs per airplane. If we use the same estimates for the KC-10 and the F-15C, we can get an upper bound on the annual costs for using these airplanes for geoengineering, as we would expect the KC-10 to be cheaper, as it is newer than the KC-135, and the F-15C to be cheaper, just because it is smaller and would require less fuel and fewer pilots.

4.2. Artillery Shells

[26] *COSEPUP* [1992] made calculations using 16-inch (41-cm) naval rifles, assuming that aluminum oxide (Al_2O_3) dust would be injected into the stratosphere. They envisaged 40 10-barrel stations operating 250 days per year with each gun barrel replaced every 1500 shots. To place 5 Tg of material into the stratosphere, they estimated the annual costs, including ammunition, gun barrels, stations, and personnel, as $100 billion (1992 dollars), with the cost of the Al_2O_3 only $2.5 million of the total. So the cost for 1 Tg would be $30 billion (2008 dollars). It is amusing that they conclude, with a total lack of irony, "The rifles could be deployed at sea or in empty areas (e.g., military reservations) where the noise of the shots and the fallback of expended shells could be managed."

4.3. Stratospheric Balloons

[27] Requiring no fuel, weather balloons are launched on a daily basis to high levels of the atmosphere. Balloons can made out of either rubber or plastic, but plastic would be needed due to the cold temperatures at the tropical tropopause or in the Arctic stratosphere, as rubber balloons would break prematurely. Weather balloons are typically filled with helium, but hydrogen (H_2) is less expensive and more buoyant than helium and can also be used safely to inflate balloons.

[28] Balloons could be used in several ways for geoengineering. As suggested by L. Wood (personal communication, 2008), a tethered balloon could float in the stratosphere, suspending a hose to pump gas upwards. Such a system has never been demonstrated and should probably be included in the next section of this paper on exotic future ideas. Another idea is to use aluminized long-duration balloons floating as reflectors [*Teller et al.*, 1997], but again, such a system depends on future technology development. Here we discuss two options based on current technology: lofting a payload under a balloon or mixing H_2 and H_2S inside a balloon. In the first case, the additional mass of the balloon and its gas would be a weight penalty,

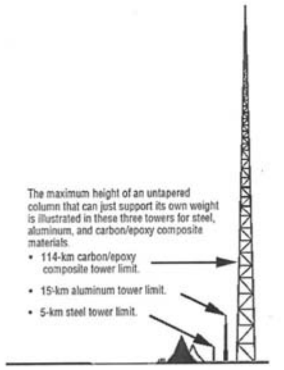

Figure 3. The maximum height of an untapered tower that can support its own weight, showing that one tower on the Equator could be used for stratospheric geoengineering. (From "Space Elevator Schematics" page at end of *Smitherman* [2000]).

but in the second case, when the balloons burst, the H_2S would be released into the stratosphere.

[29] *COSEPUP* [1992] discussed a system to loft a payload under large H_2 balloons, smaller multi-balloon systems, and hot air balloons. To inject 1 Tg of H_2S into the stratosphere with H_2 balloons, the cost including balloons, dust, dust dispenser equipment, hydrogen, stations, and personnel, was estimated to be $20 million, which would be $30 million in 2008 dollars. Hot air balloon systems would cost 4 to 10 times that of using H_2 balloons.

[30] We examined another idea, of mixing H_2 and H_2S inside a balloon, and then just releasing the balloons to rise themselves and burst in the stratosphere, releasing the gases. The H_2S would then oxidize to form sulfate aerosols, but the H_2 would also have stratospheric impacts. Since H_2S has a molecular weight of 34 g/mol, as compared to 29 g/mol for air, by mixing it with H_2, balloons can be made buoyant. The standard buoyancy of weather balloons as compared to air is 20%. The largest standard weather balloon available is model number SF4-0.141-.3/0-T from Aerostar International, with a maximum volume of 3990 m^3, and available in quantities of 10 or more for $1,711 each. The balloons would burst at 25 mb.

[31] To calculate the mix of gases, if the temperature at 25 mb is 230 K and the balloon is filled at the surface at a pressure of 1000 mb and a temperature of 293 K, then the volume of the balloon would be:

$$V = 3990\ \mathrm{m}^3 \times \frac{25\ \mathrm{mb}}{1000\ \mathrm{mb}} \times \frac{293\ \mathrm{K}}{230\ \mathrm{K}} = 127\ \mathrm{m}^3 \quad (1)$$

The mass of air displaced would be:

$$m = \frac{pV}{RT} = \frac{1000\ \mathrm{mb} \times 127\ \mathrm{m}^3}{287 \frac{\mathrm{J}}{\mathrm{kg\ K}} \times 293\ \mathrm{K}} = 151\ \mathrm{kg} \quad (2)$$

To produce the required buoyancy, the balloon with its mixture of H_2 and H_2S would have a mass $m' = m/1.2 =$ 125.9 kg. Normally a weather balloon is filled with He, allowing it to lift an additional payload beneath it. In our case, the payload will be the H_2S inside the balloon. Since each balloon has a mass of 11.4 kg, the total mass of the gases would be 114.5 kg. To produce that mass in that volume would require a mixture of 37.65% H_2 and 62.35% H_2S by volume, for a total mass of H_2S of 110.6 kg. To put 1 Tg of gas into the stratosphere per year would therefore require 9 million balloons, or 36,000 per day (using 250 days per year). This would cost $15.5 billion per year just for the balloons. According to *COSEPUP* [1992], the additional costs for infrastructure, personnel, and H_2 would be $3,600,000,000 per year, or $5.5 billion in 2008 dollars, for their balloon option, and as rough guess we adopt it for ours, too. So our balloon option would cost $21 billion per year in 2008 dollars.

[32] The option above would also inject 0.04 Tg H_2 into the stratosphere each year. This is 2 to 3 orders of magnitude less than current natural and anthropogenic H_2 emissions [*Jacobson*, 2008], so would not be expected to have any detectable effects on atmospheric chemistry.

[33] Because about 1/10 of the mass of the balloons would actually be the balloons, this would mean 100 million kg of plastic falling to Earth each year. As *COSEPUP* [1992] said, "The fall of collapsed balloons might be an annoying form of trash rain."

[34] We repeated the above calculations using SO_2. Since SO_2 has a molecular weight of 64 g/mol, it would require a much higher ratio of H_2 to the sulfur gas to make the balloons buoyant. The number of balloons and the cost to loft 1 Tg of S as SO_2 would be approximately twice that as for H_2S, as it would be for the other means of lofting.

4.4. Ideas of the Future

[35] All the above systems are based on current technology. With small changes, they would all be capable of injecting gases into the stratosphere within a few years. However, more exotic systems, which would take longer to realize, could also be considered.

4.4.1. Tall Tower

[36] The tallest structure in the world today is the KTHI-TV transmission tower in Fargo, North Dakota, at 629 m high [*Smitherman*, 2000]. However, as *Smitherman* [2000] explains, the heights of this tower and current tall buildings are not limited by materials or construction constraints, but only because there has been no need. Currently, an untapered column made of aluminum that can just support its own weight could be built to a height of 15 km. One made of carbon/epoxy composite materials could be built to 114 km (Figure 3). If the tower were tapered (with a larger base), had a fractal truss system, were stabilized with guy wires (like the KTHI-TV tower), or included balloons for buoyancy, it could be built much higher.

[37] We can imagine such a tower on the Equator with a hose to pump the gas to the stratosphere. The weather on the Equator would present no strong wind issues, as tornadoes and hurricanes cannot form there, but icing issues for the upper portion would need to be addressed. If the gas were pushed up a hose, adiabatic expansion would cool it to temperatures colder than the surrounding atmosphere, exacerbating icing problems. Because such a tower has never been built, and many engineering issues would need to be considered, from the construction material to the pumping needed, we cannot offer an estimate of the cost. Only one tower would be needed if the hoses were large enough to pump the required amount of gas, but one or two additional backup systems would be needed if the planet were to depend on this to prevent climate emergencies. Weather issues, such as strong winds, would preclude such a tower at high latitudes, even though it would not need to be as tall. (A tethered balloon system would have all the same issues, but weather would be even more of a factor.)

4.4.2. Space Elevator

[38] The idea of a geostationary satellite tethered to Earth, with an elevator on the cable was popularized by *Clarke* [1978]. A material for the cable that was strong enough to support its own weight did not exist at the time, but now carbon nanotubes are considered a possibility [*Smitherman*, 2000; *Pugno*, 2006]. Such a space elevator could use solar power to lift material to stratospheric levels for release for geoengineering. However, current designs for such a space elevator would have it anchored to Earth by a tower taller than the height to which we would consider doing geoengineering [*Smitherman*, 2000]. So a tall tower would suffice without an exotic space elevator.

5. Conclusions

[39] Using existing airplanes for geoengineering would cost several billion dollars per year, depending on the amount, location, and type of sulfur gas injected into the stratosphere. As there are currently 522 F-15C Eagles, 481 KC-135 Stratotankers, and 59 KC-10 Extenders, if a fraction of them were dedicated to geoengineering, equipment costs would be minimal. Systems using artillery or balloons would cost much more and would produce additional potential problems of falling spent artillery shells or balloons, or H_2 injections into the stratosphere. However, airplane systems would still need to address several issues before being practical, including the effects of acid clouds on the airplanes, whether nozzles could be designed to produce aerosol particles of the desired size distributions, and whether injection of sulfur gases into an existing sulfuric acid cloud would just make existing droplets grow larger rather than producing more small droplets. All the systems we evaluate would produce serious pollution issues, in terms of additional CO_2, particles, and noise in the production, transportation, and implementation of the technology at the location of the systems.

[40] Several billion dollars per year is a lot of money, but compared to the international gross national product, this amount would not be a limiting factor in the decision of whether to proceed with geoengineering. Rather, other concerns, including reduction of Asian monsoon rainfall, ozone depletion, reduction of solar power, psychological effects of no more blue skies, and political and ethical issues (Table 1), will need to be compared to the potential advantages before society can make this decision. As *COSEPUP* [1992] already understood, "The feasibility and possible side-effects of these geoengineering options are poorly understood. Their possible effects on the climate system and its chemistry need considerably more study and research. They should not be implemented without careful assessment of their direct and indirect consequences."

[41] Table 1 gives a list of the potential benefits and problems with stratospheric geoengineering. But for society to make a decision as to whether to eventually implement this response to global warming, we need somehow to quantify each item on the list. While it may be impossible for some of them, additional research can certainly provide valuable information about some of them. For example, reduction of summer precipitation in Asia and Africa could have a negative impact on crop productivity, and this is why this climate change is a potential major concern. But exactly how much will precipitation go down? How will the effects of increased diffuse insolation and increased CO_2 ameliorate the effects of reduced soil moisture on agricultural production?

[42] If stratospheric geoengineering were to be implemented, it would be important to be able to observe the resulting stratospheric aerosol cloud. After the 1991 Pinatubo eruption, observations with the Stratospheric Aerosol and Gas Experiment II (SAGE II) instrument on the Earth Radiation Budget Satellite [*Russell and McCormick*, 1989] showed how the aerosols spread, but there was a blind spot in the tropical lower stratosphere where there was so much aerosol that too little sunlight got through to make measurements [*Antuña et al.*, 2002]. To be able to measure the vertical distribution of the aerosols, a limb-scanning design, such as that of SAGE II, is optimal. Right now, the only limb-scanner in orbit is the Optical Spectrograph and InfraRed Imaging System (OSIRIS), a Canadian instrument on Odin, a Swedish satellite. SAGE III flew from 2002 to 2006, and there are no plans for a follow on mission. A spare SAGE III sits on a shelf at a NASA lab, and could be used now. Certainly, a dedicated observational program would be needed as an integral part of any geoengineering implementation.

[43] As already pointed out by *Robock* [2008b] and the *American Meteorological Society* [2009], a well-funded national or international research program, perhaps as part of the currently ongoing Intergovernmental Panel on Climate Change Fifth Scientific Assessment, would be able to look at several other aspects of geoengineering and provide valuable guidance to policymakers trying to decide how best to address the problems of global warming. Such research should include theoretical calculations as well as engineering studies. While small-scale experiments could examine nozzle properties and initial formation of aerosols, they could not be used to test the climatic response of stratospheric aerosols. Because of the natural variability of climate, either a large forcing or a long-term (decadal) study with a small forcing would be necessary to detect a response above climatic noise. Because volcanic eruptions occasionally do the experiment for us and climate models have been validated by simulating volcanic eruptions, it would not be important to fully test the climatic impact of stratospheric geoengineering in situ as part of a decision about implementation. However, the evolution

of aerosol properties, including size distribution, for an established stratospheric aerosol cloud would need careful monitoring during any full-scale implementation.

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B. Kravitz, A. Marquardt, and A. Robock, Department of Environmental Sciences, Rutgers University, 14 College Farm Road, New Brunswick, NJ 08901, USA. (benkravitz@envsci.rutgers.edu; abmarq18@eden.rutgers.edu; robock@envsci.rutgers.edu)

G. Stenchikov, Department of Environmental Science, King Abdullah University of Science and Technology, P.O. Box 55455, Thuwal 21534, Saudi Arabia. (georgiy.stenchikov@kaust.edu.sa)

Chairman GORDON. Thank you, Dr. Robock. Dr. Fleming, you are recognized.

STATEMENT OF DR. JAMES FLEMING, PROFESSOR AND DIRECTOR, SCIENCE, TECHNOLOGY AND SOCIETY PROGRAM, COLBY COLLEGE

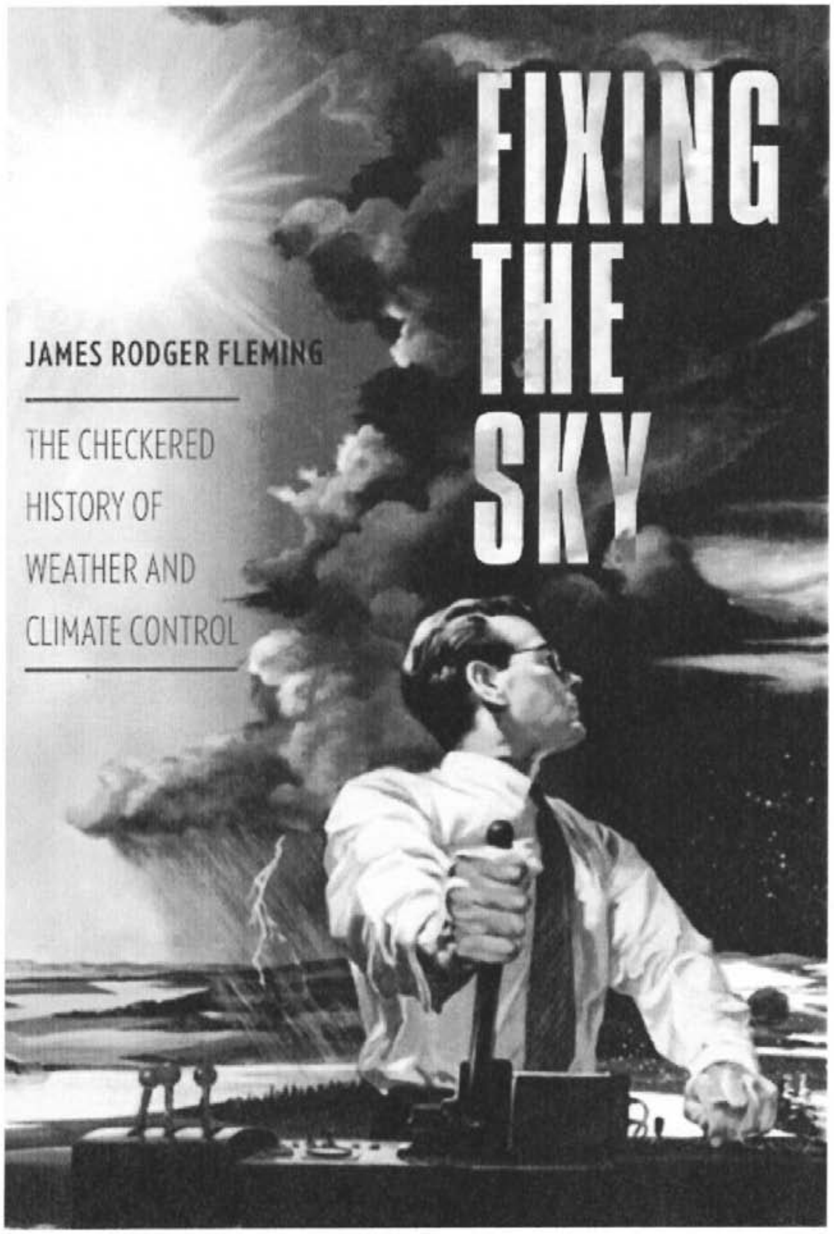
Dr. FLEMING. Thank you, Mr. Chairman, Ranking Member Hall, and Members of the Committee on Science and Technology. I want to talk about history, and one of my epigraphs is that in facing unprecedented challenges, which I think we are, it is good to seek historical precedents. History matters, and informed policy decisions are going to require interdisciplinary, international, and intergenerational perspectives. So I applaud your international move, and I would like to make a case for intergenerational perspectives as well that are informed by history.

I was once asked when humans first became concerned about climate change, and I immediately responded, in the Pleistocene. That is, our whole history comes out of ice age variations of climate, and all of human history lies within the last interglacial era, which was 12,000 years ago. We have experienced huge variations in climate, up to 27 degrees Fahrenheit, and I am sure the early humans had important tribal councils, too, to talk about these things, although they didn't have mitigation yet as an option.

European explorers and early American settlers were surprised that the New World was so much colder than the areas of the same latitude in Europe. For example, Washington D.C. is on the same parallel as Lisbon, Portugal. Colonists worked to improve the climate by cutting the forest, tilling the soil, and draining the marshes. Benjamin Franklin thought this was possible. Thomas Jefferson thought it was actually happening. He called for an index of the American climate, which is one reason we have great weather records in this country, to document the changes being caused by human intervention.

I will show a few pictures.

[The information follows:]



The quest to control nature, including the sky, is deeply rooted in the history of western science. Some climate engineers claim they are the first generation to propose the deliberate manipulation of the planetary environment, but history says otherwise. In the 1830s, America's first national meteorologist, James Espy, who worked for the U.S. Army Surgeon General, advocated large-scale engineering proposals to emulate "artificial volcanoes." He proposed lighting huge fires each week—he preferred Sunday evenings—all along the Appalachian Mountains. Each week he was going to make it rain and control and enhance the Nation's rainfall. Espy argued that the heated updrafts would trigger rain that would not only eliminate droughts but also temperature extremes and would render the air healthy by clearing it of miasmas. A popular writer at the time, Eliza Leslie, pointed out that manufactured weather control would generate more problems than it solved and would satisfy no one. This is 1842.

The image of the technocrat pulling the levers of weather control appeared on the cover of Collier's Magazine in 1954. We were in a weather control race with the Soviet Union at the time, and an Air Force general had just announced to the press that the nation that controls the weather will control the world. The magazine article inside, by President Eisenhower's Weather Advisor, Harold Orville, provided detailed ways of conducting weather warfare. A year later, the noted Princeton mathematician, Johnny Von Neumann, in an article called, Can We Survive Technology?, wrote that climate control through managing solar radiation was not necessarily a rational undertaking. In his opinion, climate control could alter the entire globe, shatter the existing political order, merge each nation's affairs with every other, and lend itself to forms of warfare as yet unimagined. He compared climate control to the threat of nuclear proliferation.

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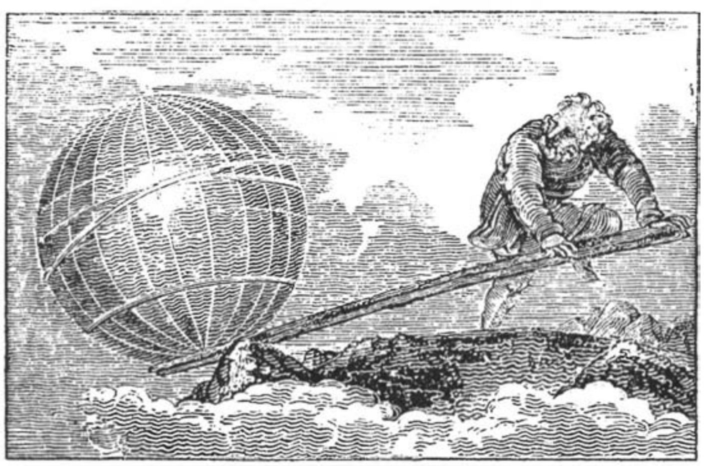

"Give me a place to stand and I will move the earth"—Archimedes. Engraving from Mechanics Magazine, London, 1824.

Here, Archimedes is acting as a geoengineer and technology is his lever, but where is he standing and where will the earth roll if tipped? Geoengineering is not cheap since we don't know the side-effects. Quoting Ron Prinn of MIT, "How do you engineer a system you don't understand?" While some argue that we can control the temperature of the globe, ironically, at a recent NASA meeting on the topic of managing solar, a meeting coordinator apologized for not being able to control the temperature of the room. Think about it.

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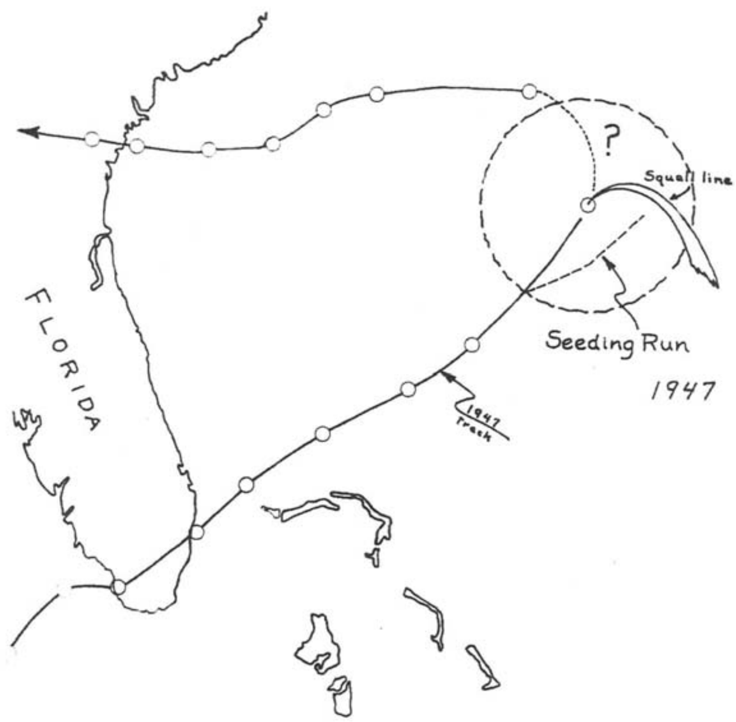


This is Hurricane King, 1947, when Project Cirrus intervened and seeded it. They wanted to announce to the press that they can control hurricanes, but basically they cancelled the press conference when it came ashore and devastated Savannah, Georgia.

Other diplomatic disasters include Project Stormfury in the 1960s where Fidel Castro accused America of cloud seeding over Cuba and in Vietnam, Operation Popeye, when the UN subsequently outlawed hostile use of weather modification.

People have said that climate control is not a good idea. Harry Wexler, head of research at the Weather Bureau, said this in 1962, and just two years ago, Bert Bolin, the first chair of the IPCC, wrote that the political implications of geoengineering are largely impossible to assess and it is not a viable solution because in most cases, it is an illusion to assume that all possible changes can be foreseen. Climate change is simple. We should do the right thing. Climate is complex. It involves oceans and atmospheres, ice sheets and now monsoons, so studying the human dimension is essential. We need the interdisciplinary, international and intergenerational emphasis.

Thank you for your time.

[The prepared statement of Dr. Fleming follows:]

PREPARED STATEMENT OF JAMES FLEMING

Thank you Mr. Chairman, Ranking Member Hall, and Members of the Committee on Science and Technology for the opportunity to appear before you to provide testimony on Geoengineering: Assessing the Implications of Large-Scale Climate Intervention.

I am a historian of science and technology with graduate training in and life-long connections to the atmospheric sciences, and the founding president of the International Commission on History of Meteorology. I have just written a book on the history of weather and climate control, and I am currently working to connect the history of science and technology with public policy. I have been asked to provide a general historical context for geoengineering as a political challenge and to recommend first steps toward effective international collaboration on geoengineering research and governance.

Introduction

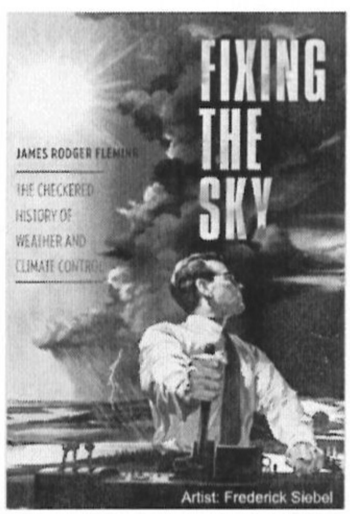
I would like to state my conclusions in advance, which are all based on the premise that history matters:

First, a coordinated *interdisciplinary*—effort is needed to study the historical, ethical, legal, political, and societal aspects of geoengineering and to make policy and governance recommendations. This is one conclusion of the American Meteorological Society's 2009 Policy Statement on Geoengineering.

Second, an *international*—"Working Group 4" on historical, social, and cultural dimensions of climate change in general and geoengineering in particular should be added to the Intergovernmental Panel on Climate Change (IPCC).

Third, a robust *intergenerational*—component of training and participation, especially by young people, should be included in these efforts.

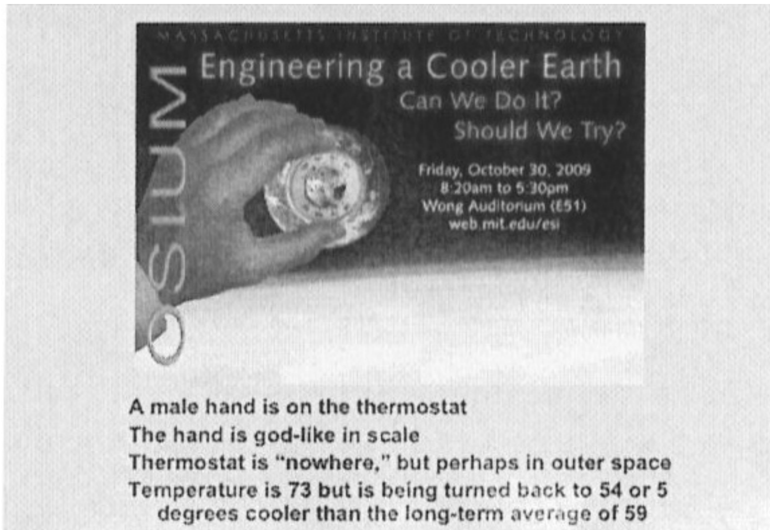
That is to say climate change is not quintessentially a technical issue. It is a socio-cultural and technical hybrid, and our effective response to it must be historically and technically informed, interdisciplinary in nature, *international* in scope, and *intergenerational* in its inclusion of graduate, undergraduate, and younger students.



A year later, in a prominent article titled, "Can We Survive Technology?" the noted Princeton mathematician and pioneer in computerized weather forecasts and climate models John von Neumann referred to climate control through managing solar radiation as a thoroughly "abnormal" industry that could have "rather fantastic effects" on a scale difficult to imagine. He pointed out that altering the climate of specific regions or purposefully triggering a new ice age were not necessarily rational undertakings. Tinkering with the Earth's heat budget or the atmosphere's general circulation "will merge each nation's affairs with those of every other more thoroughly than the threat of a nuclear or any other war may already have done." In his opinion, climate control could lend itself to unprecedented destruction and to forms of warfare as yet unimagined. It could alter the entire globe and shatter the existing political order. He made the Janus-faced nature of weather and climate control clear. The central question was not "What can we do?" but "What should we do?" This was the "maturing crisis of technology" for von Neumann, a crisis made more urgent by the rapid pace of progress.

First of all, a male hand is on the thermometer, the hand is god-like in scale, and the thermostat is "nowhere," but perhaps in outer space. The temperature of 73 F is being turned back to 54, or 5 degrees cooler than the long-term planetary average of 59 F. Looking closely at the center of dial, the thermometer is centered on Roswell, New Mexico, which I take to be symbolic.

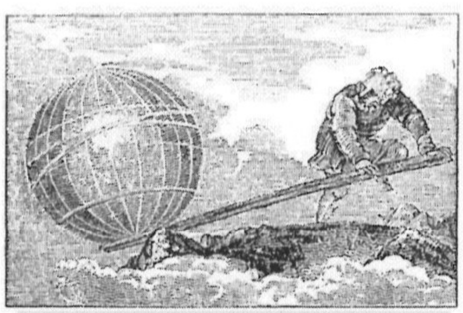
An emergent property of the MIT meeting was that the social science component the voices calling for the study of history, politics, and governance of geoengineering convinced more people than those engaged in geo-scientific speculation of a more technical nature. It is an emerging view in climate studies that humanities and governance perspectives are sorely needed. This was also clear this past summer at "America's Climate Choices" meeting on geoengineering, sponsored by Congressman Mollohan of West Virginia and convened by the National Academies of Science.



The image of Archimedes is sometimes invoked by geoengineers with the assertion that our technological levers are now getting long enough and powerful enough to move the Earth. But if Archimedes is a supposed geoengineer, where is he standing? And where will the Earth roll if tipped? With what consequences? Widespread discussions of "tipping points," have involved the physical climate system or public opinion, but it is important to remember that the geoengineering community has also passed a tipping point, and many of them actually wish to try it! But while some argue we can control the temperature of the globe, ironically, at a recent NASA meeting in 2006 on the topic of "Managing Solar Radiation," a meeting coordinator apologized for not being able to control the temperature of the room.

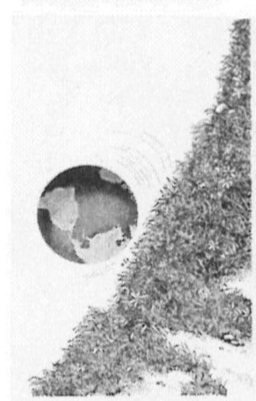
A Geopolitical Perspective on Aerosol Haze

The "Tipping Point"

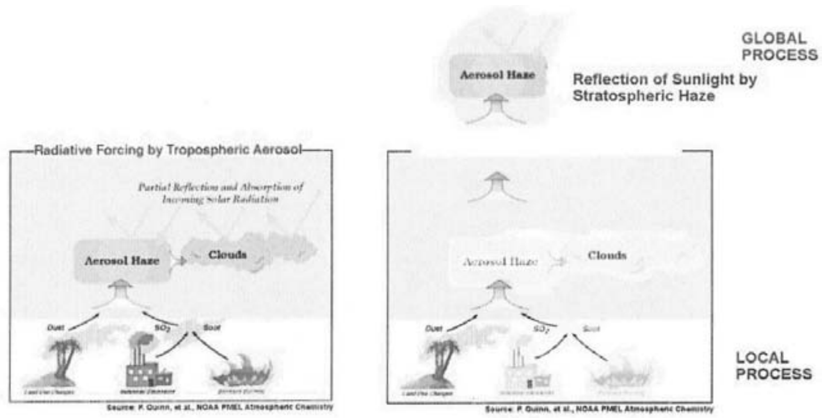


"Give me a place to stand and I will move the earth"—Archimedes. Engraving from Mechanics Magazine, London, 1824.

Where will it roll?



The aerosol haze from dust storms, industrial sulfate emissions, and biomass burning is widely believed have a *local* cooling effect by reflecting sunlight and by making clouds brighter in the troposphere, below about 30,000 feet. As we clean up industrial pollution and reduce biomass burning, the warming effects of greenhouse gases may become more pronounced. Since the early I960s some geoengineers have repeatedly proposed injecting a sulfate aerosol haze into the high, dry, and stable stratosphere, where it would spread worldwide and have *global* cooling effects that might not fully offset greenhouse warming, might have unwanted side effects that might not be welcomed by all nations.



Although the heating effect of the major greenhouse gases is well known, the level of scientific understanding of the cooling effect of aerosols ranges from "low" to "very low." Geoengineers propose to transfer this cooling effect, and the lack of understanding about it, to the stratosphere, where it will become a global rather than a local process, again with likely unwanted side effects that others will address.

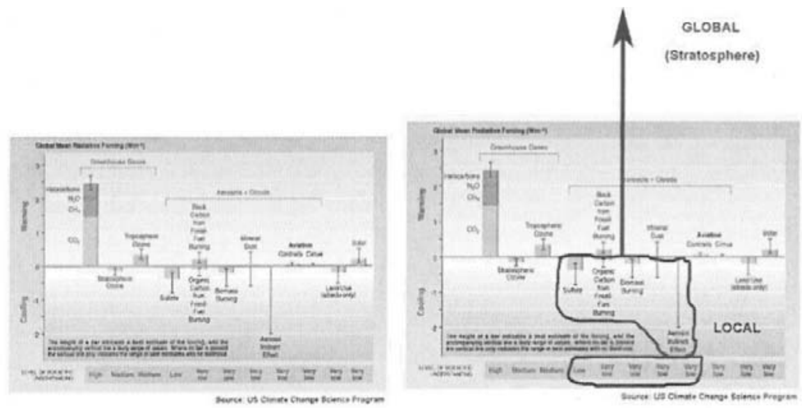
What's Wrong with Climate Engineering? (the short list)

1. We don't have the understanding (Ron Prinn, MIT).
2. We don't have the technology (Brian Toon, Univ. of Colorado).
3. We don't have the political capital, wisdom, or will to govern it.
4. It is not "cheap" since the side effects are unknown.
5. It poses a moral hazard, reducing incentives to mitigate.
6. It could be attempted unilaterally, or worse, proliferate.
7. It could be militarized, and learning from history it likely would be militarized.
8. It could violate a number existing treaties such as ENMOD (1978).
9. It does nothing to solve ocean acidification.
10. It will alter fundamental human relationships to nature.

What Role for History?

We have known this for a long time. Some climate engineers claim they are the "first generation" to propose the deliberate manipulation of the planetary environment. History says otherwise. In the 1790s Thomas Jefferson called for an "index" of the American climate to document its changes being effected by the clearing of the forests and the draining of the marshes. In the 1830s the first serious large scale engineering proposal to emulate "artificial volcanoes" was advanced by James Espy, the distinguished theorist of convection as the cause of rain who was employed by the U.S. Army as the first national meteorologist. Espy proposed lighting huge fires all along the Appalachian Mountains to control and enhance the nation's rainfall, arguing that the heat, updrafts would trigger rain and would not only eliminate droughts, but also heat waves and cold snaps, rendering the air healthy by clearing it of miasmas. A popular writer, Eliza Leslie, immediately pointed out that manufactured weather control would generate more problems than it solved.

In 1946, Nobel Laureate Irving Langmuir believed he and his team at the General Electric Corporation had discovered means of controlling the weather with cloud seeding agents such as dry ice and silver iodide. A year later, in conjunction with the U.S. military, they sought to deflect a hurricane from its path. After seeding, but not because of seeding, the hurricane veered due to what were later determined to be natural steering currents and smashed ashore on Savannah, Georgia. The planned press conference was cancelled, but Langmuir continued to claim he could control hurricanes, influence the nation's weather, and even planned to seed the entire Pacific basin in a mega-scale experiment intended to generate climate-scale effects.

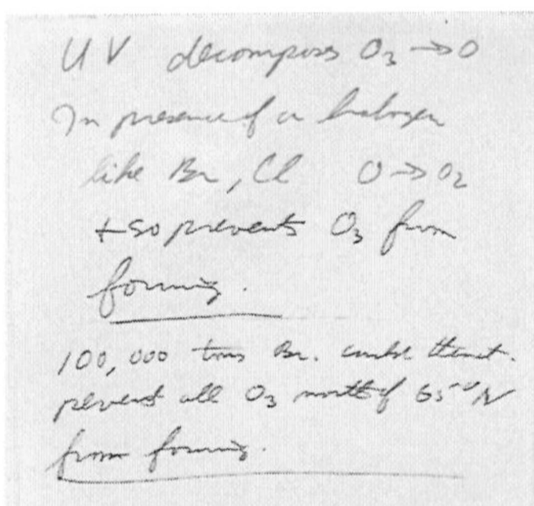


Commercial and military interests inevitably influence what scientists might consider purely technical issues. Agricultural interests drove the nineteenth-century charlatan rainmakers in the American west as well as commercial cloud seeding since the 1940s. In the early Cold War era, as mentioned earlier, the military sought to control clouds and storms as weapons and in the service of an all-weather air force. There was a "weather race" with the Russians and secret cloud seeding in Vietnam. The 1978 United Nations Convention on the Prohibition of Military or any other Hostile Use of Environmental Modification Techniques (ENMOD), a landmark treaty, may have to be revisited soon to avoid or at least try to mitigate possible military or hostile use of climate control.

In 1962 Harry Wexler, Head of Research at the U.S. Weather Bureau, shown here in the Oval Office, used computer models and satellite observations to study techniques to change Earth's heat budget. Wexler helped pen Kennedy's notable line, "We choose to go to the moon in this decade and do the other things . . ." Wexler was in charge of "the other things," such as the World Weather Watch and ways to influence or control weather and climate. It was Wexler, in the era of JFK (not Paul Crutzen in 2006) who first claimed climate control was now "respectable to talk about," even if he considered it quite dangerous and undesirable. Wexler described techniques to warm or cool the planet by two degrees. He also warned, notably, that the stratospheric ozone layer was vulnerable to inadvertent or intentional damage, perhaps by hostile powers, from small amounts of a catalytic agent such as chlorine or bromine.

Wexler in the Oval Office

Here is an important discovery, made just next door in the Library of Congress. It is Harry Wexler's handwritten note of 1962 that reads (substituting words for symbols), "Ultraviolet light decomposes ozone into atomic oxygen. In the presence of a halogen like bromine or chlorine, atomic oxygen becomes molecular oxygen and so prevents ozone from forming. 100,000 tons of bromine could theoretically prevent all ozone north of 65° N from forming." Recently, I have been in correspondence with three notable ozone scientists about Wexler's early work: Nobel Laureates Sherwood Rowland, Paul Crutzen, and current U.S. National Academy of Sciences President Ralph Cicerone. They are uniformly interested and quite amazed by Wexler's insights and accomplishments.



UV decompose $O_3 \rightarrow O$
In presence of a halogen
like Br, Cl $O \rightarrow O_2$
+ so prevents O_3 from
forming.

100,000 tons Br. could theoret.
prevent all O_3 north of 65°N
from forming.

Wexler wrote in 1962, "[Climate control] can best be classified as "interesting hypothetical exercises" until the consequences of tampering with large-scale atmospheric events can be assessed in advance. Most such schemes that have been advanced would require colossal engineering feats and contain the inherent risk of irremediable harm to our planet or side effects counterbalancing the possible short-term benefits." This is still true today.

Today's science is tomorrow's history of science

"In facing unprecedented challenges, it is good to seek historical precedents," this is the epigraph of my new book *Fixing the Sky: The checkered history of weather and climate control.* History matters—it shapes identity and behavior; it is not just a celebratory record of inevitable progress; and its perspective should inform sound public policy. Each of our personal identities is the sum of our integrated past, including personal and collective memories, events, and experiences. It is not just who and where we are now, how we feel today, and what we had for breakfast. Applied to geoengineering, we should base our decision-making not on what we think we can do "now" and in the near future. Rather our knowledge is shaped by what we have *and have not* done in the past. Such are the grounds for making informed decisions. Students of climate dynamics who are passionate about climate change would be well-served to study science dynamics (history), since on decades to centuries and millennial time scales ideas and technologies have changed as dramatically or perhaps more dramatically than the climate system itself.

History can provide scholars in other disciplines with detailed studies of past interventions by rainmakers and climate engineers as well as structural analogues from a broad array of treaties and interventions. Only in such a coordinated fashion, in which researchers and policymakers participate openly, can the best options emerge that promote international cooperation, ensure adequate regulation, and avoid the inevitable adverse consequences of rushing forward to fix the sky.

Climate change is simple, and we all should seek ways of having less impact on the planet though a "middle course" of mitigation and adaptation that is amenable to all, reasonable, practical, equitable, and effective. But the climate system is extraordinarily complex, perhaps the most complex system ever modeled or observed, with the most important consequences imaginable for life and ecosystems. At best we can only apprehend climate change, with three senses of the word apprehension implied: (1) awareness and understanding, (2) anticipation, dread, fear, and (3) intervention and control. Certainly clouds, oceans, ice sheets and other factors make it more complex. But the wildest of the wild cards in the system is the human dimension, so studying that is absolutely essential.

Recommendations

I repeat my recommendations to the committee. We need:

1. A coordinated and autonomous *interdisciplinary* effort to study the historical, ethical, legal, political, and societal aspects of geoengineering and to make

policy and governance recommendations, not as an afterthought and not necessarily within an existing scientific society.

2. An *international* "Working Group 4" on historical, social, and cultural dimensions of climate change in general and geoengineering in particular, perhaps under the auspices of the IPCC.
3. A robust *intergenerational* component of training and participation in such efforts.

In these ways I believe history can effectively inform public policy. Thank you for your attention.

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Fleming, James Rodger. *Fixing the Sky: The checkered history of weather and climate control.* Columbia University Press, 2010.

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BIOGRAPHY FOR JAMES FLEMING

James Rodger Fleming is Professor of Science, Technology, and Society at Colby College. He earned degrees in astronomy (B.S., Penn State), atmospheric science (M.S. Colorado State), and history (M.A. and Ph.D. Princeton) and worked in atmospheric modeling, airborne observational programs, consulting meteorology, and as historian of the American Meteorological Society. Professor Fleming has held major fellowships from the Smithsonian Institution, the National Science Foundation, the National Endowment for the Humanities, and the American Association for the Advancement of Science. He has been a visiting scholar at MIT, Harvard, Penn State, the National Air and Space Museum, the National Academy of Sciences, and the Woodrow Wilson International Center for Scholars.

Awards and honors include election as a Fellow of the AAAS "for pioneering studies on the history of meteorology and climate change and for the advancement of historical work within meteorological societies," participation as an invited contributing author to the Intergovernmental Panel on Climate Change, appointment to the Charles A. Lindbergh Chair in Aerospace History by the Smithsonian Institution, the Roger Revelle Fellowship in Global Stewardship by the AAAS, and a number of named lectureships including the Ritter at Scripps Institution of Oceanography, the Vetelsen at the University of Rhode Island, and the Gordon Manly Lectureship of the Royal Meteorological Society.

He is the author of *Meteorology in America,* 1800–1870 (Johns Hopkins, 1990), Historical Perspectives on Climate Change (Oxford, 1998), *The Callendar Effect* (American Meteorological Society, 2007), and his latest, *Fixing the Sky: The Checkered History of Weather and Climate Control* (Columbia University Press, 2010). Recent co-edited volumes include Intimate Universality (Science History/U.S.A., 2006), Globalizing Polar Science (Palgrave, 2010), and Osiris 26 (forthcoming) on climate. He is currently working to link the local and global in the history of Earth system science and to connect the history of science and technology with public policy.

Professor Fleming was the founder and first president of the International Commission on History of Meteorology and associate editor of the *New Dictionary of Scientific Biography,* He currently serves as editor-in-chief of *History of Meteorology,* domain editor for *Wiley Interdisciplinary Reviews on Climate,* history editor of the Bulletin of the American Meteorological Society, and member of the history committee of the *American Meteorological Society* and the American Geophysical Union.

Jim is a resident of China, Maine (not Mainland China!) with his wife Miyoko. Together they raised two sons. He enjoys fishing, good jazz, good BBQ, seeing students flourish, and building the community of historians of the geosciences. "Nothing is really work unless you would rather be doing something else."

DISCUSSION

Chairman GORDON. Thank you, Dr. Fleming. At this point, we will begin the first round of questions, but first I would like to give a premise. Listening to the panel makes me think that for most people, this is like coming in after the intermission to Mr. Hall's movie about the elephants, and that we might want to give a little bit more of a premise. And I would really advise that anyone that has an interest in this issue to review the Royal Society's report. It is very good.

I was thinking about giving Mr. Hall the two-page summary, but I didn't want to overwhelm him. So Professor Shepherd——

Mr. HALL. You would have had to read it to me.

THE ERUPTION OF MT. PINATUBO: NATURAL SOLAR RADIATION MANAGEMENT

Chairman GORDON. Professor Shepherd, just quickly, would you sort of remind everyone about the volcano in Pinatubo in 1991 and what happened? I think that is a good foundation for everyone to know.

Dr. SHEPHERD. Yes, thank you. The volcano emitted a large amount of sulfur dioxide, amongst other things, some of which made its way to the stratosphere, and the result of this was the formation of a natural sulfate-based aerosol that spread very rapidly around the world and lasted for a couple of years, causing a fall in temperature of approximately 1° degree Fahrenheit for a couple of years.

So this gives us some confidence that aerosols in the stratosphere do have a cooling effect and that the quantities of material required to do this are not unthinkably large. However, volcanoes, of course, emit a lot of other stuff, as well as sulfur dioxide, and so they are not a perfect analogue. And one of the other issues in relation to——

Chairman GORDON. I just wanted you to sort of point out that really nature has already given us somewhat of a model and this is not completely not out of line.

Mr. HALL. I don't really understand it yet.

STRUCTURING A RESEARCH INITIATIVE

Chairman GORDON. I am going to give the panel some questions to take home with you, and I would like your response later. But let us just start a discussion if we could today because if we are looking at a research program, I would like to get a little better idea of what we should do. So let me put out some questions for the panel and get some reaction, and again, I would like for you to take it back and respond to us later.

What would be the critical features of such a program? Would there be just one coordinated program in the United States? Which U.S. agencies would have to be involved from the start and which would need to play a later role? What scale of investment would be necessary, both initially and in the long term, and what kind of expertise would be required? I will later ask about the international implications but I would like to get your thoughts on a research program here in the United States. Who wants to start? Yes, sir. Dr. Fleming?

Dr. FLEMING. I think based on what I said, we would have to have more humanists involved, a lot more social science component, and I know that the National Academy has done things, but it is the National Academy of Science. And so I would like to recommend that we go multi-agency but include not only technical outfits in the discussion.

Chairman GORDON. We will just go down the hall. Professor Shepherd and then Caldeira and then Lane and then Robock?

Professor SHEPHERD. Yes, I would suggest that the program has to be international and that it should not focus exclusively on one technology and specifically that it should not focus exclusively on solar radiation management, because that is a technology which requires you to maintain your activity for as long as the greenhouse gases stay in the atmosphere, which is several centuries to a thousand years. And it is not clear that human society has the ability to sustain an activity on that time scale.

So I think it would be very dangerous to start solar radiation management without having figured out your exit strategy, and your exit strategy would almost certainly include one or other of the carbon dioxide removal methods. So I would suggest that a small portfolio of methods of both of these types should be researched in parallel.

Chairman GORDON. Dr. Caldeira?

Dr. CALDEIRA. I would like to suggest that we should be thinking in terms of several research programs, each multi-agency in character but led by different agencies. If we separate the solar radiation management proposals from the carbon dioxide removal proposals, I think the solar radiation management proposals, the research, should perhaps be led by the National Science Foundation [NSF], possibly the National Aeronautics and Space Administration [NASA].

On the carbon dioxide removal, approaches again could be divided into two major classes. Some are essentially growing plants and burying the organic carbon made by plants. We already have some research programs into growing new forests and similar techniques. And those programs could perhaps be expanded to encompass a broader range of biologically based methods to remove carbon dioxide from the atmosphere.

The Department of Energy is already leading projects to remove carbon dioxide from gases coming out of power plants. Those programs could be expanded to also consider removal of gases from the atmosphere. And so I think there is at least three separate programs, and some of them might involve expansion of existing programs on the carbon dioxide removal side, but there is really no program at all on the solar radiation management side. And I personally would like to see NSF probably lead it, although NASA might make sense as well.

Chairman GORDON. Let us move to Mr. Lane.

Mr. LANE. I would suggest that the solar radiation management—first of all, let me agree with Dr. Shepherd that I think there ought to be research in both families, both air capture and solar radiation management. However, solar radiation management offers much larger economic payoffs potentially and a much greater ability to reverse rapid, highly destructive climate change should that occur. Therefore, I guess I would reverse Dr. Shepherd's judgment of priorities and say that of the two approaches, solar radiation management deserves more attention, and as Dr. Caldeira has suggested, it is not really receiving any support from the U.S. Government at this time. It is clearly the sort of problem that is going to require multiple agency inputs and poses a very difficult organizational challenge for combining science and engineering.

Chairman GORDON. I am going to let everybody respond in writing later, but Dr. Robock, if you would maybe just quickly close us.

Dr. ROBOCK. First of all, I would like to mention that although the Pinatubo volcanic eruption cooled the planet, it also produced drought in Asia and Africa. It destroyed ozone, and it reduced solar radiation generation from direct solar radiation by 30 percent in those technologies that were developing. So it is a lesson of efficacy but also of problems.

I think that research into solar radiation management needs to be done in a coordinated way, internationally, with climate models. The National Science Foundation should probably take the lead in the United States along with the National Oceanic and Atmospheric Administration [NOAA] and NASA. There also needs to be a research program to the technology. Can we actually get particles into the stratosphere, and probably NASA, the—Aeronautics, and the Department of Defense might be looking into the technology of it, whether it is possible.

Chairman GORDON. I thank you. I now yield to Mr. Hall for rebuttal.

Mr. HALL. I always come out second on that one when you are the Chairman. You have got the gavel.

I will be serious with you because I appreciate you and I appreciate your backgrounds and many years of studying and the gifts you have made to this country, and your very appearance here today makes me even more appreciative of you. I especially like Dr. Shepherd, Professor Shepherd, because he at least discussed global warming and he added the term cost to it, and that is what we can't get hardly anybody to talk about, who is going to pay it or how much China is going to continue to pollute the world and not pay a dollar and then increase it on an increasing ratio. So thank you for that. I agree with you on that.

I don't disagree with you on anything you have said, I just don't fully understand it. But he has given me the right to write you, and you will be hearing from me. Thank you.

THE POTENTIAL EFFICACY OF GREENHOUSE GAS MITIGATION

Mr. Lane, you said you advocate research and not deployment, I guess that is what I am trying to say. Would you expand on your comment and your testimony that a steep decline in greenhouse gas emissions may well cost more than the perceived value of the benefits? And let me say before that, we had a study, I chaired one of the committees one time when we were studying and we studied about asteroids. A professor told us about volcanoes, but we were studying asteroids and the danger and trying to get an international thrust on them. We got no help on that because we had I think about $1.5 million budget on that, and that was a couple of brilliant people and their workers, co-workers with them. But we learned during that hearing something that none of the group knew, including the chairman, and that was me, that an asteroid just missed the earth by five minutes some time in 1987 or 1988. So I think this is worthwhile. And I was just spoofing the Chairman. He is so good-natured. He is the only Chairman I can kid like that.

But go ahead now and answer me, if you would, Mr. Lane.

Mr. LANE. Yes, sir. It seems that the last 20 years have shown not only that it is difficult to get agreement on greenhouse gas controls, but that that is happening for very clear reasons. China and India both have very rapidly growing emissions, and yet it is clear from the way their governments are dealing with the negotiations that they do not perceive greenhouse gas emissions reductions, at least not steep ones, as being in their national interest. And both of those countries are too powerful to coerce, and the cost of bribing them to reduce emissions when they don't feel that it is in their national interests are likely to be prohibitively high. I don't want to give the impression that I believe that we can go on emitting greenhouse gases at ever-increasing rates. I don't. I think eventually controls are going to be essential, but I really strongly believe that the conditions are not in place yet for a global agreement on significantly reducing emissions. And until those conditions are in place, there really isn't very much that the United States can do to change the global trajectory of emissions.

RESEARCH AND DEVELOPMENT BEFORE APPLICATION

Mr. HALL. Well, I thank you for that, and also I guess I would ask you, your testimony seemed to suggest at the time that there is R&D and not implementation. Are there entities, organizations or countries that see an urgent need for implementation versus the process of R&D? I know most of the really rabid advocates of global warming mention everything but the cost and mention everything but the fact that China I think every six days are spewing—not using clean coal. And I think we will fall back on coal one day, we are going to have to. But it has to be clean coal. But they are increasing again I say on an increasing ratio the damage to the earth without paying anything. That goes for them, that goes for Russia, it goes for India, it goes for Mexico, and it could go on and on of those that want the benefits of the work that you probably all believe in but don't want to participate in the cost. One or the others of you made mention of that. I will let you have whatever—I think I have may be two seconds left, but if you can do your best to give me——

Mr. LANE. I do support R&D rather than deployment. Dr. Robock is absolutely right. We don't have the technology yet to do deployment, nor would it be prudent. For me personally, if I were going to put my bet on where to do R&D in the U.S. Government, along with NSF, as that Dr. Caldeira mentioned, I would suggest that DARPA [Defense Advanced Research Projects Agency] might have a role.

Mr. HALL. Thank you.

Chairman GORDON. Thank you, Mr. Hall. I think we can submit unanimously that this panel would say that there should be no deployment, only research. I don't think you are going to find anybody that is going to disagree with that.

Dr. Baird is recognized.

THE DIRE NEED FOR MITIGATION AND BEHAVIOR CHANGE

Mr. BAIRD. Thank you, Mr. Chairman. I thank our panelists. Roughly, how much CO_2 do human beings put into the air, anthropogenic CO_2 on a daily basis? Anyone have an estimate of that or annual, whatever number? Dr. Caldeira?

Dr. CALDEIRA. The average American puts out something like their own average body weight each day in the form of carbon dioxide. So something like 150 pounds of CO_2 per person per day in the United States.

Mr. BAIRD. Times 300 million people?

Dr. CALDEIRA. Right, times 365 days a year.

Mr. BAIRD. Mr. Robock, did you want to add to that? The reason I ask the question is, we are doing geoengineering on a massive scale. If 100 years ago somebody had said, hey, here is a bright idea. We should promote a plan to put that much carbon into the air—And Dr. Caldeira, I commend you for mentioning ocean acidification—25 percent of which will go into the oceans to make the oceans 30 percent more acidic within 50 years, and then continuing on after that to make it so acidic that it reaches levels since not seen since the age of the dinosaurs and dissolve coral reefs. Shouldn't Congress support that? People would say, you are crazy. Geoengineering on that scale, which is what we are doing, and now we are looking at ways to reverse that.

Second observation would be, you know, years ago there was a psychologist named Elizabeth Kübler-Ross who looked at what happens when people are dying, and not everybody goes through her five stages of dying, which got a lot of play at the time. Nevertheless, her stages of dying went, you know, denial and then bargaining, and the bargaining tends to be, isn't there going to be someone to come rescue me from this cancer or this other illness that I have got?

It strikes me that we are in sort of in those stages now, and the reason I raise that, in the context of geoengineering. We have had a whole series of hearings in my subcommittee and this full committee on carbon sequestration, on nuclear fusion, on geoengineering, and it seems to be everybody is trying to say, isn't there someway out there that we don't have to make changes in our behavior, that we can continue to spew just as much CO_2 or use just as much energy and something somewhere is going to save us from just having to make this horrific changes like turning down our thermostat, putting air in our tires, et cetera? And so I applaud you all for suggesting that we are not going to have this—to rescue us by, you know, chemtrails or whatever people want to distribute into the air.

There are some positive things that we could do. What would be the impact of simple things like changing the color of roof shingles or painting the rooftops? My rooftop here in town is black. It is a black rubber surface. It gets hot as blazes up there. I am told we can make substantial differences in temperature and energy consumption, not on the scale that we need. It is not enough. But the point is, piece together the small stuff that doesn't require massive interventions. What are some of the things we could do?

Dr. ROBOCK. Actually, if we put solar panels on our roofs, that would be a much better way to respond because we would produce electricity from the sun and that would reduce the amount of CO_2 emissions from other sources, and that would be much better than just painting the roofs white. It would cost a little bit more money to start with, but in the long run, it would be the best investment and it would be a business opportunity. Why doesn't every new house have solar panels built into the shingles rather than retrofitting it like I did on my house, thanks to the subsidies from the State of New Jersey?

And there are lots of little things we can do, and they will all add up to a mitigation plan.

Mr. BAIRD. We focused mostly today so far on atmosphere and solar radiation management. What about in water? I mean, we are also geoengineering our water system. We are putting hundreds of billions of pounds of effluent and fertilizers, et cetera, in the water. What are some positive changes that we can do to agricultural practices, runoff practices, et cetera, that could help improve the quality of our water, not, you know, dumping clay as a flocculent of algal blooms but some positive things to reduce them from occurring to begin with. Do any of you have comments on that? Are we mostly atmospheric today? You get the point I am trying to make here, that we are causing the problem through our own behavior and then we are somehow going to try to fix the earth instead of fixing ourselves. If you had to summarize that, which would you say is easier, change our behavior or change the planet? Dr. Shepherd?

Dr. SHEPHERD. Well, you are making it into a black-and-white choice, and my answer would be both. The problem is there is an awful lot that we could do in Europe, in the United States and in China and everywhere to reduce the impacts that we are having, but however hard we try, that may not be enough. So I think it is a mistake to make it black and white and say it is either/or. I think we need to do both, and that may at some stage involve geoengineering.

Mr. BAIRD. My time is expired. Thank you.

Chairman GORDON. Thank you, Dr. Baird. Dr. Barlett. Excuse me, Dr. Ehlers is recognized.

Mr. EHLERS. Thank you, Mr. Chairman. I appreciate the interesting interaction you just had. I am not quite sure what Mr. Baird meant when he talked about fixing people. I know a lot of people fix their dogs and cats, but on the other hand that might be part of a good solution.

Mr. HALL. Professor, do you remember the name of that woman that wrote that book?

THE NEED FOR A MULTIDISCIPLINARY AND REALISTIC APPROACH TO CLIMATE CHANGE

Mr. EHLERS. Anyway, hearing this discussion I am very much reminded of Garrett Hardin who was a great environmentalist, and he had a statement which I framed and hung on my wall for a while. You can't do just one thing. And that is the heart of the issue we are facing here today. I think we have a lot of good ideas, a lot of things we might want to try, but you can't do just one thing. And almost everything you do has side-effects, some may be good, some may be bad. Frequently you don't know until you have tried it. And that is what is going to be the major impediment here as we proceed.

There is also a public attitude problem that—well, the best example that I can give you, in the 1973 gas shortages, when we had the big long gas lines, and you know, as a physicist I was very interested in people's attitude toward energy, and I thought we could do a much better job of conserving energy. The response of most people even talking to me would say, well, we really don't have to worry about this. The scientists will come up with a solution. This intrinsic faith that science can solve mammoth problems like that is not—it is nice they think that much of me, but I don't think it is realistic. I think we have to face these problems in all of their dimensions.

And the point was made about China and India and what their attitude is going to be. As long as we continue with the current economic behavior of this Nation, we have no leverage in which to try to solve the environmental problems. How can we threaten the Chinese? If you don't do this for us, we are going to stop borrowing money from you. That is not an awful lot of leverage.

So I think you have to keep all these factors in mind. I am not in the least bit skeptical about geoengineering. I think that is something we really have to investigate. I am skeptical about saying this is the answer to a major problem until we get some data, do some experiments, find out what works and what doesn't work, and above all, continue to recognize you can't do just one thing.

I remember very clearly—I am showing my age by this—but in the era when everyone believed we could shoot silver iodide up into the atmosphere and make rain wherever we had a drought spot. And we seriously pursued this in some areas of our Nation and found that it just didn't work well because we had a lot of side-effects we didn't anticipate.

So this was a bit more of a sermon than a question, and you are welcome, any of you who wish to, can feel free to comment on this and how you think our Nation and other nations can address this problem in a thoughtful, reasonable, meaningful way to try to come up with some solutions of geoengineering that would work. Any comments? Yes. Dr. Caldeira.

Dr. CALDEIRA. I think you are correct in that we can't do just one thing, and that I think everybody on the panel here believes that we need to eventually get to an energy system that does not use the atmosphere as a waste dump for our industrial products, but that there is a potential for some of these methods to reduce the risks that we are facing and reduce these risks cost-effectively. And while the panel disagrees about maybe the scale and scope of what a research program should be, I think it is indicative that the entire panel asserts the need for a research program.

I would just also like to take this opportunity to support something Alan Robock said before when I was talking about the structure of research, that on the solar radiation management side, there is an environmental science component that might be NSF but there is another component about developing and engineering hardware that might better fit in the agencies that Alan mentioned. Thank you.

Mr. EHLERS. Dr. Robock?

Dr. ROBOCK. I would just like to say that we can't hold geoengineering as a solution and allow that to reduce our push toward mitigation. It is never going to be a complete solution. We may need it in the event of an emergency, but let us not stop mitigation and wait and see if geoengineering would work. That is not the right strategy.

Mr. EHLERS. Along that line, I think it would be very important for us to continue very strongly the approach of reducing our use of fossil fuels. For example, I have advocated for years that we try to move to solar shingles, that every house has to be built with solar shingles.

Dr. ROBOCK. We don't really need all these lights on in here, either.

Mr. EHLERS. No, we don't.

Chairman GORDON. Well, the cameras wouldn't work as well. Dr. Ehlers, if you don't—I am going to be a little more strict because we are going to votes, unfortunately, in a few minutes.

Mr. EHLERS. It is so amazing how the clock runs so much faster when it is my time.

Chairman GORDON. Well, it is also moving up, not down.

Mr. EHLERS. Thank you.

Chairman GORDON. Dr. Griffith, you are recognized for five minutes.

THE CHALLENGE OF INTERNATIONAL COLLABORATION

Mr. GRIFFITH. Thank you, Mr. Chairman. I appreciate this opportunity, and I do think the initial discussions of this subject are important, even though we may not reach a conclusion. We do know we have a wide diversity here, with the life expectancy of a male in China of 73 and the life expectancy of the male in India of 63, which points out a great disparity in what the needs of the various countries are. And it makes it greatly difficult for a country like the United States that represents only five percent of the world's population to come to a conclusion or reach an agreement on how we should approach or sell ourselves to the rest of the world. I guess if we included Germany, France and England in that population group, and Denmark, we may get up to six or seven percent of the world's population.

So it is a good subject, and it is certainly necessary. I appreciate each and every one of you being here, and I appreciate the Chairman bringing the subject up. I think this is a start, so thank you.

Chairman GORDON. Thank you, Dr. Griffith. Dr. Bartlett is not here right now. We will recognize him when he gets here, so Mr. Smith, you are up to bat.

AGRICULTURE AND LIVESTOCK

Mr. SMITH OF NEBRASKA. Thank you, Mr. Chairman. I will try to be brief. This is my third year here, and it is interesting being on the Science Committee and trying to sift through the science and, you know, whether something is peer reviewed, whether it is not, and rejection of recommendations that are science is peer reviewed. It has been for this Nebraskan interesting and how we might contribute and especially as it relates to industry in my district. And if any of you could speak to the impact, your perceived impact, of livestock industry, I have heard various accusations, and if any of you would care to comment on that.

Dr. CALDEIRA. I am not expert on the livestock industry, but I do know that one of the concerns with respect to livestock and global warming are methane emissions from livestock. And I know that people are working on various ways of removing methane from gases that might be in barns or pens where livestock are held, and it might be potential for the kind of research to remove greenhouse gases from the atmosphere in general also to be applied to facilities such as livestock pens or barns.

Mr. SMITH OF NEBRASKA. Thank you. Anyone else?

Dr. FLEMING. Yes, I am involved with the University of Kansas in a group that is doing this interdisciplinary graduate education, and certainly as one of your neighbors, the group there is getting technical training in agricultural sciences as well as in techniques to mitigate or perhaps reduce some of this. But the group is also looking at behavioral issues and choices and ways of working together with the industries to advance their purposes as well as other goals.

And so the point I was making is that I think the education we have often is in content and technique of science or techniques of engineering, but that social dimension is very important. And so in looking at issues like global warming, making personal commitments and personal decisions I think is a very significant aspect of this program. It is not a solution to the beef issue, but if smoking is bad for you or beef is bad for the planet, people have to make some decisions or alignments.

Mr. SMITH OF NEBRASKA. Are you suggesting that beef is bad for the planet?

Dr. FLEMING. No, but others have. It has been in the news recently.

Mr. SMITH OF NEBRASKA. Well, I did read the comments of a writer one time who said that eating a T-bone steak is more egregious to the environment than driving a Hummer per se. I was astounded, you know. I am not sure the nutritional values were considered, you know, in the bigger picture, but certainly there are some concerns, especially in the midst of this economy, that in the so-called mitigating efforts, whether it is cap and trade, which is called a lot of other things, or whatever approach we might take, I hope that we remember that we need to look at the big picture economically, that there are some important factors here. Dr. Caldeira?

Dr. CALDEIRA. We do not know how well these methods will work, these solar radiation methods will work at affecting regional climates, but there is at least some possibility that as a result of climate change, weather conditions will change in America's heartland and that this will impact on the production of grain. And you know, I would be misleading you if I said oh, I thought we could reverse this, but I think there is at least the potential that a research program with a relatively small investment could understand, you know, if the American heartland does turn into a dustbowl, is there a potential to change weather patterns to allow us to engage in agriculture once again? And so even if there is a small probability that this will occur, the investment is small and so the expected benefit of this investment is very high.

Mr. SMITH OF NEBRASKA. In my part of the country that I represent we had an extended drought, and now we have certainly a wet October. Is that wet October a result of climate change and carbon emissions?

Dr. ROBOCK. There is a lot of weather variability that, because of the chaotic nature of the weather, you can't attribute any drought or any flooding event to global warming. The probability of different weather events changes over time, but certainly that is just part of normal weather variability.

But cows do put a burden on the climate system. There are the methane emissions and there is all the energy used in the production of beef, and so that is—one of the mitigation strategies is for people to eat less beef. And maybe there could be a way for your constituents to gradually transition to other things that they could do that would create less greenhouse gases.

Chairman GORDON. I am sure that is the answer you wanted to hear, Mr. Smith.

Mr. SMITH OF NEBRASKA. If only my time had not expired. Thank you, Mr. Chairman.

Chairman GORDON. Ms. Kosmas is recognized.

THE POWER OF SCIENTIFIC INNOVATION

Ms. KOSMAS. Thank you, Mr. Chairman. I appreciate the opportunity to listen to these gentleman before us today and to suggest to all of you here—I am from Florida, and Kennedy Space Center is in my district, and so I am really big on solar and sun as well as NASA and space exploration. So my remarks will be focused for the most part on the solar radiation management, my remarks and questions. But I want to suggest to my friend, Mr. Hall, that while you might think this is science fiction, I was talking with my daughter yesterday who was telling me my son, who is in China, was saying that they had a massive snowstorm induced by the state of China or the nation of China. So do you not believe that that happened?

Dr. ROBOCK. I believe that the snowstorm happened, but I don't think you can prove that they caused it.

Ms. KOSMAS. Okay. All right. Well, maybe it is science fiction. I don't know. But it is interesting, and I suspect if they could, they would. And so I think all the comments mentioned today about the necessity for research and development and international cooperation in so doing are valid and worth great consideration, that it is not impossible and maybe not even improbable that someone, somewhere will ultimately take advantage of the scientific opportunity. I would like to see us move forward with research and development, and I appreciate the comment of Dr. Shepherd that, you know, be careful what you ask for because you are going to have to wind it down eventually. And as you suggested with the volcanoes, you need to know where you are going next.

Nevertheless, I think in this Nation we have both the brains and the capability to move forward on new frontiers as this is, mitigation, obviously, combined with new opportunities for better ways to produce energy and also to protect the environment. They kind of seem like they go without saying.

In fact, one of the reasons that I ran for office is exactly that. I think we needed to be moving in a different direction in this country with regard to protection of the environment and conservation of energy and new energy methodology. So I am pleased to be here and pleased to be on this Committee.

Geoengineering and Climate Simulations

I wanted to just discuss for a moment with Dr. Caldeira, you discussed in your comments the simulations and small-scale field experiments of solar radiation management. Can you discuss what the simulations and the experiments entailed? Let us start with that.

Dr. CALDEIRA. Today there have been a number of modeling groups using climate models to simulate the effects of deflecting more sunlight away from the earth, and I believe that all of the simulations that used some reasonable amount of sunlight deflection found that sunlight deflection was able to reduce most of the climate change in most places most of the time. But as Alan Robock points out, after Mount Pinatubo, the Amazon and the Ganges River delta had some of the lowest river flow on record. And so there are negative consequences we need to be aware of and to study more deeply.

In terms of experiments, so far no experiments have gone on in the field, but we could think of process-based experiments. You know, if you did put some material into the stratosphere, what kind of chemical reactions would occur? Would the particles stick together? So there are a lot of small-scale field studies that could be done short of something that affects climate. And we need to think carefully about how to go about conducting these experiments.

A Potential Role for NASA

Ms. KOSMAS. Okay. I know that it has been suggested that the National Science Foundation and DARPA, maybe, would be agencies. Could you tell me something about your feeling about NASA being involved perhaps in these projects? Yes, sir. I am sorry.

Dr. ROBOCK. We use a NASA climate model with NASA computers to do our simulations, and certainly NASA should be heavily involved in the climate research. And also, NASA puts up satellites, and we need a capability being able to measure particles in the stratosphere. There used to be the SAGE satellite, stratospheric aerosol and gas experiment, but they no longer exist. There is a spare sitting on a shelf in Hampton, Virginia.

Ms. KOSMAS. We could bring it down to the Kennedy Space Center, and I guarantee you we could get it out there.

Dr. ROBOCK. That is right. And so NASA really needs to be involved in an enhanced earth-observing program that can really help us. I was here in Washington earlier this year at the National

Academy of Sciences in a panel, are we ready for the next volcanic eruption? And the answer was no. And Jim Hansen was sitting next to me. He said, no, we need a better capability of being able to observe the stratosphere for a volcanic eruption and for any geoengineering experiments. And NASA could be heavily involved in that.

Chairman GORDON. Thank you, Ms. Kosmas. I think you are going to get some business down there.

Ms. KOSMAS. Good. Thank you.

Chairman GORDON. Mr. Rohrabacher, Mr. Hall has been anxious by awaiting your five minutes.

Mr. ROHRABACHER. Thank you very much, Mr. Chairman, and no hearing like this would be fulfilled without my adding a list at this point of 100 top scientists from around the world who are very skeptical of the very fact that global warming exists at all, but I would like to submit that for the record at this time.

[The information follows:]

Submission from Rep. Rohrabacher

List of more than 100 Scientists Who Agree That:

- The case for alarm regarding climate change is grossly overstated;
- Surface temperature changes over the past century have been episodic and modest;
- There has been no net global warming for over a decade;
- The computer models forecasting rapid temperature change abjectly fail to explain recent climate behavior; and
- Characterization of the scientific facts regarding climate change and the degree of certainty informing the scientific debate is simply incorrect.

1. Syun Akusofu, Ph.D
   University of Alaska
2. Arthur G. Anderson, Ph.D
   Director of Research, IBM (Retired)
3. Charles R. Anderson, Ph.D
   Anderson Materials Evaluation
4. J. Scott Armstrong, Ph.D
   University of Pennsylvania
5. Robert Ashworth
   Clearstack LLC
6. Ismail Baht, Ph.D
   University of Kashmir
7. Colin Barton
   CSIRO (Retired)
8. David J. Bellamy, OBE
   The British Natural Association
9. John Blaylock
   Los Alamos National Laboratory (Retired)
10. Edward F. Blick, Ph.D
    University of Oklahoma (Emeritus)
11. Sonja Boehmer-Christiansen, Ph.D
    University of Hull
12. Bob Breck
    AMS Broadcaster of the Year 2008
13. John Brignell
    University of Southampton (Emeritus)
14. Mark Campbell, Ph.D
    U.S. Naval Academy
15. Robert M. Carter, Ph.D
    James Cook University
16. Ian Clark, Ph.D
    Professor, Earth Sciences, University of Ottawa, Ottawa, Canada
17. Roger Cohen, Ph.D
    Fellow, American Physical Society
18. Paul Copper, Ph.D
    Laurentian University (Emeritus)
19. Richard S. Courtney, Ph.D
    Reviewer, Intergovernmental Panel on Climate Change
20. Uberto Crescenti, Ph.D
    Past-President, Italian Geological Society
21. Susan Crockford, Ph.D
    University of Victoria
22. Joseph S. D'aleo
    Fellow, American Meteorological Society

23. James Demeo, Ph.D
University of Kansas (Retired)

24. David Deming, Ph.D
University of Oklahoma

25. Diane Douglas, Ph.D
Paleoclimatologist

26. David Douglass, Ph.D
University of Rochester

27. Christopher Essex, Ph.D
University of Western Ontario

28. John Ferguson, Ph.D
University of Newcastle Upon Tyne
(Retired)

29. Michael Fox, Ph.D
American Nuclear Society

30. Gordon Fulks, Ph.D
Gordon Fulks and Associates

31. Lee Gerhard, Ph.D
State Geologist, Kansas (Retired)

32. Gerhard Gerlich, Ph.D
Technische Universitat
Braunschweig

33. Ivar Giaever, Ph.D
Nobel Laureate, Physics

34. Albrecht Glatzle, Ph.D
Scientific Director, INTTAS
(Paraguay)

35. Wayne Goodfellow, Ph.D
University of Ottawa

36. James Goodridge
California State Climatologist
(Retired)

37. Laurence Gould, Ph.D
University of Hartford

38. Vincent Gray, Ph.D
New Zealand Climate Coalition

39. William M. Gray, Ph.D
Colorado State University

40. Kenneth E. Green, D.Env.
American Enterprise Institute

41. Kesten Green, Ph.D
Monash University

42. Will Happer, Ph.D
Princeton University

43. Howard C. Hayden, Ph.D
University of Connecticut (Emeritus)

44. Ben Herman, Ph.D
University of Arizona (Emeritus)

45. Martin Hertzberg, Ph.D.
U.S. Navy (Retired)

46. Doug Hoffman, Ph.D
Author, The Resilient Earth

47. Bernd Huettner, Ph.D

48. Ole Humlum, Ph.D
University of Oslo

49. Neil Hutton
Past President, Canadian Society of
Petroleum Geologists

50. Craig D. Idso, Ph.D
Center for The Study of Carbon
Dioxide and Global Change

51. Sherwood B. Idso, Ph.D
U.S. Department of Agriculture
(Retired)

52. Kiminori Itoh, Ph.D
Yokohama National University

53. Steve Japar, Ph.D
Reviewer, Intergovernmental Panel on Climate Change

54. Sten Kaijser, Ph.D
Uppsala University (Emeritus)

55. Wibjorn Karlen, Ph.D
University of Stockholm (Emeritus)

56. Joel Kauffman, Ph.D
University of the Sciences, Philadelphia (Emeritus)

57. David Kear, Ph.D
Former Director-General, NZ Dept. Scientific and Industrial Research

58. Richard Keen, Ph.D
University of Colorado

59. Dr. Kelvin Kemm, Ph.D
Lifetime Achievers Award, National Science and Technology Forum, South Africa

60. Madhav Khandekar, Ph.D
Former Editor, Climate Research

61. Robert S. Knox, Ph.D
University of Rochester (Emeritus)

62. James P. Koermer, Ph.D
Plymouth State University

63. Gerhard Kramm, Ph.D
University of Alaska Fairbanks

64. Wayne Kraus, Ph.D
Kraus Consulting

65. Olav M. Kvalheim, Ph.D
Univ. of Bergen

66. Roar Larson, Ph.D
Norwegian University of Science and Technology

67. James F. Lea, Ph.D

68. Douglas Leahy, Ph.D
Meteorologist

69. Peter R. Leavitt
Certified Consulting Meteorologist

70. David R. Legates, Ph.D
University of Delaware

71. Richard S. Lindzen, Ph.D
Massachusetts Institute of Technology

72. Harry F. Lins, Ph.D.
Co-Chair, IPCC Hydrology and Water Resources Working Group

73. Anthony R. Lupo, Ph.D
University of Missouri

74. Howard Maccabee, Ph.D, MD
Clinical Faculty, Stanford Medical School

75. Horst Malberg, Ph.D
Free University of Berlin

76. Bjorn Malmgren, Ph.D
Goteburg University (Emeritus)

77. Jennifer Marohasy, Ph.D
Australian Environment Foundation

78. Ross Mckitrick, Ph.D
University of Guelph

79. Patrick J.Michaels, Ph.D
University of Virginia

80. Timmothy R. Minnich, MS
Minnich and Scotto, Inc.

81. Asmunn Moene, Ph.D
Former Head, Forecasting Center, Meteorological Institute, Norway

82. Michael Monce, Ph.D
Connecticut College

83. Dick Morgan, Ph.D
Exeter University (Emeritus)

84. Nils-Axel Mörner, Ph.D
Stockholm University (Emeritus)

85. David Nowell, D.I.C.
Former Chairman, NATO
Meteorology Canada

86. Cliff Ollier, D.Sc.
University of Western Australia

87. Garth W. Paltridge, Ph.D
University of Tasmania

88. Alfred Peckarek, Ph.D
St. Cloud State University

89. Dr. Robert A. Perkins, P.E.
University of Alaska

90. Ian Pilmer, Ph.D
University of Melbourne (Emeritus)

91. Brian R. Pratt, Ph.D
University of Saskatchewan

92. John Reinhard, Ph.D
Ore Pharmaceuticals

93. Peter Ridd, Ph.D
James Cook University

94. Curt Rose, Ph.D
Bishop's University (Emeritus)

95. Peter Salonius M.Sc.
Canadian Forest Service

96. Gary Sharp, Ph.D
Center for Climate/Ocean
Resources Study

97. Thomas P. Sheahan, Ph.D
Western Technologies, Inc.

98. Alan Simmons
Author, The Resilient Earth

99. Roy N. Spencer, Ph.D
University of Alabama—Huntsville

100. Arlin Super, Ph.D
Retired Research Meteorologist,
U.S. Dept. of Reclamation

101. Eduardo P. Tonni, Ph.D
Museo De La Plata (Argentina)

102. Ralf D. Tscheuschner, Ph.D

103. Dr. Anton Uriarte, Ph.D
Universidad Del Paisvasco

104. Brian Valentine, Ph.D
U.S. Department of Energy

105. Gosta Walin, Ph.D
University of Gothenburg
(Emeritus)

106. Gerd-Rainerweber, Ph.D
Reviewer, Intergovernmental Panel
on Climate Change

107. Forese-Carlowezel, Ph.D
Urbino University

108. Edward T.Wimberley, Ph.D
Florida Gulf Coast University

109. Miklos Zagoni, Ph.D
Reviewer, Intergovernmental Panel
on Climate Change

110. Antonio Zichichi, Ph.D
President, World Federation of
Scientists

Skepticism of Global Climate Change

Mr. Rohrabacher. There you go. Let me just note that there is ample reason for us to question whether or not things that are being suggested today are really needed because there is reason to question whether there is global warming, considering the fact that it has gotten—it is not gotten warmer for the last nine years, and the Arctic polar cap is now refreezing for the last two years.

But that argument isn't what today's hearing is about, so I will just make sure that that is on the record and in people's minds when looking at some of these suggestions.

Let me ask about some of the specific suggestions. I understand at 9/11 when they grounded all the airplanes that it actually increased the temperature of the planet, is that right? And thus——

Dr. ROBOCK. Excuse me, that is not correct.

Mr. ROHRABACHER. It is not correct?

Dr. ROBOCK. There was one study that showed that without clouds from contrails that the diurnal cycle of temperature went up, the daily temperature went up, the nighttime temperature went down, but later disproven. It was shown that was just part of natural weather variabilities. So that wasn't a very——

Mr. ROHRABACHER. Let me note that every time it doesn't fit into the global warming theory, it becomes natural variability but when it does fit in, it becomes proof that there is global warming.

Let me ask you this. That really wasn't then? Does anyone else have another opinion of vapor trails, by the way? So we have learned today that we really just have—and am I misreading you by suggesting that you, too, are part of the group that believes in global warming that would like to restrict air travel or try to find ways of eliminating frequent flyer miles? We know you don't want us to eat steak now. Are we also not going to be able to fly on airplanes?

Dr. ROBOCK. Airplanes are one of the sources of emissions. If they use biodiesel and it recycles the fuel, then it wouldn't be part of the problem. But indeed, if we—we can do some emissions of CO_2. We don't have to—these mobile transportation sources are very hard to retrofit on airplanes. With cars, you can, of course, generate electricity with wind and solar, but airplanes, we still have to keep flying and we can live with a little bit of CO_2 emission if we deal with other sources.

Mr. ROHRABACHER. Again, let me note that—by the way, you are a scientist here. What is the percentage of the atmosphere that is CO_2? What percentage of the atmosphere?

Dr. ROBOCK. It is .039 percent.

Mr. ROHRABACHER. Okay. And most people, when I ask that question, Mr. Chairman, out in the hinterland, people believe it is 25 percent, and instead of this miniscule, that is .03, that is 3 percent of 1 percent of the atmosphere. And there are those who have realized—in the past there have been many times when that CO_2 content was enormously greater, wasn't that right? And during that time period there were lots of animals, like dinosaurs and lots of things growing, and the world seemed to be doing pretty good.

Dr. CALDEIRA. CO_2 concentrations were high in the past, and the biosphere flourished. And even if we disagree about what the threats are from climate change, and I think we do, that, you know, I don't think my house is going to burn down, but I buy fire insurance. And——

Mr. ROHRABACHER. But you don't tell your neighbor that he can't have steak or visit his kids in an airliner, and that is the point.

Dr. CALDEIRA. I don't——

Mr. ROHRABACHER. There are going to be changes. People have to understand, there are going to be huge changes in our lifestyle——

Dr. CALDEIRA. I don't——

Mr. ROHRABACHER.—if this nonsense is accepted.

Dr. CALDEIRA. I don't believe we are going to solve this problem by asking people to behave differently.

Mr. ROHRABACHER. Okay.

Dr. CALDEIRA. I think we are going to solve it by improving the systems that surround us. But to get back to my point, even if we don't believe that climate change will damage us, we have to say there is some risk. So then we have to say, well, how much should we invest to try to mitigate that risk.

Mr. ROHRABACHER. We are broke right now, and the bottom line is that we have very little to invest in theories that may or may not be correct, and we also have a lot of indication, just the fact that you are using the word climate change is a difference than what was used 10 years ago which was global warming. And most of us realize that is because people now are trying to hedge their bets so they can have these controls, whatever way the temperature goes.

Dr. CALDEIRA. No, I don't think that is true. You know——

Chairman GORDON. Time.

Mr. ROHRABACHER. Thank you very much.

Chairman GORDON. Speaking of dinosaurs, the time for Mr. Rohrabacher has run out, and we will need to proceed to——

Mr. ROHRABACHER. Thank you, Mr. Chairman.

Chairman GORDON. Mrs. Dahlkemper.

PRIORITIZING GEOENGINEERING STRATEGIES

Mrs. DAHLKEMPER. Thank you very much, Mr. Chairman, and I want to thank our witnesses for coming today. This is a fascinating hearing, and I look forward to more hearings on this as we delve into this subject further.

I have a question for the panel and anyone who would like to address it. Do you believe that any particular geoengineering options should be removed from consideration completely? If so, why?

Dr. CALDEIRA. You know, I think we have to think in terms of a portfolio and that there are some things that are clearly more promising. There are some things that can be scaled up on the solar radiation management side. There are things that could be scaled up and deployed rapidly, and I think those two are really particles in the stratosphere and perhaps whitening clouds over the ocean.

On the carbon dioxide removal side, there are a bunch of land-based options to increase the storage from carbon from photosynthesis that need to be explored, and also industrialized capture of CO_2 from the air, and also spreading minerals around on the earth. My own view is that other options such as ocean fertilization, for example, are not going to play a significant role in solving the problem. That is not to say I would put zero money into them. I would just put them way down in the list of my portfolio of investments.

Mrs. DAHLKEMPER. Anyone? Dr. Robock?

Dr. ROBOCK. There has been a suggestion to put frisbees into space to put a cloud of particles, of satellites, up to block the sun at a point between the earth and the sun, and that would probably cost trillions of dollars and nobody is sure if it would work. So I wouldn't suggest we invest money in that idea.

Ms. DAHLKEMPER. Dr. Shepherd?

Mr. SHEPHERD. I would personally exclude from consideration the idea of covering desert areas with reflective material because of the potential impacts on local rainfall patterns, not to mention the environmental impacts on the desert ecosystems themselves.

Ms. DAHLKEMPER. Dr. Fleming?

Dr. FLEMING. Given the hurricane I showed that came ashore, I would also suggest we be very careful about redirecting storms.

Mrs. DAHLKEMPER. Dr. Caldeira.

Dr. CALDEIRA. I think we need to be clear what kind of research we are considering. If we are talking about a climate model and somebody wants to say, well, what would happen if we changed the reflectivity of a desert in a climate model, that is a small-scale, non-invasive kind of research that might be good to do. But if somebody wants to start rolling out giant plastic sheets over the deserts, that is something that we shouldn't do. So what I am talking about portfolio, there are some things that we should do at small scale, maybe just in climate models and that should receive relatively low priority.

Dr. ROBOCK. And I would say there is nothing that we should do right now. We need a lot more research, theoretical research, with climate models to see what the benefits but also the risks would be of different suggested strategies. So far everybody has done a different climate model experiment. It is hard to compare the results. So I am organizing an international program where all the climate modeling groups in the world do exactly the same experiment so we can see, do they really get drought in certain regions for certain experiments. And if everybody does the same experiment, we can compare it, and we will have a much better confidence that our models are correct, just like we do for global warming experiments.

NEEDED INTERNATIONAL AGREEMENTS

Mrs. DAHLKEMPER. If we are looking at this climate system being so complex, and we haven't even talked about some of the international agreements, what kinds of things do we need to have in place in terms of international agreements and legal steps before we could really do a large-scale testing initiative? Mr. Lane?

Mr. LANE. Yes, I would pick up on something that I said in my written statement which is that nations may differ in their interests in geoengineering, at least in solar radiation management, which is the kind we are talking about for the most part here. I would suggest that the United States really needs to learn a lot more about the potential risks and benefits of solar radiation management for the United States before it embarks on any kind of international agreement or international protocol. We need to be clear on U.S. interests, not that it ultimately isn't going to turn into international bargaining, but each country needs to be clear about its own interests before we are ready for diplomatic bargaining, I would suggest.

Chairman GORDON. Thank you, Mr. Lane.

Mrs. DAHLKEMPER. Thank you.

Chairman GORDON. To demonstrate that the California Republican Party is a big tent, Mr. Bilbray is recognized.

Mr. BILBRAY. Thank you, Mr. Chairman. I would like to quickly yield to the gentleman from the frozen wasteland of Nebraska at this time.

MORE ON LIVESTOCK METHANE OUTPUT

Mr. SMITH OF NEBRASKA. I didn't realize that was a—thank you, I guess.

Dr. Robock, following up on your suggestion that mitigating the consumption of beef would help the environment, do you see any nutritional drawbacks to that? Do you consume beef yourself?

Dr. ROBOCK. Yes. Now, I am not an expert on nutrition or on the entire system of agriculture. I have just seen papers that calculate how much greenhouse gases are admitted for, say, a pound of beef versus a pound of pork or a pound of chicken or a pound of potatoes, and just in that one narrow way of looking at it, there is more emitted that causes more global warming from beef.

Mr. SMITH OF NEBRASKA. But a narrow way of looking at it, you are suggesting?

Dr. ROBOCK. Yes. Yes. There are a lot of other considerations. I am just talking about the impact on global warming.

Mr. SMITH OF NEBRASKA. But you would advocate mitigating consumption of beef as a means of accomplishing your objective?

Dr. ROBOCK. Yes.

Mr. SMITH OF NEBRASKA. And how would you suggest going about that? And in the interest of time, I do want to leave some time. How would you suggest going about that?

Dr. ROBOCK. Education. I mean, people—you can't—I don't—it is your job to decide what to tax or not to tax. Obviously, if you wanted people to behave differently, you give them incentives and disincentives for behavior. But that is just one of the ways that the climate system responds to methane and it responds to carbon dioxide, and the current way of producing beef emits a lot of those gases. That is just—what to do about it? What the entire portfolio of mitigation should be? I am not——

Mr. SMITH OF NEBRASKA. However, you just advocated for something to mitigate the consumption of beef?

Dr. ROBOCK. Well, so the way—if you do want to do that, of course, then you give——

Mr. SMITH OF NEBRASKA. For the record, I don't want to.

Dr. ROBOCK. I mean, I guess I am trying not to say something that will make you feel bad but I am trying also to be honest about——

Mr. SMITH OF NEBRASKA. I think you are a little too late.

Dr. ROBOCK. Sorry.

Mr. SMITH OF NEBRASKA. But thank you.

THE NEED FOR MITIGATION

Mr. BILBRAY. Reclaiming my time, Mr. Chairman, as stated before, the changing, you know, quote unquote, lifestyles or whatever is going to be too little, too late. I want to thank you for having this hearing. The fact is after seeing what kind of proposal that supposedly was going to address climate change that came out of the political structure here, I have come to the conclusion that we need to talk about mitigation of the crisis because we are not going to avoid it. There is not the political will to do what it takes. There is not even the political will to make it legal in the United States to do what it takes to avoid climate change because I believe strongly that we have got to have the ability to produce energy that doesn't emit greenhouse gases so we can shut down all those facilities that do, and there is not the political will to do with that what we did with the interstate freeway system where the government went out and sited, did the planning, did the things so we can shut down the coal producing and the emissions and all that other stuff. We are not willing to do that. We are just willing to talk about how terrible it is.

GLOBAL DIMMING AND RISKS OF STRATOSPHERIC INJECTIONS

So this is going to be a treating the crisis and trying to mitigate the adverse impact, and I appreciate that approach. The question is, there was a comment, have we now eliminated global dimming as a consideration in this issue?

Dr. ROBOCK. If by global dimming you mean the effect of——

Mr. BILBRAY. The pooling effect of particulates——

Dr. ROBOCK. In the troposphere. That is not global but it is continuing in places that emit a lot of particles, like in India and China. But solar radiation management is global dimming on a global scale. People are talking about putting a cloud in the stratosphere, not down near here where we breathe it.

Mr. BILBRAY. My concern is as somebody who has worked on air pollution, I would assume eliminating coal—I mean, clean coal is like safe cigarettes. I am hard-core against it, but that is fine. But if you eliminate coal which puts a lot of particulates in, I am concerned that there may be an adverse impact we don't consider.

Dr. CALDEIRA. If we eliminated coal use today, the earth would probably heat up by about another degree Fahrenheit from removing the sulfur. If we put just a few percent of that sulfur in the stratosphere, we would get the same cooling effect on a global average while eliminating something like 95 or more percent of lower-level pollution. And so we need to think about what if China were to say, for each power plant that we put sulfur scrubbers on, we will take three or four percent of that sulfur and put it higher in the atmosphere to get that cooling effect while eliminating 95 or more percent of the——

Chairman GORDON. Excuse me, Doctor. We have about eight minutes until we have to go vote. So I just want to assure Mr. Smith that he can go home and tell his constituents that the beef police will not be knocking on their door. And I recognize Mr. Luján to conclude our questions.

THE IMPACT OF INGENUITY AND BEHAVIOR CHANGE

Mr. LUJÁN. Mr. Chairman, I appreciate that, and as someone that enjoys a T-bone or a lamb chop, sometimes it is raised on the family farm that I live on. And I hope to do more wonderful hunting in New Mexico. I would invite my colleagues to come down to New Mexico to see for themselves. I appreciate the emphasis with mitigation and what we are talking about here. I would say that as we look to see what we have to do as a Nation and what I hope that we are truly looking at here is not telling people they don't have to fly to visit their family or that they don't have to eat beef or that they don't have to do whatever it is that is being said today, but that we are telling people we can be smarter about the way that we do things—that we are saying when we are talking about human behavior, I do not see how encouraging people to be more efficient with their home energy use or with vehicle use or being smarter about things like that, that that doesn't have a positive impact on all that we are looking at.

Again, being smarter about the way we do things, being able to embrace ingenuity and challenge our scientists, our engineers, our researchers to continue to do great things. You know, when I was young I remember watching cartoons about science fiction and this whole notion that people could one day be in space, building a space station, not only walking on the moon but staying up there for months upon end to do research. Lo and behold, yesterday there were three astronauts that came to visit us here on Capitol Hill who came back from making improvements where there are more and more people that are living in space, staying there for months upon end, where in a global community we're doing some of these things that were once considered science fiction. We are being smarter about the way we do things, and we are doing them better.

And so as we look to see what is happening around the earth, I know that there are many who truly believe that there still isn't a problem, that this isn't something that we have to do something about. And I would hope that we could get something submitted into the record from those of you that are willing to speak to them, to tell us what it is that we can share with them as well, to talk about this problem that I believe is facing us as a Nation and facing us as a global community.

CLIMATE MODELING RESOURCES

As we talk about the science, though, and what indeed that we can employ to be more aware of what is actually occurring with the warming of the oceans or weather patterns, can you talk about the importance of how we are able to include computer modeling capabilities, of research laboratories, of our national laboratories, of our colleges and our universities around the United States that have super-computing capabilities and the ability to now use new data to be able to feed you the information that you need so that we can indeed solve some of these problems? Dr. Caldeira?

Dr. CALDEIRA. I and my colleagues did some of the first computer model simulations of the solar radiation management methods at a Department of Energy National Lab, Lawrence Livermore Lab, and the kind of computing facilities at places like Los Alamos and the other labs in the system are really valuable and were a great place to be able to do this work.

I am also, as an academic, a strong supporter of our academic research institutions and the computing facilities at those institutions. And I think that there is potential through investing in this research area to revitalize our science, education and the computing facilities that support that education.

Chairman GORDON. Dr. Caldeira and for the rest of the panel, we are down to less than five minutes now, so I will quote, if he doesn't mind, Dr. Ehlers in saying, Mr. Luján, you brought us to an eloquent conclusion. Thank you for your statement.

Before we close the hearing, as I told the witnesses earlier, I will provide for them two questions, one, what does a research program look like, and the second one, if we have any type of international treaties or collaboration, what should that look at. We would also welcome any comments to follow up, Mr. Luján, or anything else.

You have been an excellent panel. This has been I think an important hearing, the start of a longer-term discussion, and I think that we can say with consensus that no one is advocating that geoengineering is a one-stop shop or any type of an alternative to mitigation, but is something that needs to be reviewed. And so I will say now that the record will remain open for two weeks for additional statements from Members and for answers to any follow-up questions the Committee might ask the witnesses. The witnesses are excused, and the hearing is adjourned. Thank you.

[Whereupon, at 11:45 a.m., the Committee was adjourned.]

Appendix:

ANSWERS TO POST-HEARING QUESTIONS

BART GORDON, TENNESSEE
CHAIRMAN

RALPH M. HALL, TEXAS
RANKING MEMBER

U.S. HOUSE OF REPRESENTATIVES

COMMITTEE ON SCIENCE AND TECHNOLOGY

SUITE 2320 RAYBURN HOUSE OFFICE BUILDING
WASHINGTON, DC 20515–6301
(202) 225–6375
TTY: (202) 226–4410
http://science.house.gov

November 19, 2009

The Honorable Bart Gordon
Chairman
Committee on Science and Technology
U.S. House of Representatives
2320 Rayburn House Office Building
Washington, DC 20515

Dear Mr. Chairman:

Pursuant to rule 7(e) of the Rules of the Committee on Science and Technology, I request that you include the attached follow-up questions for the record to the identified witnesses who appeared before the full Committee at the hearing entitled *Geoengineering: Assessing the Implications of Large-Scale Climate Intervention*. This letter and the attached questions and the witness responses should be included in the printed hearing record.

In addition, when responses are received, please forward a copy of each to Tara Rothschild (Tara.Rothschild@mail.house.gov) and Alex Matthews (Alex.Matthews@mail.house.gov) of the Science and Technology Committee's Republican staff.

If there are any further questions please have your staff contact Tara Rothschild at 226-5342 or Alex Matthews at 225-6371 or via email.

Sincerely,

Ralph M. Hall

Ralph Hall
RANKING MEMBER

Geoengineering: Assessing the Implications of Large-Scale Climate Intervention

<u>Questions for the Record from Ranking Member Ralph Hall</u>

Professor John Shepherd, FRS, Professorial Research Fellow in Earth System Science at the University of Southampton.

1) Mr. Shepherd, in your written testimony you mention that the technologies required to achieve sufficient mitigation action are available and affordable right now.
    a. Would you please comment on what those technologies are?
    b. Would you consider carbon capture and sequestration technologies available and affordable?
    c. Would you consider the installation and use of such technologies available and affordable?

2) We've heard a great deal today about Solar Radiation Management techniques. Would you please tell us of some of the significant side effects and risks associated with stratospheric aerosol methods?

3) During your "Working Group" deliberations, were there any discussions surrounding liability? For example, if one nation were to act, using a stratospheric aerosol method, and several nations gained from the resultant "cooling", but there were unintended negative impacts as well, would each nation be liable in some way or just the one nation taking the action? How would the liability or remediation be shared?

Dr. Ken Caldeira, Professor of Environmental Science in the Department of Global Ecology and Director of the Caldeira Lab at the Carnegie Institution of Science at Stanford University.

1) For the Solar Radiation Management options, you state that there are only two that would be able to address a significant part if not all warming issues, sulfate injections and cloud seeding.
    a. Although smaller options like white roofs and surfaces or desert reflectors would not address the whole warming issue, would it be useful to deploy these low impact options?
    b. Or, is the idea that once the radiation infiltrates the earth's atmosphere to a point where it would be reflected off the surface, the battle has already been lost since it will be captured on its return to space?

2) In your testimony you mention the Mt. Pinatubo volcanic eruption in 1991 that caused a 1 degree Fahrenheit cooling of the earth for about a year or two. Then the particles in the stratosphere discharged by the volcano left, and the cooling effect wore off.
   a. Where did those particles go to?
   b. Is there a similar concern about acid rain or particulate matter pollution if we inject particles into the stratosphere to simulate a volcanic eruption?

3) Ultimately, almost all the energy we use here on earth comes from the sun. Coal, oil and natural gas are essentially the remainder of large amounts of biomass from millions of years ago. Water, wind, and to a lesser extent, tidal energy are all derived from the Earth-Sun system. Solar and bioenergy quite obviously require energy from the sun. Only nuclear and geothermal energy seem to be independent of energy from the sun. What are the potential risks to global energy resources if we reduce the amount of solar radiation reaching the Earth?

Dr. Lee Lane, Resident Fellow and the Co-director of the Geoengineering Project at the American Enterprise Institute (AEI) and former Executive Director of the Climate Policy Center.

1) Mr. Lane, would you expand on your comments in your testimony that a steep decline in greenhouse gas (GHG) emissions may well cost more than the perceived value of its benefits?

2) How do you see R&D informing or defining the scope of the potential problems associated with solar radiation management (SRM)?

3) While the U.S. is party to many international treaties, some of the more significant ones are agreements that we have not been able to sign on to, like the Law of the Sea.
   a. How does this affect our future abilities to develop international governance and regulatory structures to address development and deployment of geoengineering technologies?
   b. How soon should these international negotiations begin? Before the technologies are deemed feasible by research? Or should we wait until the technology is mature enough to be considered deployable?

Dr. Alan Robock, Distinguished Professor of Climatology in the Department of Environmental Sciences at Rutgers University and Associate Director of Rutgers Center for Environmental Prediction.

1) In your testimony, you indicate that one of the shortcomings of "solar radiation management" geo-engineering is that it could produce drought in Asia and Africa and threaten the food supply for billions of people. Some scientists have suggested that global climate change could have the same result; others have suggested that it will actually increase agricultural production in some areas of the world.
   a. If we were to undertake some type of large scale geo-engineering experiment, how would we be able to differentiate between the effects of global climate change and those from the geo-engineering and make the necessary modifications to prevent catastrophe?
   b. If we were able to differentiate between the effects of global climate change and effects from geoengineering, is it now possible to determine whether a drought is caused by anthropogenic climate change or just natural variability?

2) In your testimony you indicate that you have been using NASA climate models and NASA computers to conduct climate model simulations. You also indicate that increases in funding for research are necessary to explore these concepts further.
   a. Do you believe much of this research can be done utilizing existing resources such as those at NASA?
   b. What additional resources and capabilities would be required to further research in this area?
   c. Are these models peer reviewed? Are you privy to the assumptions that go into building the models before you run your simulations?

3) In reading your testimony, one comes to the conclusion that regardless of how much research we perform ahead of time, we will never really know the true effects geo-engineering would have on the planet without actually doing it because of all the possible variables. Is that an accurate statement? How accurate is that for other technological ventures we have undertaken?

Dr. James Fleming, Professor and Director of Science, Technology and Society at Colby College.

1) Dr. Fleming, in your statement you include a short list of reasons that many people have claimed as the fundamental problems with climate engineering. Just to name a few, you mention the claims regarding lack of understanding, lack of technology, lack of political will to govern over it, etc.
    a. Are these claims very similar to the ones people have heard every time a new technology or concept arises that threatens to alter our fundamental understandings of the universe?
    b. How has society managed to get through those previous technological growth spurts?

2) Just for the sake of argument, if it was decided that such climate engineering projects needed regulation, which Federal agency would be the most appropriate to do it?

3) I find it interesting that you state that the human dimension is the biggest wildcard in the whole climate change debate that essentially makes it unpredictable. One of the reasons the hearing is important is due to the concern that one nation, or even just one individual, could take it upon themselves to "fix the climate change problem" and utilize some technology that would have global effects.
    a. Should we be looking at this issue as a national security problem? Not unlike a rogue state or terrorist group that releases a biological, chemical or nuclear weapon on some unsuspecting populace?
    b. Could the actions of a lone "climate savior" have global effects that would rise to this level of concern? Or is the technology really not in a place where this is an issue now, but we should be discussing it for the future?

Questions for the Record from Representative Dana Rohrabacher

Dr. Ken Caldeira, Professor of Environmental Science in the Department of Global Ecology and Director of the Caldeira Lab at the Carnegie Institution of Science at Stanford University.

1) If stopping coal use immediately would cause more supposed warming than the entire CO_2 increase since the beginning of industrialization, why is that a good thing?

ANSWERS TO POST-HEARING QUESTIONS

Responses by Ken Caldeira, Professor of Environmental Science, Department of Global Ecology, The Carnegie Institution of Washington, and Co-Author, Royal Society Report

Questions submitted by Representative Ralph M. Hall

Q1. For the Solar Radiation Management options, you state that there are only two that would be able to address a significant part if not all warming issues, sulfate injections and cloud seeding.

a. Although smaller options like white roofs and surfaces or desert reflectors would not address the whole warming issue, would it be useful to deploy these low impact options?

b. Or, is the idea that once the radiation infiltrates the earth's atmosphere to a point where it would be reflected off the surface, the battle has already been lost since it will be captured on its return to space?

A1. Dr. Caldeira did not provide an answer to this question.

Q2. In your testimony you mention the Mt. Pinatubo volcanic eruption in 1991 that caused a 1 degree Fahrenheit cooling of the earth for about a year or two. Then the particles in the stratosphere discharged by the volcano left, and the cooling effect wore off.

a. Where did those particles go to?

b. Is there a similar concern about acid rain or particulate matter pollution if we inject particles into the stratosphere to simulate a volcanic eruption?

A2. Dr. Caldeira did not provide an answer to this question.

Q3. Ultimately, almost all the energy we use here on earth comes from the sun. Coal, oil and natural gas are essentially the remainder of large amounts of biomass from millions of years ago. Water, wind, and to a lesser extent, tidal energy are all derived from the Earth-Sun system. Solar and bioenergy quite obviously require energy from the sun. Only nuclear and geothermal energy seem to be independent of energy from the sun. What are the potential risks to global energy resources if we reduce the amount of solar radiation reaching the Earth?

A3. Dr. Caldeira did not provide an answer to this question.

Questions submitted by Representative Dana Rohrabacher

Q1. If stopping coal use immediately would cause more supposed warming than the entire CO_2 increase since the beginning of industrialization, why is that a good thing?

A1. Dr. Caldeira did not provide an answer to this question.

ANSWERS TO POST-HEARING QUESTIONS

Responses by John Shepherd, FRS, Professional Research Fellow in Earth System Science, National Oceanography Centre, University of Southampton, and Chair, Royal Society Geoengineering Report Working Group

Questions submitted by Chairman Bart Gordon

Q1. Please describe what you think a comprehensive federal research program on geoengineering should entail. What are the critical features of such a program?

- *Which U.S. agencies would contribute to a research initiative, and in what capacity?*
- *What scale of investment would be necessary, both initially and in the longer term?*
- *What kind of professional and academic expertise would be required?*

A1. A comprehensive research programme should involve research on ***both*** Solar Radiation Management (SRM) and Carbon Dioxide Removal (CDR) methods, since CDR methods are less risky, and would be needed for a long-term solution, to provide the exit strategy for SRM methods, and to deal with the ocean acidification problem. Since it is too early to pick winners, research on several of the more promising methods of each class should be undertaken. The scientific and technological research should comprise technological development, computer modelling of both intended and unintended environmental impacts, laboratory and pilot-plant scale experiments, and field testing on various scales in due course. For methods which involve dispersion of material in the environment and/or transboundary effects (other than simply the removal of greenhouse gases (GHGs) from the atmosphere), large-scale field tests should await the establishment of appropriate national and/or international arrangements for the regulation of such research. Research on economic aspects (especially life-cycle assessment on financial, energy and carbon accounting bases), and on social, legal, ethical and political aspects should be undertaken in parallel.

I am not an expert on U.S. research funding or institutional capability, but would advocate that the research should be undertaken as a coordinated joint programme by academic institutions, national laboratories and where appropriate also by contracted commercial research organisations. Funding of various aspects by NSF, DOE, NOAA and NASA would be appropriate. Private and philanthropic funding should not be excluded if channelled via a suitably transparent "arms length" mechanism.

A suitable scale of investment for the U.S.A. would be of the order of $100 million per year (direct costs only) for the first five years, as a contribution to a coordinated international programme, increasing progressively thereafter (possibly doubling each five years) until one or more methods are selected for deployment, or all are abandoned as unnecessary or undesirable.

A very wide range of scientific and engineering expertise will be required (the precise requirement will depend on the technology in question), together with professional expertise in socio-economic and legal fields. Particular areas which may require additional support are in all aspects of Earth System & Environmental Sciences, and Chemical, Electrical & Mechanical Engineering. The further enhancement of Earth System Models (and the computing infrastructure to run them) are likely to be an early requirement.

Q2. Please prioritize the geoengineering strategies you believe warrant extensive research, and explain your reasoning.

- *Within these, please highlight examples of potential negative impacts you predict might accompany their deployment and/or large-scale research.*
- *Are there any strategies that you believe should be eliminated from consideration due to unacceptable risks and costs?*

A2. Estimates of costs for all methods are very uncertain at present, so cost should not be taken as a decisive selection criterion for the time being (and it is premature to attempt comparative cost-benefit analyses except at a very broad-brush level).

Among SRM methods the order of priority, nature of the research, and potential negative impacts should be

High: Stratospheric aerosols [R&D on all aspects especially deployment technology, and intended and unintended environmental impacts: possible negative impacts on stratospheric ozone, upper tropospheric clouds, poor cancellation of precipitation pattern changes].

Medium: Cloud brightening [R&D on all aspects especially deployment technology, radiative forcing attainable, and intended and unintended environmental impacts: possible negative impacts on regional weather patterns & ocean upwelling due to strongly localised radiative forcing].

Low: Space-based methods [R&D: Desk-based feasibility studies only: potential negative impacts due to non-uniform forcing and release of rocket fuel combustion products etc to the atmosphere].

Among CDR methods the order of priority, nature of the research, and potential negative impacts should be

High: Engineered capture of CO_2 from ambient air [R&D on technological development especially energy use and cost reduction: potential negative impacts due to materials used and CO_2 sequestration]

Medium: Enhanced weathering methods (both terrestrial and oceanic) [R&D on technological development, effectiveness, and environmental impacts: potential negative impacts due to materials & energy used, and possibly on soil and ocean ecosystems]

Low: Biological methods (SECS, Biochar, enhanced soil carbon & afforestation). [R&D on ecological impacts and land-use requirements & conflicts: potential negative impacts on forest & grassland ecosystems]

Unpromising methods include land-surface (desert) albedo enhancement, and ocean fertilisation (by both iron and macronutrients) because of their expected high impacts on natural ecosystems.

[Please see Royal Society report for further explanation of rationale]

Q3. Could some geoengineering activities be confined to specific geographic locations?

- *For example, could solar radiation management be localized specifically for the protection of polar ice?*

A3. In general CDR methods can be applied at any location (e.g. where energy and other costs are low) as convenient, though not all would necessarily be confined within national boundaries (e.g. ocean fertilisation).

It would on the other hand be generally undesirable to attempt to localise SRM methods, because any localised 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 & upwelling patterns. It would be particularly undesirable to attempt to cool some area (e.g. the polar regions) of one hemisphere but not the other, as this is very likely to lead to a shift in the location and seasonal range of the inter-tropical convergence zone (ITCZ) with possible alteration of low-latitude weather systems (especially the seasonal pattern and strength of monsoon systems).

It could however be useful to engineer a slight and smooth latitudinal variation of SRM forcing {e.g. by aerosol release primarily at high latitudes), to balance the spatial pattern of greenhouse warming more precisely, and so to reduce any residual over-compensation effects which are likely with a spatially uniform forcing (such as a simple fractional reduction of solar radiation).

Q4. In his submitted testimony, Dr. Robock explained simply: "To actually implement geoengineering, it needs to be demonstrated that the benefits of geoengineering outweigh the risks."

- *What do you believe are the "tipping points" that would justify large scale deployment of geoengineering?*
- *Based on the current pace of carbon increases (about 2 parts per million a year) and your prediction of the efficacy of conventional mitigation strategies, what would be an appropriate timeline for research and possible deployment?*

A4. I do not consider that a "tipping point" or "emergency" rationale for implementation of geoengineering is appropriate, simply because it will be extremely difficult to detect tipping points (at which irreversible state changes occur) before they are passed, or even to be certain when they have been passed. Moreover, waiting for an emergency situation more or less implies introducing a high level of intervention rapidly, which is likely to be imprudent. I think it is more constructive to consider trigger or threshold levels at which it would be prudent to commence progressive implementation of geoengineering over several decades (allowing the intervention to commence at a low level so that one could verify its intended impacts and hopefully detect any adverse impacts before they become serious). It could for example be appropriate to commence geoengineering intervention in time and in such a way as to limit the increase of global temperature to 2° C (or any other agreed level) and maintain it at that level for some considerable time, before deciding whether to seek to reduce it. As stated above and in the Royal Society report, it would be imprudent to commence SRM intervention without an exit strategy, such as simultaneously commencing CDR intervention on a scale sufficient to supplant the SRM intervention in the long term.

In the light of current (i.e. post-Copenhagen) expectations of climate change, it would be desirable to commence a substantial programme of R&D immediately, with a view to possible large-scale deployment in about 20 years time, i.e. about 20 years before it is expected that the global mean temperature increase will reach 2° C.

Q5. The effects of many geoengineering strategies such as stratospheric injections could not likely be tested at less than full-scale. To your knowledge, what types of international agreements would address the challenges of large-scale testing?

- *Can you identify any existing treaties or agreements that would apply to large-scale testing of geoengineering?*

A5. To the best of my knowledge, there are no international treaties or institutions which are at present appropriate to deal with regulation of geoengineering in general, or stratospheric aerosol release in particular (see fuller discussion in the Royal Society report). A major revision and extension of ENMOD, and the creation of an executive arm for this treaty, could be a possible route for the future. However, any such body would have to cooperate closely with the UNFCCC eventually, to ensure coordinated development of mitigation, adaptation and geoengineering activities, and such a formal linkage should be created in any new legal and institutional framework. A critical review of existing treaties and institutions is a necessary and important early action.

Questions submitted by Representative Ralph M. Hall

Q1. Mr. Shepherd, in your written testimony you mention that the technologies required to achieve sufficient mitigation action are available and affordable right now.

a. Would you please comment on what those technologies are?

b. Would you consider carbon capture and sequestration technologies available and affordable?

c. Would you consider the installation and use of such technologies available and affordable?

A1. (a) Please see the report of the Royal Society "Towards a Low Carbon Energy Future" (available at *http://royalsociety.org/WorkArea/DownloadAsset.aspx?id=5453*) which summarises technologies available for implementation in the immediate future, the medium term (up to 2050) and thereafter. Most such technologies would result in somewhat higher energy prices, but should nevertheless be regarded as affordable, since energy prices are rarely the dominant component of domestic or industrial costs. Moreover energy prices have historically been held at artificially low levels (because the costs of the environmental impacts have hitherto been ignored). Society and industry will of course need time to adapt to higher energy prices.

(b) Given a sufficient investment of effort CCS would be available for deployment over the next few decades, beginning well before 2020. It would result in a substantial increase in electricity prices, but for the reasons given above this should not be regarded as an insurmountable obstacle.

(c) There are a number of technologies (see above) available for rapid development and progressively increasing deployment, but the timescale for the transition to a low-carbon energy system is nevertheless several decades even using existing technology such as nuclear fission.

Q2. We've heard a great deal today about Solar Radiation Management techniques. Would you please tell us of some of the significant side effects and risks associated with stratospheric aerosol methods?

A2. Please refer to the Royal Society report "Geoengineering the Climate" for a detailed account of the possible side effects and risks associated with SRM using stratospheric aerosols. Briefly the possible side-effects identified to date are:

(a) Imperfect cancellation (over-compensation) of important facets of climate change, including regional temperature patterns, but more seriously of the regional and seasonal distribution of precipitation (rainfall) especially at low latitudes. It should be noted that rainfall is notoriously difficult to predict in all weather forecasting and climate models anyway, and the reliable prediction of the effects of SRM intervention is similarly difficult. Advances in computer modelling are required for all of these purposes.

(b) Reduction of stratospheric ozone levels.

(c) Possible modification of high-level tropospheric clouds (with consequences for climate which have not yet been evaluated).

(d) SRM methods have no effect on CO_2 levels and therefore do almost nothing to ameliorate ocean acidification.

The most serious risk is however that SRM techniques "would create an artificial, approximate, and potentially delicate balance between increased greenhouse gas concentrations and reduced solar radiation, which would have to be maintained, potentially for many centuries. It is doubtful that such a balance would really be sustainable for such long periods of time, particularly if emissions of greenhouse gases were allowed to continue or even increase." Moreover, if the intervention were terminated for any reason, all the climate change to be expected from the elevated level of GHGs still in the atmosphere would then occur very rapidly indeed (this is the "termination problem").

Q3. During your "Working Group" deliberations, were there any discussions surrounding liability? For example, if one nation were to act, using a stratospheric aerosol method, and several nations gained from the resultant "cooling", but there were unintended negative impacts as well, would each nation be liable in some way or just the one nation taking the action? How would the liability or remediation be shared?

A3. We did discuss liability issues briefly (see sections 4.5 and 5.4 of the report) but did not feel able to offer firm conclusions on this difficult subject (which also already arises, of course, over liability for the impacts of climate change itself). As with climate change, it is likely to be extremely difficult to attribute specific events causing losses to the intervention undertaken, with sufficient confidence to underpin a system for compensation. It may be more practicable to establish a generic system, similar to that which is evolving under the UNFCCC for compensation for the impacts of climate change on vulnerable communities.

ANSWERS TO POST-HEARING QUESTIONS

Responses by Lee Lane, Co-Director, American Enterprise Institute (Aei) Geoengineering Project

Questions submitted by Chairman Bart Gordon

Q1. Please describe what you think a comprehensive federal research program on geoengineering should entail. What are the critical features of such a program?

A1. **Overview:** Such a program should include both scientific research and technology development. Over time, resource allocation should shift from the former to the latter. Research should explore both the possible benefits and the possible risks of geoengineering options. Both solar radiation management (SRM) and air capture (AC) deserve to be explored, but the former is far more important and less likely to win adequate private sector support; it should receive the lion's share of the public funding. The SRM program will eventually entail field testing. The scale of the testing should gradually increase. To advance SRM, the U.S. government will need to build its capacity to model and to observe Earth's climate.

Three broad principles are crucial:

First, the 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.

Second, each program should have a clearly defined and accountable "owner". He or she must be accountable for project performance: therefore, he or she must also be able to allocate the available budget. The R&D process is uncertain; surprises are inevitable; therefore, managers must be free to respond to them.

Third, Congress, too, would have to play a part in the success of R&D on geoengineering. R&D involves failures; indeed, an R&D program that experiences no failures is almost certainly too conservative. Members of Congress may be tempted to react to agency failures in ways that reinforce this tendency. The temptation to view R&D through the lens of local jobs is another notorious source of R&D inefficiency.

Q1a. Which U.S. agencies would contribute to a research initiative, and in what capacity?

A1a. For SRM, R&D will involve Earth observation, modeling, and several different areas on scientific research. NASA, NOAA, and NSF all possess relevant expertise. As R&D progresses, skill in managing technology development will play a growing role. Few civilian agencies of the U.S. government have demonstrated talent for tasks of this kind.

A critical issue will be to choose the project's lead agency. The lead agency should have a budget that allows it to draw on the expertise available in other government agencies without granting any of them the status of monopoly supplier. Congress would need to refrain from allocating tasks and dollars to favored agencies and facilities.

Q1b. What scale of investment would be necessary, both initially and in the longer term?

A1b. Initially, a few million dollars a year would suffice. At some point, SRM would require sub-scale testing. Eventually a full scale test might be warranted. These tests, and the needed global observation, could eventually cost several billion annually. Seeking alternatives to satellite observation might be an important cost saving R&D task. At least some experts believe that such alternatives exist.

Q1c. What kind of professional and academic expertise would be required?

A1c. The natural scientists on the panel are better qualified than Ito respond to this question as it pertains to those disciplines; however, Professor Fleming has observed that geoengineering also poses a number of questions that fall within the ambit of the social sciences. On this point, he is, I believe, correct. How government should respond to this need is an open question. In an earlier era, with the RAND Corporation, the U.S. government had great success in productively using social science. The Committee is, I believe, going to be hearing from Dr. Thomas Schelling. Dr. Schelling has had experience with RAND and with other similar ventures. The Committee might wish to draw on his views on this subject.

One fundamental question about SRM is the way in. which it should be integrated with other means of coping with climate change. While the natural sciences provide important inputs to answering this question, economists, decision theorists, and political scientists also have crucial contributions to make.

Q2. Please prioritize the geoengineering strategies you believe warrant extensive research, and explain your reasoning.

A2. SRM may offer a defense against the possible onset of rapid and very harmful climate change. Should such climate change occur, no other response appears to offer a comparable option for avoiding harm. This feature of SRM, combined with its apparently low cost, makes exploring it a high priority. AC may also warrant R&D, but does not offer either of these advantages; further, the private sector has fairly strong economic incentives to explore AC. In contrast, if we are to have an SRM option, the public sector will have to develop it.

Q2a. Within these, please highlight examples of potential negative impacts you predict might accompany their deployment and/or large-scale research.

A2a. Professor Robock has developed an extensive list of possible objections. This list constitutes a starting point for the defensive research agenda associated with SRM. I have nothing to add to his list.

In the case of AC, most of the technologies entail relatively localized impacts; however, to have a global scale impact, AC must capture and safely store truly gargantuan quantities of mass. The shear scale of the task seems to dictate that its environmental costs will be substantial.

Q2b. Are there any strategies that you believe should be eliminated from consideration due to unacceptable risks and costs?

A2b. For reasons laid out in a recent paper (Bickel and Lane, 2009) 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 fail or be abandoned for any reason.

Q3. Could some geoengineering activities be confined to specific geographic locations?

A3. My understanding is that Dr. Michael MacCracken has been considering some SRM options for localized interventions. See: MacCracken, Michael, C. "On the possible use of geoengineering to moderate specific climate change impacts." *Environ. Res. Lett.* **4** (2009), 045107, available at: *http://www.iop.org/EJ/article/1748-9326/4/4/045107/er19_4_045107.html#er1317855s3*

Another line of research has been summarized in recent work by Rasch, Latham, and Chen. See: Rasch, Philip J., John Latham, and Chih-Chieh (Jack) Chen. "Geoengineering by cloud seeding: influence on sea ice and climate system." Environ. Res. Lett. 4 (2009), 045112, available at: *http://www.iop.org/EJ/article/1748-9326/4/4/045112/er19_4_045112.pdf?request-id=dc8ba35701-01a3-4aec-b654-eee98f4a8a71*

The Committee may wish to query these scholars on the results of their findings.

Q3a. For example, could solar radiation management be localized specifically for the protection of polar ice? If so, how?

Q4. In his submitted testimony, Dr. Robock explained simply: "To actually implement geoengineering, it needs to be demonstrated that the benefits of geoengineering outweigh the risks."

A4. The potential net benefits of SRM are, however, very large. One recent study found that, globally, the difference between the benefits of deploying SRM and the direct costs of doing so range from $200 billion to $700 billion a *year* in perpetuity. If other studies confirm this result, SRM should be deployed unless its side-effects entail annual net costs of at least $200 to $700. Determining if they do is a key part of a research agenda for exploring this option. (Professor Eric Bickel of the University of Texas at Austin is currently doing innovative work in this field, and the Committee might wish to consult him on these matters.)

Research of this kind must also encompass the indirect benefits of deploying SRM, *e.g.* lowering the risk of trade wars triggered by GHG controls, the ecologic havoc wreaked by biofuel mandates, and so forth. No valid study can weigh only the indirect costs of SRM while ignoring those of other approaches.

Q4a. What do you believe are the "tipping points" that would justify large-scale deployment of geoengineering?

A4a. The natural scientists on the panel are better qualified than Ito respond to this question.

Q4b. Based on the current pace of carbon increases (about 2 parts per million a year) and your prediction of the efficacy of conventional mitigation strategies, what would be an appropriate timeline for research and possible deployment?

A4b. Globally, no consensus exists about paying the costs of GHG controls, nor is such a consensus likely to emerge in less than several decades at the very least. Under these conditions, global emissions will continue rising for many decades to come. Atmospheric concentrations will continue rising until long after emissions have peaked.

At the same time, research on SRM is likely to progress rather slowly. Larger scale field tests in particular might have to proceed at a deliberate pace. It would be better to observe the climate's reaction to one intervention at a time and with a significant interval between interventions. The latter precaution would ensure that time-lagged impacts were discovered. This combination of factors implies that R&D on SRM should begin as soon as possible in order to allow the eventual field tests to proceed cautiously.

Q5. The effects of many geoengineering strategies such as stratospheric injections could not likely be tested at less than full-scale. To your knowledge, what types of international agreements would address the challenges of large-scale testing? Can you identify any existing treaties or agreements that would apply to large-scale testing of geoengineering?

A5. In a recent paper prepared for the American Enterprise Institute, Professor Scott Barrett of Columbia University observed:

> "According to Daniel Bodansky (1996: 316), "international law has relatively little specific to say about climate engineering." Moreover, he adds, "we should be cautious about drawing conclusions from existing rules, for the simple reason that these rules were not developed with climate engineering in mind" (Bodansky 1996: 316). Geoengineering creates a new institutional challenge.

Professor Barrett's observations seem to suggest that no clear regime exists. SRM is a problem that is likely to require arrangements that are designed to fit its unique characteristics.

I would reinforce the caution that I expressed in my written statement There is too much uncertainty about the nature of the U.S. national interest in geoengineering for the U.S. government to consider international agreements that might restrict our government's future freedom of action.

Questions submitted by Representative Ralph M. Hall

Q1. Mr. Lane, would you expand on your comments in your testimony that a steep decline in greenhouse gas (GHG) emissions may well cost more than the perceived value of its benefits?

A1. Most economic studies of climate change have concluded that a policy of gradually restraining global GHG emissions would yield net benefits. These same studies indicate that attempts to apply more rapid emission restraints would be likely to impose costs that exceed their benefits. Professor Richard Tol's recent paper for the Copenhagen Consensus Center basically reaffirms this consensus.

A few studies have departed from this consensus. Some of these, like the analyses of Lord Stern and. William Cline, produce different results largely because of atypical assumptions about the rate at which future benefits should be discounted. William Nordhaus of Yale has presented a cogent critique of this approach. It is my personal impression that, on this point, at least here in the U.S., most economists who have examined the question, although not all of them, would favor the basic thrust of Nordhaus' analysis over that offered by Stern and Cline.

On a different point, Professor Martin Weitzman of Harvard has argued that the possible harm from low-probability, but very high-impact, climate change events is so great that benefit-cost analysis becomes, in his view, a poor guide to policy. Other economists, including Nordhaus, disagree. Debate continues, but unless GHG controls have a large impact on the trend in emissions, they might have little probability of lowering the risk of high-impact climate change. Nothing in the last twenty years' history of GHG control talks suggests that controls will, in fact, produce sharp reductions in emissions.

Finally, but perhaps most importantly, how GHG controls are structured will have a major effect on their costs. GHG control policies that are overly stringent, or those that fall unevenly across countries or economic sectors, will drastically raise the costs of reaching any given emission reduction target. Unfortunately, both globally and in the U.S., GHG controls are taking on exactly these cost increasing features. China's and India's refusal at the Copenhagen climate talks to make firm commitments or to pledge more than business-as-usual steps guarantees that either GHG controls will have virtually no effect on emissions or that they will do so only at an exorbitant cost.

Q2. How do you see R&D informing or defining the scope of the potential problems associated with solar radiation management (SRM)?

A2. Current climate models do a poor job of replicating regional rainfall patterns. Yet changes in regional rainfall, if they occur, are likely to account for the most economically significant unwanted side effect of SRM. Without improved models, it will be impossible to determine if a problem exists and, if it does, how severe it might be. With all of the potential drawbacks of SRM, the initial scientific research should then supply inputs for studies monetizing any costs that are found.

Where research finds real problems with current SRM, concept redesign may avoid them. Alternatively, new SRM concepts might avoid problems; thus, earlier defensive research may partly shape the course of development.

Q3. While the U.S. is party to many international treaties, some of the more significant ones are agreements that we have not been able to sign on to, like the Law of the Sea.

a. How does this affect our future abilities to develop international governance and regulatory structures to address development and deployment of geoengineering technologies?

A3. Agreements designed for other purposes, as suggested by Dr. Bodansky, may fit awkwardly with the features of SRM. A workable SRM option would not require universal participation. Indeed, if transaction costs of managing the system were to be kept within reason, a relatively small subset of major powers would have to assume disproportionate authority over its operations. For the "governance" arrangements for SRM, a coalition of the willing might be a better model than agreements based on the fiction of international equality.

Q3b. How soon should these international negotiations begin? Before the technologies are deemed feasible by research? Or should we wait until the technology is mature enough to be considered deployable?

A3b. The U.S. interest in the various kinds of geoengineering remains unclear. It is clear, however, that the concept of geoengineering as a weapon is nonsense, but it is also clear that the benefits and costs of geoengineering are likely to vary from country to country. U.S. interests in the future development of this concept may, therefore, differ from those of other countries; yet the substance and the form of a possible international regime on geoengineering would be likely to affect the course of its development. Indeed, a regime that did not have such an effect would be a waste of effort. The U.S. government should acquire substantially more knowledge about geoengineering's potential benefits and risks before embarking on any talks that might restrict its future freedom of action.

ANSWERS TO POST-HEARING QUESTIONS

Responses by Alan Robock, Professor, Department of Environmental Sciences, School of Environmental and Biological Sciences, Rutgers University

Questions submitted by Chairman Bart Gordon

As stated in my original testimony, geoengineering proposals can be separated into solar radiation management (by producing a stratospheric cloud or making low clouds over the ocean brighter) or carbon capture and sequestration (with biological or chemical means over the land or oceans). My expertise is in the first area. In particular, my work has focused on the idea of emulating explosive volcanic eruptions, by attempting to produce a stratospheric cloud that would reflect some incoming sunlight, to shade and cool the planet to counteract global warming. In these answers, except where indicated, I will confine my remarks to solar radiation management, and use the term "geoengineering" to refer to only it. I do this because it is the suggestion that has gotten the most attention recently, and because it is the one that I have addressed in my work.

Q1. Please describe what you think a comprehensive federal research program on geoengineering should entail. What are the critical features of such a program?

A1. A comprehensive federal research program should follow the advice of the policy statement on geoengineering endorsed by both the American Meteorological Society and the American Geophysical Union in 2009, who recommend:

1. "Enhanced research on the scientific and technological potential for geoengineering the climate system, including research on intended and unintended environmental responses.
2. "Coordinated study of historical, ethical, legal, and social implications of geoengineering that integrates international, interdisciplinary, and intergenerational issues and perspectives and includes lessons from past efforts to modify weather and climate.
3. "Development and analysis of policy options to promote transparency and international cooperation in exploring geoengineering options along with restrictions on reckless efforts to manipulate the climate system."

Being only an expert in the first category, I will confine my responses to those issues, but urge you to seek advice from historians, social scientists, and political scientists on items 2 and 3, which are also very important.

A research program devoted to the scientific and technological potential should include computer modeling, engineering studies of systems that could create particles in the stratosphere or brighten clouds, and observing systems for marine stratocumulus clouds and stratospheric aerosols.

State-of-the-art climate models, which have been validated by previous success at simulating past climate change, including the effects of volcanic eruptions, should be used for theoretical studies. They would consider different suggested scenarios for injection of gases or particles designed to produce a stratospheric cloud, and different scenarios of marine cloud brightening, and evaluate the positive and negative aspects of the climate response. So far, the small number of studies that have been conducted have all used different scenarios, and it is difficult to compare the results to see which are robust. Experiments should be coordinated among the different climate modeling groups that are performing runs for the Climate Modeling Intercomparison Project (CMIP) of the *World Climate Research Programme Working Group on Coupled Modelling,* described at *http://cmip-pcmdi.11n1.gov/,* for assessing climate models and their response to many different causes of climate change, including anthropogenic greenhouse gases and aerosols. As they explain at the above website, CMIP is "a standard experimental protocol for studying the output of coupled atmosphere-ocean general circulation models (AOGCMs). CMIP provides a community-based infrastructure in support of climate model diagnosis, validation, intercomparison, documentation and data access. This framework enables a diverse community of scientists to analyze GCMs in a systematic fashion, a process which serves to facilitate model improvement. Virtually the entire international climate modeling community has participated in this project since its inception in 1995." Financial support from a national research program, in cooperation with other nations, will produce more rapid and more comprehensive results. The studies need to include advanced treatment of aerosol particles in climate models, including how they form and grow, as well as their effects on radiation and ozone.

Another area of research that needs to be supported under the first category is the technology of producing a stratospheric aerosol cloud. *Robock et al.* [2009] calculated that it would cost several billion dollars per year to just inject enough sulfur gas into the stratosphere to produce a cloud that would cool the planet using existing military airplanes. Others have suggested that it would be quite a bit more expensive. However, even if SO_2 (sulfur dioxide) or H_2S (hydrogen sulfide) could be injected into the stratosphere, there is no assurance that nozzles and injection strategies could be designed to produce a cloud with the right size droplets that would be effective at scattering sunlight. However, the research program will also need to fund engineers to actually build prototypes based on modification of existing aircraft or new designs, and to once again examine other potential mechanisms including balloons, artillery, and towers. They will also have to look into engineered particles, and not just assume that we would produce sulfate clouds that mimic volcanic eruptions. In addition, engineering studies will be needed for ships that could inject salt into marine clouds.

At some point, given the results of climate models and engineering, there may be a desire to test such a system in the real world. But this is not possible without full-scale deployment, and that decision would have to be made without a full evaluation of the possible risks. Certainly individual aircraft or balloons could be launched into the stratosphere to release sulfur gases. Nozzles can be tested. But whether such a system would produce the desired cloud could not be tested unless it was deployed into an existing cloud that is being maintained in the stratosphere. While small sub-micron particles would be most effective at scattering sunlight and producing cooling, current theory [e.g., *Heckendorn et al.,* 2009] tells us that continued emission of sulfur gases would cause existing particles to grow to larger sizes, larger than volcanic eruptions typically produce, and they would be less effective at cooling Earth, requiring even more emissions. Such effects could not be tested, except at full-scale.

Furthermore, the climatic response to an engineered stratospheric cloud could not be tested, except at full-scale. The weather is too variable, so that it is not possible to attribute responses of the climate system to the effects of a stratospheric cloud without a very large effect of the cloud. Volcanic eruptions serve as an excellent natural example of this. In 1991, the Mt. Pinatubo volcano in the Philippines injected 20 Mt (megatons) of SO_2 (sulfur dioxide) into the stratosphere. The planet cooled by about 0.5° C (1° F) in 1992, and then warmed back up as the volcanic cloud fell out of the atmosphere over the next year or so. There was a large reduction of the Asian monsoon in the summer of 1992 and a measurable ozone depletion in the stratosphere. Climate model simulations suggest that the equivalent of one Pinatubo every four years or so would be required to counteract global warming for the next few decades, because if the cloud were maintained in the stratosphere, it would give the climate system time to cool in response, unlike for the Pinatubo case, when the cloud fell out of the atmosphere before the climate system could react fully. To see, for example, what the effects of such a geoengineered cloud would be on precipitation patterns and ozone, we would have to actually do the experiment. The effects of smaller amounts of volcanic clouds on climate can simply not be detected, and a diffuse cloud produced by an experiment would not provide the correct environment for continued emissions of sulfur gases. The recent fairly large eruptions of the Kasatochi volcano in 2008 (1.5 Mt SO_2) and Sarychev in 2009 (2 Mt SO_2) did not produce a climate response that could be measured against the noise of chaotic weather variability.

Any field testing of geoengineering would need to be monitored so that it can be evaluated. 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 Stratospheric Aerosol and Gas Experiment II (SAGE II) instrument on the Earth Radiation Budget Satellite 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. Right now, the only limb-scanner in orbit is the Optical Spectrograph and InfraRed Imaging System (OSIRIS), a Canadian instrument on Odin, a Swedish satellite. SAGE III flew from 2002 to 2006, and there are no plans for a follow on mission. A spare SAGE III sits on a shelf at a NASA lab, and could be used now. There is one satellite in orbit now with a laser, but it is not expected to last long enough to monitor future geoengineering, and there is no organized system to use it to produce the required observations of stratospheric particles. Certainly, a dedicated observational program would be needed as an integral part of any geoengineering implementation.

Q1a. Which U.S. agencies would contribute to a research initiative, and in what capacity?

A1a. The U.S. agencies most involved in climate modeling are the National Science Foundation (NSF), National Center for Atmospheric Research (funded mostly by NSF), National Oceanic and Atmospheric Administration, National Aeronautics and Space Administration (NASA), and Department of Energy (DOE). I would recommend that NSF be in charge of a climate modeling research program, coordinated with the other agencies, with the Program for Climate Model Diagnosis and Intercomparison of the DOE continuing their program of archiving all the model output for intercomparisons. For the engineering studies, I recommend that NASA be in charge, in cooperation with the Department of Defense, which may be able to provide expertise in some of the proposed delivery systems. For an improved system of stratospheric aerosol observing, as well as better cloud observing from space, NASA should be in charge.

Q1b. What scale of investment would be necessary, both initially and in the longer term?

A1b. A geoengineering research program should not be at the expense of existing research into climate change, mitigation, and adaptation. Our first goal should be rapid mitigation, and we need to continue the current increase in support for green alternatives to fossil fuels. We also need to continue to better understand regional climate change, to help us to implement mitigation and adapt to the climate change that will surely come in the next decades no matter what our actions today. But a small increment to current funding to support geoengineering will allow us to determine whether geoengineering deserves serious consideration as a policy option. The total expenditure for climate model experimentation should be on the order of $10 million per year, which would include expanding current efforts as well as training of new scientists to work on these problems, through postdocs and graduate student fellowships.

As for the engineering studies, you would have to ask engineering experts. Certainly studies should be done of the feasibility of retrofitting existing U.S. Air Force planes to inject sulfur gases into the stratosphere, as described by *Robock et al.* [2009], as well as of developing new vehicles, probably remotely-piloted, for routine delivery of sulfur gases or production of aerosol particles. A separate engineering effort aimed at ships that could inject salt into marine clouds should be part of the effort.

The dedicated observational effort described above would involve field campaigns to observe cloud experiments, which could probably be conducted with existing aircraft, but the campaigns would need to be funded. In addition, NASA needs to develop a robust, ongoing set of satellites to observe stratospheric aerosols, to prepare for the next volcanic eruptions, which serve as natural analogs for stratospheric geoengineering, as well as to monitor any in situ stratospheric experiments that may be conducted in the future. However, right now NASA could devote $1 million per year to just using current satellites to produce a continuous record of stratospheric aerosols and precursors. Many different observations are not being analyzed in a routine manner, and are only used by individual investigators to study specific cases, such as the Australian forest fires early in 2009 or the Kasatochi volcanic eruption of 2008. If a NASA-produced database were available routinely, much could be learned from these ongoing natural experiments. For new systems, experts on aircraft field campaigns and satellite development would need to be consulted about the costs.

Q1c. What kind of professional and academic expertise would be required?

A1c. Climate modelers; experts in atmospheric chemistry and aerosols; cloud physicists; specialists in aircraft and satellite observations; satellite, aircraft, balloon, artillery, and tower engineers; historians; social scientists; political scientists.

Q2. Please prioritize the geoengineering strategies you believe warrant extensive research, and explain your reasoning.

A2. Two types of solar radiation management, using stratospheric aerosols and marine cloud brightening, warrant extensive research. Both mimic observed changes in the atmosphere that have already occurred. We know that volcanic eruptions reduce solar radiation and cool the planet and we know that particles injected into marine stratocumulus clouds make them brighter, which presumably would cool the surface if there were no other compensating changed in the clouds. In both cases, there are no obvious serious side effects from the sulfur gases or salt proposed for the injections.

Q1a. Within these, please highlight examples of potential negative impacts you predict might accompany their deployment and/or large-scale research.

A1a. Computer modeling research of stratospheric aerosols or marine cloud brightening would only have negative effects if it took resources, such as the time of scientists or computers, away from more productive activities. But if funded in addition to other ongoing climate research, it would enhance our understanding of the climate system both in theory and in enhanced observations.

Actual deployment of either scheme into the atmosphere, however, would have the potential to produce serious side effects. That is why I advocate extensive computer modeling before any such decision is made, to better understand and quantify each of the potential problems. I have enumerated many potential negative impacts of stratospheric geoengineering in *Robock* [2008a, 2008b], so will only list them briefly here, from *Robock et al.* [2009]:

1. Drought in Africa and Asia
2. Continued ocean acidification from CO_2
3. Ozone depletion
4. No more blue skies
5. Less solar power
6. Environmental impact of implementation
7. Rapid warming if stopped
8. Cannot stop effects quickly
9. Human error
10. Unexpected consequences
11. Commercial control
12. Military use of technology
13. Conflicts with current treaties
14. Whose hand on the thermostat?
15. Ruin terrestrial optical astronomy
16. Moral hazard - the prospect of it working would reduce drive for mitigation
17. Moral authority - do we have the right to do this?

As for marine cloud brightening, cooling over the oceans with persistent cloudiness might affect the entire oceanic biosphere and food chain. Because marine clouds would only be in certain locations, the differential cooling would change weather patterns. *Jones et al.* [2009] found in their climate model experiments that this could produce a drought in the Amazon rainforest, with devastating effects on the forests and other life there.

Q2b. Are there any strategies that you believe should be eliminated from consideration due to unacceptable risks and costs?

A2b. Angel [2006] proposed placing shades in orbit between the Sun and Earth to reduce the amount of insolation, but it would be very expensive and difficult to control, so I would not recommend research into this idea.

Q3. Could some geoengineering activities be confined to specific geographic locations?

A3. Marine cloud brightening could be conducted in specific locations, but that might not be very effective at dealing with global warming.

Q3a. For example, could solar radiation management be localized specifically for the protection of polar ice?

A3a. Not that I know of. Marine cloud brightening would not be effective in the Arctic, since there is no proposed technology to whiten clouds that would operate on ice in the Arctic. Furthermore, one would need clouds in the correct location in order to brighten them. In the Arctic, unlike off the west coasts of North and South America and Africa, marine stratocumulus do not persist as regularly in specific locations. In addition, because of the low angle of the Sun in the Arctic, changing cloud albedo would not be very effective.

With respect to stratospheric aerosols, *Robock et al.* [2008c] showed that if aerosols were created in the Arctic stratosphere, while Arctic temperature could be controlled and sea ice melting could be reversed, there would still be large consequences for the summer monsoons over Asia and Africa, since the aerosols would not be confined to the polar region.

Q3b. If so; how?

Q4. In your submitted testimony, you explained simply: "To actually implement geoengineering, it needs to be demonstrated that the benefits of geoengineering outweigh the risks." What do you believe are the "tipping points" that would justify large scale deployment of geoengineering?

A4. The declaration of a planetary emergency that would justify large-scale geoengineering would require more climate research. While increased melting of Greenland or Antarctica along with rapidly rising sea level, or an increased frequency of severe hurricanes, droughts or floods, might appear to be a tipping point or an emergency, we would need much more research to quantify whether these changes were indeed caused by global warming and whether geoengineering would halt them. We would also have to be sure that the negative side effects of any proposed geoengineering would be much less than the problems it was attempting to solve, and that those affected by these actions would be fairly compensated.

Q4a. Based on the current pace of carbon increases (about 2 parts per million a year) and your prediction of the efficacy of conventional mitigation strategies, what would be an appropriate timeline for research and possible deployment?

A4a. No matter how effective conventional mitigation strategies prove to be in the next decade, the amount of global warming will be about the same, as the greenhouse gases already in the atmosphere will continue to cause warming. Mitigation will only make a difference in the longer term. So geoengineering research should not depend on the short-term political decisions in the next few years (and mitigation should definitely not wait for the possibility of safe and effective geoengineering). So independent of short-term changes in greenhouse gases emissions, I would recommend a 10-year research program that will use climate models to investigate the efficacy, risks, and costs of proposed geoengineering schemes, include technical research to determine whether it is even possible to implement the proposed schemes, and develop and deploy robust observing systems. This will allow policymakers to have enough information in a decade to decide whether geoengineering should ever be implemented as an emergency measure. Since these proposed schemes would work very quickly, within a year or two, this would leave enough time to adequately research them and still implement them before catastrophic climate change is likely.

Q5. The effects of many geoengineering strategies such as stratospheric injections could not likely be tested at less than full-scale. To your knowledge, what types of international agreements would address the challenges of large-scale testing?

A5. There are several current international treaties, such as the Montreal Protocol on Substances That Deplete the Ozone Layer, the Antarctic Treaty, the Law of the Sea, the Framework Convention on Climate Change, and Nuclear Test Ban treaties, that seek to limit environmental damage from human emissions. These treaties, while they do not apply directly to geoengineering, serve as a warning that humans can have a strong, inadvertent, negative impact on the environment, and that we must keep this in mind with respect to geoengineering. They also serve as models for the types of treaties that different nations can sign to agree to protect the environment.

Q5a. Can you identify any existing treaties or agreements that would apply to large-scale testing of geoengineering?

A5a. I am not a lawyer, but the U.N. Convention on the Prohibition of Military or Any Other Hostile Use of Environmental Modification Techniques (ENMOD) may apply. The terms of ENMOD explicitly prohibit "military or any other hostile use of environmental modification techniques having widespread, long-lasting or severe effects as the means of destruction, damage, or injury to any other State Party." Any geoengineering scheme that adversely affects regional climate, for example, producing warming or drought, would therefore violate ENMOD if done in a hostile manner, which would be difficult to determine. Therefore, new governance mechanisms would have to be developed before any experimentation in the atmosphere.

SEE END OF DOCUMENT FOR ALL REFERENCES.

Questions submitted by Representative Ralph M. Hall

Q1. In your testimony, you indicate that one of the shortcomings of "solar radiation management" geo-engineering is that it could produce drought in Asia and Afri-

ca and threaten the food supply for billions of people. Some scientists have suggested that global climate change could have the same result; others have suggested that it will actually increase agricultural production in some areas of the world.

a. *If we were to undertake some type of large scale geo-engineering experiment, how would we be able to differentiate between the effects of global climate change and those from the geo-engineering and make the necessary modifications to prevent catastrophe?*

A1,1a. There is a certain natural variability of climate because of the chaotic nature of the atmosphere and oceans. This randomness limits our ability to make weather forecasts beyond about two weeks and limits our ability to make ocean forecasts, such for El Niñno events, beyond about six months. So the attribution of particular weather and climate events, such as strong hurricanes, tornado outbreaks, droughts, and floods, to a particular geoengineering experiment or to the effects of greenhouse gases is not possible in the absolute sense and can only be done statistically. That is, theory (models) tell us that the probability of events like this would change in response to different things human might put into the atmosphere, but we cannot attribute any particular event to a particular cause. Therefore, a real-world geoengineering experiment would have to be conducted for a long time, 10 or 20 years or longer, so as to gather enough data to calculate the statistics. It is only after 60 years of global warming since about 1950 and decades of the IPCC process that we have a clear understanding the greenhouse gases are responsible.

The answer to the question would depend on what type of geoengineering were conducted, such as stratospheric aerosols or marine cloud brightening, and the strength of the geoengineering. For a massive injection of aerosols into the stratosphere, or massive seeding of clouds, the effects of geoengineering would be stronger and a shorter experiment would be needed to separate the effects from global warming. Climate model experiments will be able to give us a good idea of how strong and how long a real-world experiment would be needed to separate the effects from natural variability and from global warming.

Q1b. If we were able to differentiate between the effects of global climate change and effects from geoengineering, is it now possible to determine whether a drought is caused by anthropogenic climate change or just natural variability?

A1b. No. As explained above, the attribution of particular weather and climate events, such as strong hurricanes, tornado outbreaks, droughts, and floods, to a particular geoengineering experiment, to the effects of greenhouse gases, or just to natural variability is not possible in the absolute sense and can only be done statistically. That is, theory (models) tells us that the probability of events like this would change in response to different things human might put into the atmosphere, but we cannot attribute any particular event to a particular cause. For example, what if we start geoengineering and we get a reduction of summer monsoon rainfall in India for two out of the first five years? Could this have happened by chance, or was it caused by the geoengineering? We could not answer that question without many more years of experimentation in the real world. However, we could easily do that experiment in climate models.

Q2. In your testimony you indicate that you have been using NASA climate models and NASA computers to conduct climate model simulations. You also indicate that increases in funding for research are necessary to explore these concepts further.

a. *Do you believe much of this research can be done utilizing existing resources such as those at NASA?*

A2,2a. No. Climate modeling needs to be done at many different research centers with many different climate models, and the results compared to be sure they are robust. This is the current strategy of CMIP, as discussed in detail in the answer to Mr. Gordon's question 1 above.

All the world climate modeling groups are currently finalizing their latest model versions so that they can begin a suite of experiments, called CMIP–5, in preparation for the next Intergovernmental Panel on Climate Change report. While NASA and other climate modeling centers in the United States, such as at the National Oceanic and Atmospheric Administration (NOAA) Geophysical Fluid Dynamics Laboratory. and the National Center for Atmospheric Research do not need new resources to complete their model development, the current scientists working there are completely occupied with the CMIP–5 experiments. They would need more personnel and computer resources to complete additional geoengineering experiments.

Q2b. What additional resources and capabilities would be required to further research in this area?

A2b. This question is completely answered in response to questions 1 and 2 of Mr. Gordon above, and I refer you to those answers.

Q2c. Are these models peer reviewed? Are you privy to the assumptions that go into building the models before you run your simulations?

A2c. Absolutely yes. The climate model we are currently using, Goddard Institute for Space Studies ModelE, is described in peer-reviewed publications by *Schmidt et al.* [2006], *Russell et al.* [1995], and *Koch et al.* [2006]. We and anyone else who reads these papers completely understand the assumptions that go into them. Furthermore, this model is part of the CMIP experiments described above, and its capabilities are well known and documented.

Q3. In reading your testimony, one comes to the conclusion that regardless of how much research we perform ahead of time, we will never really know the true effects geo-engineering would have on the planet without actually doing it because of all the possible variables. Is that an accurate statement? How accurate is that for other technological ventures we have undertaken?

A3. I guess that depends on what "know the true effects" means. Indeed we would learn a lot by experimenting in the real world and would be able to compare the responses to those obtained theoretically by climate modeling. But as explained above, there is a certain natural variability of climate because of the chaotic nature of the atmosphere and oceans. This randomness limits our ability to make weather forecasts beyond about two weeks and limits our ability to make ocean forecasts, such for El Nino events, beyond about six months. So the attribution of particular weather and climate events, such as strong hurricanes, tornado outbreaks, droughts, and floods, to a particular geoengineering experiment or to the effects of greenhouse gases is not possible in the absolute sense and can only be done statistically. That is, the probability of events like this would change in response to different things human might put into the atmosphere. Therefore, a real-world experiment would have to be conducted for a long time, 10 or 20 years or longer, so as to gather enough data to calculate the statistics. For example, what if we start geoengineering and we get less drought in California for three out of the first five years. Could this have happened by chance, or was it caused by the geoengineering? We could not answer that question without many more years of experimentation in the real world. However, we could easily do that experiment in climate models.

As for other technical ventures, it would depend on the technology, and I am not an qualified to answer the question in general. But I would like to say that some experiments should never be conducted in the real world. For example, I have conducted a lot of research on the climatic effects of nuclear weapons. If used in warfare, the fires they would ignite would produce so much smoke that climate models tell us that the cold and dark at the Earth's surface would severely impact agriculture and even produce a nuclear winter [*Robock et al.,* 2007a, 2007b]. This is an experiment we should never try to verify in the real world.

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ANSWERS TO POST-HEARING QUESTIONS

Responses by James Fleming, Professor and Director, Science, Technology and Society Program, Colby College

Questions submitted by Chairman Bart Gordon

Q1. Please describe what you think a comprehensive federal research program on geoengineering should entail. What are the critical features of such a program?

A2. The American Meteorological Society's Statement on Geoengineering *http://www.ametsoc.org/policy/2009geoengineeringclimate_ansstatement.html* (also approved by the American Geophysical Union) recommends that proposals to geoengineer climate require more research of an interdisciplinary nature, cautious consideration, and appropriate restrictions. Here are their summary recommendations:

a. Enhanced research on the scientific and technological potential for geoengineering the climate system, including research on intended and unintended environmental responses.

b. Coordinated study of historical, ethical, legal, and social implications of geoengineering that integrates international, interdisciplinary, and intergenerational issues and perspectives and includes lessons from past efforts to modify weather and climate.

Development and analysis of policy options to promote transparency and international cooperation in exploring geoengineering options along with restrictions on reckless efforts to manipulate the climate system.

Geoengineering, understood as purposeful manipulation of the global climate and biophysical systems of the entire Earth by a particular project or entity, however well intentioned, could lead to international conflict and unpredictable ecological disasters. Humans know far too little about the climate system to imagine that any large-scale intervention would have the desired result, or even a predictable result. Any nation engaging in global-scale geoengineering could be placing itself and all other life on the plant in jeopardy.

The famous mathematician *John von Neumann* called *climate engineering a "thoroughly 'abnormal' industry,"* arguing that large-scale interventions, especially solar radiation management, were not necessarily rational undertakings and could have "rather fantastic effects" on a scale difficult to imagine. Tinkering with the Earth's heat budget or the atmosphere's general circulation, he said, "will merge each nation's affairs with those of every other, more thoroughly than the threat of a nuclear or any other war may already have done"—and possibly lead to "forms of climatic warfare as yet unimagined." In this sense, geoengineering is potentially more powerful and more destructive than an arsenal of H-bombs. Since some forms of solar radiation tinkering could be undertaken by private entities or rogue nations unilaterally and relatively cheaply, what is urgently needed is research, discussion, and education on all the possible things that are wrong with such a technocratic approach to thinking about climate change. As Harry Wexler once said, "the human race is poised precariously on a thin climatic knife-edge." One of the worst climatic disasters imaginable involves destabilizing the climate system, damaging stratospheric ozone, triggering drought, and otherwise destroying our relationship with the sky by misplaced climate tinkering.

Therefore, a comprehensive research program in geoengineering cannot be merely a scientific and technically-based effort. It must be led by historically-informed humanistic and social science efforts to understand the precedents and contextualize human desires (and hubris) involved in intervening in natural systems. Such discussions should seek to avoid being dominated by Western technocratic influences, and would need to be fully international, interdisciplinary, and intergenerational in nature so that a *global* conversation emerges.

In this sense, no technical agency in the U.S. or elsewhere has the capacity to lead such an effort. More likely international scholarly, humanitarian, and governance organizations would have to pool their resources in such an undertaking. Any scientific or technical research on geoengineering should be conducted only as part of the mainstream effort in atmospheric science. It should not be in any way be a secret effort within DoD, or a single or multi-agency effort funding mainly enthusiasts for the techniques. It should be spearheaded in the U.S. by NSF, which has the best open peer review practices and which also sponsors the National Center for Atmospheric Research (NCAR). NSF has the added virtue of funding social, economic, and behavioral studies (including Science Studies) and NCAR maintains a unit specializing in environmental and social impacts.

Support is urgently needed for historical studies of existing environmental treaties, international accords, and efforts to govern new technologies. These would include the 1978 UN Convention on the Prohibition of Military or Any Other Hostile Use of Environmental Modification Techniques (ENMOD), the Antarctic Treaty, the Law of the Sea, the Peaceful Uses of Outer Space, and gatherings such as the 1975 conference in Asilomar, California on recombinant DNA. This would be followed by meetings of historians, ethicists, social scientists, and policy experts from around the world for interdisciplinary discussion and recommendations. Funding for a program involving about 10 core staff, office support, a variety of conferences, and a publishing program with peer-reviewed reports and volumes may be able to function for approximately $2 million per year or ten times this amount for a robust international effort. To foster historical, humanistic, social, public policy, and governance discussions, the Woodrow Wilson International Center for Scholars is a likely venue. It could serve as a scholarly, non-partisan integration point for related efforts at other institutions. Investment in this program would not require much if any hardware purchases or facilities, but should involve a full program of conferences, meetings, seminars and high-level consultations. It should have a director and staff, senior and junior fellows, affiliated members from around the world, and internships and other student opportunities.

Geoengineering research is currently not ready, and may never be ready for any field testing, large scale or otherwise. It is best done indoors using computer simulations and in other controlled conditions, such as laboratories and wind tunnels. For decades, verification of weather modification experiments has been stymied by natural variability in cloud and weather conditions. The same is true many times over for experiments on the global climate.

What is most needed in atmospheric science today is more focused and basic research on atmospheric dynamics and chaotic forcings. If, as Edward Lorenz maintained, the climate system exhibits modes that are extremely sensitive to perturbations, what unknown effect might a sulfate cannon in China, Russia, or perhaps Livermore, California have on the global or regional climate? Also needed, especially now, is a concerted effort to restore scientific and public confidence in the atmospheric sciences, their peer review practices, Earth's instrumental and proxy temperature records, and the authority and behavior of computer models and their results. The Earth orbiting satellite monitoring gap identified in the National Academy's Decadal Survey (2007) also needs to be addressed. This effort alone may involve approximately doubling the current support for basic research, or about $1–2 billion per year.

So in summary, $2–20 million for open conferences on social aspects and governance, and $1–2 billion for basic peer-reviewed research on and monitoring of the climate system seem to be in order.

Q2. Please prioritize the geoengineering strategies you believe warrant extensive research, and explain your reasoning.

A2a. As described above, concerted study of the history, social aspects, and governance of technological interventions and geoengineering proposals, past and present, to cast a new light on just what is being proposed.

b. As described above, increased capacity in basic atmospheric science and climate monitoring, in which model geoengineering proposal play a role, but only a role in a better understanding of the planet.

c. All of the proposed techniques of solar radiation management (SRM) and carbon capture and sequestration (CCS) have many, many serious and unexamined problems. None are really cheap, because economists have only looked at direct costs, not at potential damages. None are ready for field testing or deployment. All of the techniques might well be researched using models and laboratory experiments. For example:

Space mirrors. In 1989 James Early, a scientist from Lawrence Livermore National Laboratory, revisited the issue of space mirrors (first proposed in the 1920s) and linked space manufacturing fantasies with environmental issues in his wild speculations on the construction of a solar shield "to offset the greenhouse effect." His back-of-the-envelope calculations indicated that a massive shield some 1,250 miles in diameter would be needed to reduce incoming sunlight by 2 percent. He estimated that an ultra-thin shield, possibly manufactured from lunar materials using nano-fabrication techniques, might cost "from one to ten trillion dollars." Launched from the moon by an unspecified "mass driver," the shield would reach a "semi-stable" orbit at the L1 point one million miles from Earth along a direct line toward the Sun, where it would perch "like a barely balanced cart atop a steep hill, a hair's-width away from falling down one side or the other." Here it would be subjected to the solar wind, harsh radiation, cosmic rays, and the buildup of electrostatic forces. It would have to remain functional for "several centuries," which would entail repair missions. It would also require an active positioning system to keep it from falling back to Earth or into the Sun. Early did not indicate what a guidance system might look like for a 5 million square mile sheet of material possibly thinner than kitchen plastic wrap, with a mass close to a billion kilograms (2.2 billion pounds in Earth gravity). In other words, it was not feasible. A recent update of this proposal by Roger Angel fares no better.

Stratospheric Aerosols. Using guns, rockets, or balloons to maintain a dust or aerosol cloud in the stratosphere to increase the reflection of sunlight may sound cheap and appealing, but it is far from rational and may have many unwanted an unexpected side effects. Geoengineering advocate Lowell Wood has proposed attaching a long hose to a nonexistent but futuristic military High Altitude Airship (a Lockheed-Martin/DOD stratospheric super blimp now on the drawing board with some twenty-five times the volume of the Goodyear blimp) to "pump" reflective particles into the stratosphere. According to Wood, "Pipe it up; spray it out!" Wood has worked out many of the details—except for high winds, icing, and accidents, since the HAAs are likely to wander as much as 100 miles from their assigned stations. Imagine a 25-mile long hose filled with ten tons of sulfuric acid ripping loose, writhing wildly, and falling out of the sky. Environmental problems from such techniques (as documented by Alan Robock) include damage to tropical rainfall patterns, unwanted stratospheric ozone depletion, and regional effects that may lead to international disagreements.

Air capture of carbon dioxide, with long-term storage. Klaus Lackner of the Earth Institute at Columbia University, collaborating with Tucson, Arizona-based Global Research Technologies, envisions a world filled with millions of inverse chimneys, some of them over 300 feet high and 30 feet in diameter, inhaling up to 30 billion tons of carbon dioxide from the atmosphere every year (the world's annual emissions) and sequestering it in underground or undersea storage areas. Lackner has built a demonstration unit in which a filter filled with caustic and energy intensive sodium hydroxide can absorb the carbon dioxide output of a single car. He admits, however, that this system is not safe or practical, so he is currently looking into proprietary "ion-exchange resins" with undisclosed energetic and environmental properties. Of course, the capture, cooling, liquefaction, and pumping of 30 billion tons of atmospheric carbon

dioxide (the world's annual emissions) would require an astronomical amount of energy and infrastructure, and it is not at all certain that Earth has the capacity for safe long-term storage of such a large amount of carbon.

Q3. Could some geoengineering activities be confined to specific geographic locations?

A3. No. If they could, they would not be "geo"—scale engineering. Also, the Earth's atmosphere is a fluid system that interacts and exchanges energy, mass, and momentum. Interventions in the radiation budget anywhere will trigger changes in the general circulation, including changes in stoma tracks and in particular storms and precipitation patterns. Proposals to restrict aerosol injections to the Arctic circle do not address the global spread of matter in the stratosphere or the interaction of air masses across latitudes. An imaginary Arctic forecasting center with authority to trigger stratospheric aerosol attacks is far beyond modem operational meteorology. Understanding and prediction are what is needed. Intervention and control are not really possible.

Q4. In his submitted testimony, Dr. Robock explained simply, "To actually implement geoengineering, it needs to be demonstrated that the benefits of geoengineering outweigh the risks." [Questions on tipping points and timeline for research and deployment].

A4. Dr. Robock has published "20 Reasons Why Geoengineering May Be a Bad Idea." His list includes the following:

(1) Potentially devastating effects on regional climate, including drought in Africa and Asia, (2) Accelerated stratospheric zone depletion, (3) Unknown environmental impacts of implementation, (4) Rapid warming if deployment ever stops, (5) Inability to reverse the effects quickly, (6) Continued ocean acidification, (7) Whitening of the sky, with no more blue skies, but nice sunsets, (8) The end of terrestrial optical astronomy, (9) Greatly reduced direct beam solar power, (10) Human error, (11) The moral hazard of undermining emissions mitigation,

(12) Commercialization of the technology, (13) Militarization of the technology, (14) Conflicts with current treaties, (15) Who controls the thermostat? (16) Who has the moral right to do this? (17) Unexpected consequences.

Some of these results (1–5) are derived from general circulation model simulations and others (6–9) from back-of-the-envelope calculations; most, however (10–17), stem from historical, ethical, legal, and social considerations. Regarding item (8), most enthusiasts for solar radiation management have overlooked its "dark" side: the scattering of starlight as well as sunlight, which would further degrade seeing conditions for both ground-based optical astronomy and general night sky gazing. Imagine the outcry from professional astronomers and the general public if the geoengineers pollute the stratosphere with a global sulfate cloud; imagine a night sky in which sixth-magnitude stars were invisible, with a barely discernable Milky Way, and fewer visible star clusters or galaxies. This would constitute a worldwide cultural catastrophe.

Since global climate change is forced by a combination of natural and human factors, since it is a relatively slowly developing problem, and since it will affect different nations and groups differently, there is no clear "cliff" or readily defined "tipping point," beyond which the sulfate cannons should roar. Mitigation and adaptation are the best strategies, so no lines in the sand can yet be set. The 1992 UN Framework Convention on Climate Change requires the "stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system." No one has yet defined "dangerous," but attempts have been made to set the goal at 2 degrees of warming or 350 or 450 ppm CO_2. SRM does not stabilize greenhouse gas concentrations at all, it does not help with ocean acidification, and it may in its own right be considered "dangerous anthropogenic interference with the climate system." CCS maybe possible, but the energetics, cost, and stability of long term sequestration, with giant pools of CO_2 underground remain unknown.

The increase in CO_2 concentration of 2 ppm per year is not in itself a significant problem. It is the *sensitivity* of the climate system to CO_2 forcings (via water vapor, clouds, and other mechanisms) that is at issue. Efforts at mitigation and adaptation must be bipartisan and international; they must be given every possibility for success. Research in the historical, social, governance aspects of geoengineering should begin now, with the possibility left open that these technologies are too dangerous and unpredictable to govern. Also research into the negative side effects of geoengineering proposals should continue with modeling studies. *There are no current prospects for responsible deployment of geoengineering techniques.*

Q5. The effects of many geoengineering strategies such as stratospheric injections could not likely be tested at less than full scale. To your knowledge, what types of international agreements would address the challenges of large-scale testing?

A5. The 1978 UN Convention on the Prohibition of Military or Any Other Hostile Use of Environmental Modification Techniques (ENMOD) serves as a landmark treaty that may have to be revisited soon to avoid or at least try to mitigate both inadvertent harm or possible military or otherwise hostile use of climate control. This includes the governance and possible side effects of large-scale outdoor testing. If "climate change has the power to unsettle boundaries and shake up geopolitics, usually for the worse," it is certain that the governments of the world will have their strategic military planners working in secret on both worst-case scenarios and technological responses.

Chairman Gordon, the U.S. Congress can play a large role in supporting efforts to study the problems and limits of the non-existent technologies of geoengineering, but there is as yet no warrant for field testing or deployment.

Questions submitted by Representative Ralph M. Hall

Q1. Dr. Fleming, in your statement you include a short list of reasons that many people have claimed as the fundamental problems with climate engineering. Just to name a few, you mention the claims regarding lack of understanding, lack of technology, lack of political will to govern over it, etc.

a. Are these claims very similar to the ones people have heard every time a new technology or concept arises that threatens to alter our fundamental understandings of the universe?

b. How has society managed to get through those previous technological growth spurts?

A1. Geoengineering does not "alter our fundamental understanding of the universe" in any Copernican sense. Nor is it a "quantum revolution" or in any way comparable to famous discoveries or theories, such as evolution, relativity, or plate tectonics. It is not a scientific discover at all, but a set of speculative intervention strategies with potential military implications. In the past new technologies such as radio or transistors allowed us to communicate across the miles and to miniaturize electronic devices such as radios and computers. New drugs such as penicillin battled infections. While they needed regulation and some guidelines, they did not offer a global threat to the planet. Recombinant DNA is a new technology that required oversight and regulatory control. This was true in spades for nuclear power and nuclear weapons. Geoengineering comes closest to these types of dangerous technologies, but it is much, much more speculative, and as yet, it does not even exist!

There is no one answer to how "society managed to get through those previous technological growth spurts." I think each case is unique and requires special historical contextualization. In some cases, such as the use of the machine gun in the Anglo-Zulu War of 1879, that society did not "manage" very well. And civil society itself was lucky to survive the escalation of civilian aerial bombing that occurred during World War II.

Q2. Just for the sake of argument, if it was decided that such climate engineering projects needed regulation, which Federal agency would be the most appropriate to do it?

A2. This answer closely parallels my response to Congressman Gordon, which I hope you have in hand. No technical or regulatory agency in the U.S. or elsewhere has the authority or capacity to lead such an effort. Just as no nation has the authority to set the global temperature, even if it could. Study and discussion of geoengineering must be international, interdisciplinary, and intergenerational, with strong historical, social, and governance efforts leading the way. In the US, the NSF would be the best agency to study the issues, but regulation would have to be international, perhaps through UN mechanisms such as the ENMOD Convention.

Q3. I find it interesting that you state that the human dimension is the biggest wildcard in the whole climate change debate that essentially makes it unpredictable. One of the reasons the hearing is important is due to the concern that one nation, or even just one individual, could take it upon themselves to "fix the climate change problem" and utilize some technology that would have global effects.

- *a. Should we be looking at this issue as a national security problem? Not unlike a rogue state or terrorist group that releases a biological, chemical or nuclear weapon on some unsuspecting populace?*
- *b. Could the actions of a lone "climate savior" have global effects that would rise to this level of concern? Or is the technology really not in a place where this is an issue now, but we should be discussing it for the future?*

A3. Unilateral or rogue nation intervention in the global climate system is indeed possible and would raise very serious national and international security concerns, as John von Neumann in 1956 and many others have repeatedly pointed out. One problem is that such interventions may start out as well-intentioned, but the effects could be widespread, harmful, and unpredictable. That is, they might be indiscriminate. Other scenarios may include climate tinkering favoring one nation and harming another, for example by redirecting rainfall. Also attribution may be a real problem, given the large variability of weather and climate, so such tinkering may be hard to prove. A favorable result of this situation may be a desire to strengthen satellite or ground-based measuring and monitoring capabilities in order to detect such activity and take more measurements. In this sense it may resemble the need for verification schemes for other potential weapons systems.

I think many of the recent and current geoengineering proposals have a tinge of "climate savior" As (rightly or wrongly) alarm over global warming spreads, some climate engineers are engaging in wild speculation and are advancing increasingly urgent proposals about how to "control" Earth's climate. They are stalking the hallways of power, hyping their proposals, and seeking support for their ideas about fixing the sky. The figures they scribble on the backs of envelopes and the results of their simple (yet somehow portrayed as complex) climate models have convinced them, but very few others, that they are planetary saviors, lifeboat builders on a sinking *Titanic,* visionaries who are taking action in the face of a looming crisis. They present themselves as insurance salesmen for the planet, with policies that may or may not pay benefits. In response to the question of what to do about climate change, they are prepared to take ultimate actions to intervene, even to do too much if others, in their estimation, are doing too little. We are already discussing these attitudes, and there may arise some day a need to stop even a well-intentioned action. Bill Gates is currently investing in geoengineering and may have such an attitude; while $25 million "Branson prize" for reducing global warming acts to encourage planetary tinkers, cum saviors.

Ranking Member Hall, the U.S. Congress can play a large role in supporting efforts to study the problems and limits of the non-existent technologies of geoengineering, but there is as yet no warrant for field testing or deployment.

Appendix 2:

Additional Material for the Record

etc group
action group on erosion, technology and concentration

Submission to the U.S. House of Representatives
Committee on Science and Technology

4 November 2009
ETC Group
www.etcgroup.org

Re: Geoengineering: Assessing the Implications of Large-Scale Climate Intervention Full Committee Hearing, 5 November 2009

ETC Group, an international civil society organization with offices in the United States (North Carolina), Canada, Mexico and the Phillippines, is dedicated to the conservation and sustainable advancement of cultural and ecological diversity and human rights. To this end, ETC Group supports socially responsible developments of technologies useful to the poor and marginalized and we address issues related to international governance and the concentration of corporate power.

ETC Group welcomes the news of Thursday's hearing on geoengineering to be held by the House of Representatives Committee on Science and Technology. We hope that the hearing will mark the beginning of a vigorous public debate on this important topic. At the same time that Committee members are listening to testimony in Washington, delegates at the UN Framework Convention on Climate Change will be negotiating in Barcelona in an effort to make progress on an agreement to bring about significant reductions in global greenhouse gas emissions. The world's leading climate scientists agree that a reduction in greenhouse gas emissions is the world's best hope for averting a climate catastrophe.[1]

ETC Group believes that geoengineering is the wrong response to climate change and that inadequate knowledge of the earth's systems makes geoengineering, or even real-world geoengineering experiments, too risky. We do not know if geoengineering is going to be inexpensive, as proponents insist – especially if geoengineering technologies don't work as intended, forestall constructive alternatives or cause adverse effects. We do not know how to recall a planet-altering technology once it has been released.

In addition to unintended consequences, geoengineering techniques could have unequal impacts around the world (sometimes referred to as "spatial heterogeneity").[2] As much as the Industrial Revolution's "inadvertant geoengineering" (i.e., human-induced climate change) has disproportionately harmed people living in tropical and subtropical areas of the world, purposeful

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[1] See for example, IPCC, 2007: Summary for Policymakers. In: *Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [B. Metz, O.R. Davidson, P.R. Bosch, R. Dave, L.A. Meyer (eds)], Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

[2] UK Royal Society, *Geoengineering the climate: science, governance and uncertainty*, 1 September 2009, p. 62; available on the Internet: http://royalsociety.org/document.asp?tip=0&id=8729

geoengineering experiments could well do the same. It is critical that those states and populations on the front lines in the fight against climate change, particularly the most vulnerable developing countries, be involved in a broadbased and international debate.

It should be recognized that states – or even corporations – with the technical and economic means to "adjust the global thermostat" may be tempted to do it. Geoengineering technologies warrant robust regulatory oversight. In the absence of a multilateral framework and a global consensus, support for geoengineering technologies would be irresponsible and would reinforce the lack of accountability of industrialized countries for climate change and for the worsening negative consequences in the global South.

ETC Group's conclusions on geoengineering include the following:

- For any geoengineering technique to have a noticeable impact on the climate, it will have to be deployed on a massive scale, and any unintended consequences are also likely to be massive. We don't know how to recall a planetary-scale technology.
- OECD governments – which have historically denied climate change or prevaricated for decades (and are responsible for 90% of historic greenhouse gas emissions) – are the ones with the budgets and the capacity to execute geoengineering projects. Will they have the rights and well-being of more vulnerable states or peoples in mind?
- It is possible – though far from certain – that some geoengineering techniques will be relatively inexpensive to deploy. The technical capacity to attempt large-scale climate interventions could be in some hands (of individuals, corporations, states) within the next ten years. It is urgent to develop a multilateral mechanism to govern geoengineering, including establishing a ban on unilateral attempts at climate modification.
- Geoengineering interventions could lead to unintended consequences due to mechanical failure, human error, inadequate understanding of the earth's climate systems, effects from future natural phenomena (e.g., storms, volcanic eruptions), irreversibility or funding lapses.
- Many geoengineering techniques are "dual use" (i.e., have military applications). Any deployment of geoengineering by a single state could be a threat to neighboring countries and, very likely, the entire international community. As such, deployment could violate the UN Environmental Modification Treaty – ratified by the United States – which prohibits the hostile use of environmental modification.
- Patent offices are already being inundated with applications on geoengineering techniques. Monopoly control of any deployed global geoengineering scheme would be unacceptable.
- Geoengineering could be seen by governments as a "time-buying" strategy and as an alternative to reducing greenhouse gas emissions.[3]
- Commercial interests should not be allowed to influence the research, development or deployment of geoengineering technologies. If, as advocates insist, geoengineering is actually a "Plan B" to be used only in a climate emergency, then it should not be a profit-making endeavor. Further, it should not be employed to meet emissions reduction targets.

[3] See, for example, "Geo-Engineering: Giving us the Time to Act," Institute of Mechanical Engineers (UK), August 2009, available at http://www.imeche.org/

GEOENGINEERING II: THE SCIENTIFIC BASIS AND ENGINEERING CHALLENGES

THURSDAY, FEBRUARY 4, 2010

HOUSE OF REPRESENTATIVES,
SUBCOMMITTEE ON ENERGY AND ENVIRONMENT
COMMITTEE ON SCIENCE AND TECHNOLOGY,
Washington, DC.

The Subcommittee met, pursuant to call, at 10:03 a.m., in Room 2318 of the Rayburn House Office Building, Hon. Brian Baird [Chairman of the Subcommittee] presiding.

BART GORDON, TENNESSEE
CHAIRMAN

RALPH M. HALL, TEXAS
RANKING MEMBER

U.S. HOUSE OF REPRESENTATIVES

COMMITTEE ON SCIENCE AND TECHNOLOGY

SUITE 2321 RAYBURN HOUSE OFFICE BUILDING
WASHINGTON, DC 20515–6301
(202) 225–6375
http://science.house.gov

Committee on Science and Technology
Subcommittee on Energy and Environment

Hearing on

Geoengineering II: The Scientific Basis and Engineering Challenges

Thursday, February 4, 2010
10:00 a.m. – 12:00 p.m.
2325 Rayburn House Office Building

Witness List

Dr. David Keith
Canada Research Chair in Energy and the Environment
Director
ISEEE Energy and Environmental Systems Group
University of Calgary

Dr. Philip Rasch
Chief Scientist for Climate Science
Laboratory Fellow
Atmospheric Sciences & Global Change Division
Pacific Northwest National Laboratory

Dr. Klaus Lackner
Department Chair
Earth and Environmental Engineering
Ewing Worzel Professor of Geophysics
Columbia University

Dr. Robert Jackson
Nicholas Chair of Global Environmental Change
Professor
Biology Department
Duke University

HEARING CHARTER

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

Geoengineering II: The Scientific Basis and Engineering Challenges

THURSDAY, FEBRUARY 4, 2010
10:00 A.M.
2325 RAYBURN HOUSE OFFICE BUILDING

Purpose

On Thursday, February 4, 2010, the House Committee on Science & Technology, Subcommittee on Energy and Environment will hold a hearing entitled "***Geoengineering II: The Scientific Basis and Engineering Challenges***." The purpose of the hearing is to explore the science, engineering needs, environmental impact(s), price, efficacy, and permanence of select geoengineering proposals.

Witnesses

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

Background

This hearing is the second of a three-part series on geoengineering. On November 5, 2009 the Full Committee held the first hearing in the series, entitled "*Geoengineering: Assessing the Implications of Large-Scale Climate Intervention*." This Subcommittee hearing will examine the scientific basis and engineering challenges of geoengineering. In the spring of 2010 the Committee will hold the final hearing in this series in which issues of governance will be discussed. This series of hearings serves to create the foundation for an informed and open dialogue on the science and engineering of geoengineering.

As discussed in the first hearing, strategies for geoengineering typically fall into two major categories: Solar Radiation Management and Carbon Dioxide Removal (hereafter SRM and CDR, respectively). The objective of Solar Radiation Management (SRM) methods is to reflect a portion of the sun's radiation back into space, thereby reducing the amount of solar radiation trapped in Earth's atmosphere and stabilizing its energy balance. Methodologies for SRM include: installing reflective surfaces in space; and increasing reflectivity, or albedo [1] of natural surfaces, built structures, and the atmosphere. To balance the impacts of increased atmospheric carbon levels, most SRM proposals recommend a goal of 1–2% reduction of absorbed solar radiation from current levels. Carbon Dioxide Removal (CDR) methods propose to reduce excess CO_2 concentrations by capturing, storing, or consuming carbon directly from air, as compared to direct capture from power plant flue gas and storage as a gas. CDR proposals typically include such methods as carbon sequestration in biomass and soils, ocean fertilization, modified ocean circulation, non-traditional carbon capture and sequestration in geologic formations, and distributing mined minerals over agricultural soils, among others.

[1] Albedo is measured on a scale from 0 to 1, with 0 representing the reflectivity of a material which absorbs all radiation and 1 represents a material which reflects all radiation. Newly laid asphalt has a typical albedo of ~0.05 and fresh snow can have an albedo of 0.90.

Geoengineering Strategies

Atmospheric solar radiation management (SRM)

One approach to atmospheric SRM is known as 'marine cloud whitening' in which a fine spray of particles, typically via droplets of salt water, would be injected into the troposphere (the lowest level of our atmosphere) to increase the number of cloud-condensation nuclei and encourage greater low level cloud formation. The objective is to increase the albedo of existing clouds over the oceans, thus reflecting more sunlight into the atmosphere before it reaches Earth. To achieve the necessary radiative forcing to stabilize global temperatures, cloud cover would need to increase 50–100% from current levels.[2]

Stratospheric sulfate injection is another atmospheric SRM approach.. The objective is to mimic the large quantity of sulfuric emissions and the consequent albedo increase that a volcanic eruption would naturally create. For example, the 1991 eruption of Mt. Pinatubo in the Philippines is thought to have caused a 1–2 year decrease in the average global temperature by ~0.5° C by increasing global albedo.[3] To accomplish this effect via stratospheric sulfate injections, a spray of sulfate particles would be injected into the stratosphere, which is between six and 30 miles above the Earth's surface. This proposal typically garners the most attention among geoengineering's scientific community.

Drawbacks and challenges

Both atmospheric SRM approaches described here could be quickly deployed at a relatively low cost and shut down if necessary; however, both approaches require further research and may carry significant unintended consequences for ocean ecosystems, agriculture, and the built environment.

Marine cloud whitening deployment strategies could include aerosol distribution from a large fleet of ships, unmanned radio-controlled ocean vessels, or aircraft. Further research is needed to optimize variables such as droplet size and concentration, cloud longevity, and the necessary increase in cloud cover to achieve desired results. The material itself (i.e. salt water) would be inexpensive for marine cloud whitening as it is abundant, and environmental impacts may be limited and somewhat predictable. However, it has been noted that marine cloud whitening activities could cause changes in local weather patterns, and deployment might be very energy-intensive.

A variety of deployment methods have been suggested for stratospheric sulfate injections, including sprays from aircraft, land-based guns, rockets, manmade chimneys, and aerial balloons.[4] Environmental impacts from sulfate injection could occur because the sulfate materials would eventually fall from the stratosphere into the troposphere and "rain out" onto the land and ocean. This would contribute to ocean acidification and could negatively impact crop soils and built structures.

The SRM strategies discussed here would be long term investments that must be carefully planned and continually maintained in order to achieve their goals and avoid rapid climatic changes. Presumably, greenhouse gas levels could continuously rise while such SRM strategies were deployed. Therefore, in the case of an interruption or termination in service, the actual impact(s) of increased greenhouse gas concentrations would be felt, i.e., the effects of SRM would be quickly negated. This would present great risk to human populations and natural ecosystems. Apart from these effects, stratospheric injections and marine cloud whitening also run the risk of creating localized impacts on regional climates throughout their deployment. In addition, the decrease in sunlight over the oceans due to marine cloud whitening could affect precipitation patterns and regional ocean ecosystem function. Furthermore, as with other geoengineering ideas, these SRM approaches are criticized for drawing attention and resources away from climate change mitigation and CO_2 reduction efforts.

Terrestrial-based biological approaches (SRM and CDR)

The terrestrial-based biological approaches to geoengineering discussed here include vegetative land cover and forestry methods (e.g., the biological sequestration of carbon, CDR strategies, and increasing the albedo of terrestrial plants, an SRM strategy). These strategies are at different stages of development and deployment,

[2] *An increase in ocean cloud cover to 37.5–50% of ocean surface area.*
[3] Groisman PY (1992)
[4] Novim (2009)

with carbon sequestration in forest ecosystems [5] likely to be the most effective in the near-term.

Increasing albedo and carbon sequestration potential in forests, grasslands, and croplands

The ability of forests and other vegetative systems such as grasslands and croplands to store CO_2 and to reflect solar radiation is crucial to climate change mitigation efforts. Certain geoengineering strategies propose to leverage these properties through massive-scale planting of more reflective or CO_2-absorbent vegetation. In traditional, terrestrial-based biological carbon sequestration, CO_2 is absorbed by trees and plants and it is stored in the tree trunks, branches, foliage, roots, and soils. Geoengineers propose to alter the ability of the plants and trees to sequester carbon or to reflect light [6] using non-native species and techniques from traditional plant breeding and genetic engineering. The basic processes of photosynthesis and light reflection would still occur, but geoengineers would either increase the carbon absorption and reflective capacities of existing vegetation, or introduce non-native species with such increased capacity(s). Deployment of these land-cover systems would be both systematic and massive to achieve the desired effect(s).

There are a number of advantages of these approaches. Development and implementation is relatively low cost and the global infrastructure required to create and propagate similar traits in crops and grasses through to large-scale cultivation already exists.[7] There are fewer potential issues concerning irreversibility than other proposed geoengineering schemes. And, the climate impacts are inherently focused in the regions that are most important to food production and to population centers, thus providing more directed benefits even when applied globally. Maintaining the technology is also less of a problem as crops are replanted annually; however, to maintain the mitigation benefit, high albedo varietals must be continually planted and mature forests must be maintained.

Biochar

Biochar [8] may have potential as an efficient method of atmospheric carbon removal (via plant growth) for storage in soil. Biomass [9] is converted to both biochar (solid) and a bio-oil (liquid) by heating it in the absence of air. The bio-oil can be converted to a biofuel after a costly conversion process, and the biochar can serve as bio-sequester (i.e. atmospheric carbon capture and storage). Biochar, is a stable charcoal-solid that is rich in carbon content, and thus can potentially be used to lock globally significant amounts of carbon in the soil.[10] Unlike typical CO_2 capture methods which typically require large amounts of oxygen and require energy for injection, the biochar process breaks the carbon dioxide cycle, releasing oxygen, and removing carbon from the atmosphere and sequestering it in the soil for possibly hundreds to thousands of years.[11]

Drawbacks and challenges

The biological systems discussed here present challenges to the development of effective deployment, accounting, and verification systems for these terrestrial-based approaches to geoengineering. For example, the climate benefits of sequestration practices can be partially or completely reversed because these resources are subject to natural decay, disturbances, and harvests, which could result in the sudden or gradual release the carbon back to the atmosphere. Forests plateau [12] in their ability to reflect light and absorb CO_2 as they mature, and they release CO_2 as they

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[5] *The Reduced Emissions Deforestation and Degradation (REDD) carbon trading concept provides a starting point for this discussion. The REDD program employs market mechanisms to compensate communities in developing countries to protect local forests as an alternative income mechanism to logging or farming the same land.*

[6] *Research suggests that vegetative land cover in the form of crops and grasslands can impact climate by increasing local albedo by up to 0.25 (on a 0–1 point scale) and thus reflect more light into the atmosphere.*

[7] *The technology exists, but to deploy it on a commercial scale across the globe could take a decade or more.*

[8] *Biochar is charcoal created by the heating of biomass, trees and agriculture waste, in the absence of air, i.e. pyrolysis.*

[9] *Biomass could consist of trees and agricultural wastes.*

[10] Laird (2008)

[11] *Not only do biochar-enriched soils contain more carbon, 150gC/kg compared to 20–30gC/kg in surrounding soils, but biochar-enriched soils are, on average, more than twice as deep as surrounding soils. Therefore, the total carbon stored in these soils can be one order of magnitude higher than adjacent soils* (Winsley 2007).

[12] *Soils also plateau in their ability to sequester CO_2.*

decay; therefore, their utilization as geoengineering strategies would require careful monitoring and accounting of CO_2 storage over time as these systems do not provide long-term storage stability. These systems would also need to be maintained even after saturation to prevent subsequent losses of carbon back to the atmosphere. This would also be the case for management of soils.[13 14 15] Addressing these challenges is important if sequestration benefits are to be compared to other approaches.

Sophisticated and verifiable carbon accounting strategies are needed across the board to optimize carbon-sensitive land uses at different climates and geographies. Existing statistical sampling, models and remote sensing tools can estimate carbon sequestration and emission sources at the global, national, and local scales. However, complex spatial-temporal models would be required for each technique described here. For example, estimating changes in soil carbon over time is generally more challenging than those for forests due to the high degree of variability of soil organic matter—even within small geographic scales like a corn field—and because changes in soil carbon may be small compared to the total amount of soil carbon. And, it is not presently clear whether there would be greater carbon savings by planting trees and then converting those trees into biochar or planting trees and allowing them to grow, thereby sequestering carbon in both the soil and in the plant material.

Tradeoffs between immediate climate objectives and environmental quality may be necessary with these techniques. If nitrogen-based fertilizers are applied to crops to increase yields for biological sequestration methods, the benefit would be partially or completely offset by increased emissions of N_2O. The installation of non-native or genetically engineered species could be associated with additional environmental disruption such counteractive changes in reflectivity. For example, a large scale afforestation initiative over snow or highly reflective grasslands would increase carbon consumption but greatly decrease local albedo. Similarly, genetic modification of crops to increase their albedo could reduce their carbon uptake. Lastly, these techniques are likely to replace diverse ecosystems with single-species timber or grass plantations to generate greater carbon accumulation at the cost of biodiversity.

Non-traditional carbon capture and sequestration or conversion

Non-traditional carbon capture and sequestration (i.e. conversion) strategies would utilize geological systems to capture carbon. First carbon would be captured by exposing it to chemical adsorbents such as calcium hydroxide ($CaCO_3$, zeolites, silicates, amines, and magnesium hydroxide ($Mg(OH)_2$).[16] Then, heat or agitation would be used to separate the carbon from the adsorbent. The carbon can then be stored in a geologic receptacle or it would be stored as a new chemical compound in a liquid or solid formation.

Most geologic carbon removal strategies can be categorized as *in situ* or *ex situ*. *Ex situ* carbonation requires the sourcing and transportation of materials that react with carbon to the source of output (e.g., the smokestack). The energy input may be quite high because the carbon absorbent must be ground up to allow for a sufficient rate of carbon absorption. Air capture is a key component to the geologic carbon sequestration and geochemical weathering of carbon. In this process, a carbon-adsorbent chemical, such as calcium hydroxide, binds to carbon and separates it from the ambient air. The adsorbent chemical is then heated, the bound CO_2 is released, and a pure CO_2 stream is produced. Air capture differs from traditional carbon capture on power plants and other high-intensity carbon emitters in that it is a distributed approach to capture (as many of the main sources of carbon are actually a collection of distributed entities, e.g. vehicles and buildings).

Alternatively, *in situ* carbonation injects carbon into geologic formations suited to the mineralization of carbon.[17] The injected material is then left in the formation to carbonize at a more natural rate. Carbon storage in a liquid or solid represents a more permanent option for carbon management and can be thought of as the mere stimulation of naturally occurring processes that take place over thousands of years instead of months. It would potentially require less stringent regulatory and liability frameworks than traditional carbon storage in a gaseous form. This could make deployment costs more manageable per unit than traditional carbon capture and storage.

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[13] Lehmann, Gaunt and Rondon (2006)
[14] Lal et al. (1999)
[15] West and Post (2002)
[16] Dubey et al. (2002)
[17] Kelemen and Matter (2008)

Challenges and drawbacks

The scale required for deployment of non-traditional carbon capture and sequestration methods present challenges to their eventual use. Geological capture and storage at a geoengineering scale would represent an immense investment, requiring hundreds or thousands of units and immense land formations suitable for storage. In addition, most suggested geological sequestration strategies require a high input of heat or pressure, either to release the carbon from its adsorbents or to speed the necessary reactions for solid storage, and thus are energy burdens for the deployment of this technology.

Ambient air is comprised of 0.04% carbon, and the slip streams of exhaust from coal fired power plants are approximately 15%; therefore, the amount of carbon gathered per unit of air processed would be far lower. In addition to issues of scale, in situ storage material may remain as a gas and be released after a period of time, which leads to additional monitoring and verification needs.

Other Strategies

Several geoengineering strategies were not emphasized in this hearing due to projected environmental impacts and project feasibility. Several of these techniques are detailed below.

Enhanced weathering techniques—Silicate minerals would be sourced, ground, and distributed over agricultural soils to form carbonates. This category of *in situ* carbonation works in the same manner as the non-traditional carbon consumption strategies discussed above. The actual mineral distribution could be performed at a relatively low direct cost; however, the mining activities would require sizable energy inputs. In addition, introducing large quantities of chemicals to a landmass could incur significant changes, both predictable and unpredictable, to the entire ecosystem.

Chemical ocean fertilization—Similar to enhanced weathering in terrestrial systems, this strategy calls for the distribution of ground minerals over the oceans. Iron, silicates, phosphorus, nitrogen, calcium hydroxide and/or limestone could enhance natural chemical processes that consume carbon, such as photosynthesis in phytoplankton. Mining and environmental impacts are major challenges. Iron is the most popular candidate chemical for this strategy as it would require the smallest quantity to significantly lower carbon concentrations.

Oceanic upwelling and downwelling—Naturally occurring ocean circulation would be accelerated in order to transfer atmospheric greenhouse gases to the deep sea. Atmospheric carbon is absorbed by the ocean at the air-water interface, and it is largely stored in the top third of the water column. This approach would use vertical pipes to transfer the carbon rich surface waters to the deep ocean for storage. It would likely require massive engineering efforts and could significantly alter the ocean's natural carbon cycle and circulation systems.

White roofs and surfaces—Painting the roofs of urban structures and pavements in the urban environment white would increase their albedo by 15–25%. A white roofs program would need global implementation to achieve a meaningful impact on radiative forcing, incurring great costs and logistical challenges; however, white roofs can help mitigate the urban heat island problem, which plagues metropolises like Tokyo and New York City.

Desert reflectors—Metallic and other reflective materials would be used to cover largely underused desert areas, which account for 2% of the earth's surface to reflect sunlight. This approach could have large detrimental impacts on local ecosystems and precipitation patterns. Preliminary cost estimates are in the high billions or trillions of dollars.

Space-based reflective surfaces—A large satellite or an array of several small satellites with mirrors or sunshades would be placed in orbit or at the sun-earth Lagrange (L l) point to reflect some percentage of sun radiation. Preliminary cost estimates for this strategy are usually in the trillions of dollars.

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Chairman BAIRD. I will call the hearing to order.[1]

As I mentioned earlier, I have already introduced our witnesses, and this is a hearing on geoengineering. As we deal with the issues of overheating of our planet and acidification of the ocean, this is one option for possibly mitigating the impacts, part of a series of hearings and an effort initiated by our Chair, Mr. Gordon.

[The prepared statement of Chairman Baird follows:]

PREPARED STATEMENT OF CHAIRMAN BRIAN BAIRD

Good morning. I want to welcome everyone to today's hearing discussing the scientific and technological premises underlying various proposals for geoengineering.

Geoengineering is a term that has come to define a range of often controversial strategies to deliberately alter the Earth's climate systems for the purpose of counteracting climate change—presumably through reflection of sunlight or absorption of CO_2 from the air.

Make no mistake, despite the sometimes far-fetched proposals, this is not a subject that should be taken lightly. As Chairman Gordon has also made clear: Geoengineering has been proposed as, and it can only be responsibly discussed as a last-ditch measure in the case that traditional carbon mitigation efforts prove ineffective on their own. Even then, a tremendous amount of research is required to know what strategies may be worth deploying.

The concentration of greenhouse gases in the atmosphere is already driving great changes in the Earth's climate.

The long-term consequences of climate change will become especially threatening, and some of these consequences are already being felt.

For example, oceans naturally absorb atmospheric carbon through the air-water interface. As the concentration of greenhouse gases has increased in the atmosphere so has the absorption of carbon by the oceans. On the surface this is good because it helps to mitigate climate change; however, below the ocean's surface the excessive absorption of carbon is changing the chemistry of the ocean—it is creating ocean acidification.

The effects of ocean acidification will span the ocean food web which will affect our fishermen, coastal communities, and our national and global economies.

Today's hearing is not about ocean acidification *per se*, but it is about controversial methods to reduce or mitigate the causes and effects of climate change through geoengineering.

Without question, our first priority is to reduce the production of global greenhouse gas emissions.

However, as I said, if such reductions achieve too little, too late, there may be a need to consider a plan B—to utilize methodologies to counteract the climatic effects of greenhouse gas emissions by 'geoengineering'.

Many proposals for geoengineering have already been made. Some may have potential, some sound downright scary, and they all carry levels of uncertainty, hazards, and risks that could outweigh their intended benefit.

Furthermore, the technologies proposed for deployment of many of these geoengineering techniques are very young or non-existent, and there are major uncertainties regarding their effectiveness, environmental impacts, and economic costs.

For example, I am especially interested in discussing the potential for the solar radiation management techniques to exacerbate ocean acidification.

The implications of geoengineering are decidedly global in scope, but geoengineering has the potential to be undertaken in a unilateral fashion, without consensus or regard for the well-being of other nations.

Therefore, an open, public dialogue is needed in the face of such hazards, risks, and uncertainties. As you may recall this hearing is the second of a three-part series on geoengineering.

On November 5, 2009, the Full Committee held the first hearing in the series, entitled *"Geoengineering: Assessing the Implications of Large-Scale Climate Intervention."*

Today's Subcommittee hearing will examine the scientific basis and engineering challenges of geoengineering.

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[1] Some discussion was held prior to the formal opening of this hearing. For a transcript of these comments, see Appendix.

This series of hearings serves to create the foundation for an informed and open dialogue on the science of geoengineering, and should in no way be regarded as supportive of deployment of geoengineering.

With that I turn it over to the distinguished Ranking Member, Mr. Inglis.

Chairman BAIRD. I thank the Ranking Member for being here, and recognize him if he has any opening remarks.

Mr. INGLIS. I don't, Mr. Chairman, and I will submit them for the record.

[The prepared statement of Mr. Inglis follows:]

PREPARED STATEMENT OF REPRESENTATIVE BOB INGLIS

Good morning, and thank you for holding this hearing, Mr. Chairman. I look forward to discussing the scientific and engineering challenges related to geoengineering.

Last November, the full committee began our examination of geoengineering as a strategy to minimize the impacts of a warming climate. What we heard was theoretically promising: geoengineering may prove to be a low-cost intervention to buy us time to reduce our greenhouse gas emissions and limit our impact on the global climate system.

Still, we face considerable uncertainty. Dr. Rasch appropriately describes geoengineering as a "gamble" in his testimony. is this a gamble worth trying? At this hearing, I hope to hear what steps we need to take to increase our understanding of geoengineering technologies and come one step closer to determining whether this is a viable option.

In particular, I hope that the witnesses will discuss what technologies, techniques, and capabilities must be developed to study and deploy geoengineering options, and what level of financial investment is required for these developments. I also hope the witnesses will discuss the gaps in our understanding of the climate system that may limit our ability to justify such large-scale intervention, and which alternatives may minimize further changes to the climate, resource cycles, or global ecology.

We also need to decide whether investments in geoengineering are worthwhile. There are a number of ecological, economic, and political uncertainties that also need to be addressed before these interventionist strategies are implemented. Moreover, there is a significant ethical question involved in deploying large-scale geoengineering techniques to forcibly change the climate in an effort to undo the damage we have already done. I hope to address these questions in a future hearing.

Again, thank you for holding this important hearing, Mr. Chairman. I look forward to hearing from the witnesses and I yield back the balance of my time.

Chairman BAIRD. Thank you, and I will submit my opening remarks for the record.

With that, we will proceed. Each witness will have five minutes to proceed. Then if we have time, we will follow up with questions. If not, we will take a break for votes.

Dr. Keith, please.

STATEMENTS OF DR. DAVID KEITH, CANADA RESEARCH CHAIR IN ENERGY AND THE ENVIRONMENT, DIRECTOR, ISEEE ENERGY AND ENVIRONMENTAL SYSTEMS GROUP, UNIVERSITY OF CALGARY

Dr. KEITH. Chairman Baird, Committee Members, thank you very much for having me here today.

We must make deep cuts in global emissions if we are going to manage the risks of climate change. Emissions reductions are necessary, but they are not necessarily sufficient. This is because even if we halt all emissions instantly today, which is not going to happen, the climate risks they pose would persist for millennia. Also, the climate's response to the amount of CO_2 we put in the air is highly uncertain. We could get lucky and see small amounts of climate change, or we could be unlucky. Risk management is the heart of climate policy, so a small risk of catastrophic impact exists even with today's carbon burden, and that risk grows with each ton of new emissions. So because risk management is central, we must hope for the best while laying plans to navigate the worst.

Geoengineering describes two distinct concepts. Carbon dioxide removal, CDR, is a set of tools for removing carbon dioxide from the atmosphere, while solar radiation management, SRM, would reduce the earth's absorption of solar energy, cooling the planet by adding sulfur aerosols to the upper atmosphere or by adding sea salt aerosols to whiten marine clouds. SRM and CDR—forgive my acronyms—do different things, entirely different things. SRM is cheap and can act quickly to cool the planet, but it introduces novel environmental and security risks, and it can at best only partially mask the impacts of CO_2 in the air. The low price tag is very attractive but it raises the risks of unilateral action and a facile cheerleading that promotes exclusive reliance on SRM.

In concert with emissions cuts, CDR can reduce the carbon burden in the atmosphere, a kind of global climate remediation. We need this capability. Unless we can remove CO_2 from the air faster than nature does, we will, we are, consigning the earth to a warmer future for millennia or a sustained and risky program of solar radiation management.

Carbon removal can only make a difference if we capture carbon by the gigaton. The sheer scale of the carbon challenge means that just like emissions cuts, CDR will always be much more expensive and much slower acting than SRM.

SRM and CDR—again, forgive the acronyms—each provide a means to manage climate risk, but they are wholly distinct with respect to the science and technology required to deploy and test them, with respect to their costs and environmental risks, and with respect to the challenges they pose for public policy and governance regulation. Because these technologies have little in common, I suggest that we will have a better chance to craft sensible policy if we separate them almost entirely in the policy process.

In the spirit of disclosure, I offer a few comments about my own work. Along with my academic work, I run a startup company, Carbon Engineering, that seeks to develop large-scale industrial technologies for capturing CO_2 from the air, a form of CDR. Professor Lackner will say more about this later. I am thrilled to work on this technology. It has a shot, however small, at providing a tool to manage one of the greatest environmental threats. I will be happy to answer questions about this and other CDR technologies but I will focus my remarks on SRM because I believe that is where there is the most urgent need for government action.

Because of the serious concerns raised by the enormous leverage SRM grants us over the global climate, I think it is crucial that development of these technologies be managed in a way that is as transparent as possible. I therefore do no commercial or proprietary work on SRM.

In my written comments, I offer some thoughts about the specific kinds of research that are needed, the funding, the agencies that might be appropriate or might not, the scale of the research program. One thing I will say here is that we don't want to start too fast. Research programs can be killed by getting too much money too quickly.

The idea of deliberately manipulating the earth's energy balance to offset human-driven climate change strikes many as dangerous hubris. Solar engineering is like chemotherapy: no one wants it. It is far better to avoid carcinogens but we all want the ability to do chemo and to understand its risks should we find ourselves with dangerous cancer. The primary argument against doing SRM research is fear that it will sap our will to cut emissions. I share this view. Yet I believe that the risks of not doing research outweigh the risks of doing it. SRM may be the only means to fend off the risk of rapid and high-consequence climate impacts. Furthermore, there are environmental and geopolitical risks posed by the potential of unilateral deployment of SRM by a small or large state acting alone which can best be managed by developing widely shared knowledge, risk assessment and norms of governance. I don't mean one big U.N.-style government system, I just mean some understanding, however it works, of how we manage this thermostat for the planet.

It is a healthy sign that a common first response to geoengineering is revulsion. It suggests we have learned something from past instances of techno-optimism and subsequent failures, but we must not overinterpret past experience. Responsible management of climate risk requires sharp emissions cuts and cleareyed research on SRM linked with the development of shared tools for managing it. The two are not in opposition. They are not dichotomies. We are currently doing very little on either, cutting emissions or this, and we urgently need action on both. Thank you.

[The prepared statement of Dr. Keith follows:]

PREPARED STATEMENT OF DAVID KEITH

Learning to manage sunlight: Research needs for Solar Radiation Management

Two kinds of geoengineering

Geoengineering describes two distinct concepts. Carbon Dioxide Removal (CDR) describes a set of tools for removing carbon dioxide from the atmosphere, while Solar Radiation Management (SRM) would reduce the Earth's absorption of solar energy, cooling the planet by, for example, adding sulfur aerosols to the upper atmosphere or adding sea salt aerosols to increase the lifetime and reflectivity of low-altitude clouds.

We must make deep cuts in global emissions of carbon dioxide to manage the risks of climate change. While emissions reductions are necessary, they are not necessarily sufficient. Emission cuts alone may be insufficient because even if we could halt all carbon emissions today, the climate risks they pose would persist for millennia—by some measures, the climate impact of carbon emissions persists longer than nuclear waste. Moreover, the climatic response to elevated carbon dioxide concentration is uncertain, so a small risk of catastrophic impacts exists even at today's concentration.

Technologies for decarbonizing the energy system, from solar or nuclear power to the capture of CO_2 from the flue gases of coal-fired power plants, can cut emissions—allowing us to limit our future commitment to warming—but they cannot reduce the climate risk posed by the carbon we have already added to the air, and that risk grows as each ton of emissions drive up the atmospheric carbon burden.

Risk management is at the heart of climate policy: planning our response around our current estimate of the most likely outcome is reckless. We must hope for the best while laying plans to navigate the worst.

SRM and CDR do different things. SRM is cheap and can act quickly to cool the planet, but it introduces novel environmental and security risks and can—at best—only partially mask the environmental impacts of elevated carbon dioxide.

In concert with emissions cuts, CDR technologies can reduce the carbon burden in the atmosphere; one might call it global climate remediation. We need a means to reduce atmospheric CO_2 concentrations in order to manage the long-run risks of climate change. Unless we can remove CO_2 from the air faster than nature does, we will consign the earth to a warmer future for millennia or commit ourselves to the risks of sustained SRM.

But, carbon removal can only make a difference if we capture carbon by the gigaton. The shear scale of the carbon challenge means that CDR will always be relatively slow and expensive.

SRM and CDR each provide a means to manage climate risks; they are, however, wholly distinct with respect to

the science and technology required to develop, test and deploy them;

their costs and environmental risks; and,

the challenges they pose for public policy and governance.

Because these technologies have little in common, I suggest that we will have a better chance to craft sensible policy if we treat them separately.

In the spirit of disclosure, I offer a few comments about my own work. I run Carbon Engineering, a startup company that aims to develop industrial scale technologies for capturing CO_2 from the air. I will be happy to answer questions about these technologies, but I will focus my remarks on SRM because I believe that is where there is the most urgent need for action that links the development of a research program to progress on learning how to manage this potentially dangerous technology.

Because of the serious and legitimate concerns raised by the enormous leverage SRM technologies grant us over the global climate, I think it is crucial that development of these technologies be managed in a way that is as transparent as possible. I therefore do no commercial or proprietary work on SRM.

The primary argument against research on SRM is fear that it will reduce the political will to lower greenhouse gas emissions. I believe that the risks of not doing research outweigh the risks of doing it. Solar-radiation management may be the only response that can fend off unlikely but rapid and high-consequence climate impacts. Further, there are environmental and geopolitical risks posed by the potential of unilateral deployment of SRM, which can best be managed by developing widely-shared knowledge, risk assessment, and norms of governance.

The idea of deliberately manipulating the Earth's energy balance to offset human-driven climate change strikes many as dangerous hubris. It is a healthy sign that a common first response to geoengineering is revulsion. It suggests we have learned something from past instances of over-eager technological optimism and subsequent failures. But we must also avoid over-interpreting this past experience. Responsible management of climate risks requires sharp emissions cuts and clear-eyed research and assessment of SRM capability. The two are not in opposition. We are currently doing neither; action is urgently needed on both.

An overview of solar radiation management

SRM has three essential characteristics: it is cheap, fast, and imperfect. Long-established estimates show that SRM could offset this century's global-average temperature rise a few hundred times more cheaply than achieving the same cooling by emission cuts. This is because such a tiny mass is required: a few grams of sulfate particles in the stratosphere can offset the radiative forcing of a ton of atmospheric carbon dioxide. At a few $1000 a ton for aerosol delivery to the stratosphere that adds up to a figure in the order of $10 billion dollars per year to provide a cooling that—however crudely—counteracts the heating from a doubling of atmospheric carbon dioxide.

This low price tag is attractive, but raises the risks of single groups acting alone and of facile cheerleading that promotes exclusive reliance on SRM.

SRM can alter the global climate within months—as shown by the 1991 eruption of Mt. Pinatubo, which cooled the globe about 0.5° C in less than a year. In contrast, because of the carbon cycle's inertia, even a massive program of emission cuts or carbon dioxide removal will take many decades to discernibly slow global warming.

A world cooled by managing sunlight will not be the same as one cooled by lowering emissions. An SRM-cooled world would have less precipitation and less evaporation. Some areas would be more protected from temperature changes than others, creating local winners and losers. SRM could weaken monsoon rains and winds. It would not combat ocean acidification or other carbon dioxide-driven ecosystem changes and would introduce other environmental risks such as delaying the recovery of the ozone hole. Initial studies suggest that known risks are small, but the possibility of unanticipated risks remains a serious underlying concern.

Cheap, fast and imperfect: each of these essential characteristics has profound implications for public policy.

Because SRM is imperfect, it cannot replace emissions cuts. If we let emissions grow and rely solely on SRM to limit warming, these problems will eventually grow to pose risks comparable to the risks of uncontrolled emissions.

Because SRM is cheap, even a small county could act alone, a fact that poses hard and novel challenges for international security.

Finally, because SRM appears to be the only fast-acting method of slowing global warming it may be a powerful tool to manage the risks of unexpectedly dangerous climate outcomes.

Towards Solar Radiation Management research plan

The capacity to implement SRM cannot simply be assumed. It must be developed, tested, and assessed. Research to date has largely consisted of a handful of climate model studies, using very simple parameterization of aerosol microphysics. More complex models of aerosol physics need to be developed and linked to global climate models. Field tests will be needed, such as experiments generating and tracking stratospheric aerosols to block sunlight and dispersing sea-salt aerosols to brighten marine clouds. Decades of upper atmosphere research has produced a mass of relevant science. But, except for a recent ill-conceived Russian test, there have been no field tests of SRM.

There has been no dedicated government research funding available for SRM anywhere in the world; though, a few programs for have begun in Europe in the past few months.

The environmental hazards of SRM cannot be assessed without knowing the specific techniques that might be used, and it is impossible to identify and develop techniques without field testing. Such tests can be small: tonnes not megatonnes.

It is widely assumed, for example, that a suitable distribution of stratospheric sulfate aerosols can be produced by releasing SO_2 in the stratosphere, but new simulations of aerosol micro-physics suggest the resultant aerosol size distribution would be skewed to large particles that are relatively ineffective. Several aerosol compositions and delivery methods may offer a way around this problem, but choosing between them and assessing their environmental impacts will require small-scale insitu testing.

To provide a specific example related to my own work, NASA's ER–2 high-altitude research plane might be used to release a ton of sulfuric acid vapor along a 10 km plume in the stratosphere, and fly through the plume to assess the formation of aerosol and its sun scattering ability and its impact on ozone chemistry. Such tests take a few years to plan and cost a few million dollars.

An international research budget growing from roughly $10 million to $1 billion annually over this decade would likely be sufficient to build the capability to deploy SRM and greatly improve understanding of its risks.

It is important to start slowly. Research programs can fail if they get too much money too quickly. Given the limited scientific community now knowledgeable about SRM, a very rapid buildup of research funding might result in a lot of ill-conceived projects being funded and, given the inherently controversial nature of the technology, the result might be a backlash that effectively ends systematic research.

The U.S. will need an interagency research program, because no single agency has the right combination of abilities to manage the whole program. For example, NSF's processes for transparent peer-review and investigator driven funding will be important in effectively supporting the diversity of critical analysis that is necessary on such an inherently controversial topic. But NSF is perhaps less suited to manage the larger mission oriented programs that link technology development and science.

NASA has some institutional history and abilities that may be particularly relevant to stratospheric SRM. The high-speed research program, for example, linked scientific efforts to understand the impacts a supersonic transport fleet on the ozone layer with technology development aimed to minimize those impacts. The management and research assets used in this program could serve as the foundation of a program to develop and test technologies for delivering stratospheric aerosols. But NASA is less suited to fostering diverse early-stage science.

DOE's Office of Science has a record managing large programs and DOE has a relevant track record with its Atmospheric Radiation Measurement (ARM) program. But SRM is not at its core an energy problem and there will be difficulties fitting it into the DOE structure.

Finally, the inherently controversial nature of SRM research makes it particularly important that it not be entrusted exclusively to either its proponents or its adversaries. The development of an interagency program may help to foster the necessary diversity. Indeed, there may be value in a "blue team/red team" approach, as sometimes used for military preparedness planning. One team is charged to make an approach as effective and low-risk as possible, while the other works to identify all the ways it can fail. Anticipating the conditions of urgency, even panic, that might attend a future decision to deploy SRM, such an adversarial approach may increase the quality and utility of information available in time to aid future decision-makers.

Concluding thoughts

Although risk of climate emergencies may motivate SRM research, it would be reckless to conduct the first large-scale SRM tests in an emergency. Instead, experiments should expand gradually to scales big enough to produce barely detectable climate effects and reveal unexpected problems, yet small enough to limit resultant risks. Our ability to detect the climatic response to SRM grows with the test's duration, so starting sooner makes the scale of experiment needed to give detectable results by any future date-say by 2030-smaller. A later start delays when results are known, or requires a bigger intervention in order to detect the response.

Beyond research, building responsibly toward future SRM capability also requires surmounting problems of international governance that are hard, and novel. These are quite unlike the problems of emissions mitigation, where the main governance challenge is motivating contributions to a costly shared goal. For SRM, the main problem will be establishing legitimate collective control over an activity that some might seek to do unilaterally. Such a unilateral challenge could arise in many forms and from many quarters. At one extreme, a state might simply decide that avoiding climate-change impacts on its people takes precedence over environmental concerns of SRM and begin injecting sulfur into the stratosphere, with no prior risk assessment or international consultation. If this were a small state, it could be quickly stopped by great-power intervention. If it were a major state, that might not be possible.

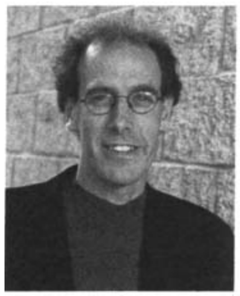
Alternatively a nation might grow frustrated at the pace of international cooperation and establish a national program of gradually expanding research and field tests. This might be linked to a distinguished international advisory board, including leading scientists and retired politicians of global stature. It is plausible that, after exhausting other avenues to limit climate risks, such a nation might decide to begin a gradual, well-monitored program of SRM deployment, even absent any international agreement on its regulation. In this case, one nation—which need not be a large and rich industrialized country—would effectively seize the initiative on global climate, making it extremely difficult for other powers to restrain it.

No existing treaty or institution is well suited to SRM governance. Given current uncertainties immediate negotiation of a treaty is probably not advisable. Hasty pursuit of international regulation would risk locking in commitments that might soon be seen as wrong-headed, such as a total ban on research or testing, or burdensome vetting of even innocuous research projects.

A better approach would be to build international cooperation and norms from the bottom up, as knowledge and experience develop—as has occurred in cases as diverse as the development of technical standards for communications technology to the landmine treaty which emerged bottom-up from action by NGOs. A first step might be a transparent, loosely-coordinated international program supporting research and risk assessments by multiple independent teams. Simultaneously, informal consultations on risk assessment, acceptability, regulation, and governance could engage broad groups of experts and stakeholders such as former government officials and NGO leaders. Iterative links between emerging governance and ongoing scientific and technical research would be the core of this bottom-up approach.

Opinions about SRM are changing rapidly. Only a few years ago, many scientists opposed open discussion of the topic. Many now support model-based research, but discussion of field testing of the sort we advocate here is contentious and will likely grow more so. The main argument against SRM research is that it would undermine already-inadequate resolve to cut emissions. I am keenly aware of this 'moral hazard'—indeed I introduced the term into the geoengineering literature—but I am skeptical that suppressing SRM research would in fact raise commitment to mitigation. Indeed, with the possibility of SRM now widely recognized, failing to subject it to serious research and risk assessment may well pose the greater threat to mitigation efforts, by allowing implicit reliance on SRM without critical scrutiny of its actual requirements, limitations, and risks. If SRM proves to be unworkable or poses unacceptable risks, the sooner we know the less moral hazard it poses; if it is effective, we gain a useful additional tool to limit climate damages.

BIOGRAPHY FOR DAVID KEITH



David Keith

Director, ISEEE Energy and Environmental Systems Group

Canada Research Chair in Energy and the Environment

Professor, Department of Chemical and Petroleum Engineering and Department of Economics, University of Calgary,

Adjunct Professor, Department of Engineering and Public Policy, Carnegie Mellon

See www.ucalgary.ca/~keith for research project summaries, publications, and a full CV.

Professor Keith has worked near the interface between climate science, energy technology and public policy for 20 years. His work in technology and policy assessment has centered on the capture and storage of CO_2. the technology and implications of global climate engineering, the economics and climatic impacts of large-scale wind power and the prospects for hydrogen fuel. As a technologist, David has built a high-accuracy infrared spectrometer for NASA's ER–2 and developed new methods for reservoir engineering increase the safety of stored CO_2. He now leads a team of engineers developing technology to capture of CO_2 from ambient air at an industrial scale.

David took first prize in Canada's national physics prize exam, he won MIT's prize for excellence in experimental physics, was listed as one of *TIME* magazine's Heroes of the Environment 2009 and was named Environmental Scientist of the Year by *Canadian Geographic* in 2006. He spent most of his career in the United States at Harvard University and Carnegie Mellon University before returning to Canada in 2004 to lead a research group in energy and environmental systems at the University of Calgary.

David has served on numerous high-profile advisory panels such as the U.K. Royal Society's geoengineering study, the IPCC, and Canadian 'blue ribbon' panels and boards. David has addressed technical audiences with articles in Science and Nature, he has consulted for national governments, global industry leaders and international environmental groups, and has reached the public through venues such as the BBC, NPR, CNN and the editorial page of the *New York Times*.

Chairman BAIRD. Thank you, Dr. Keith.

Dr. Rasch.

STATEMENTS OF DR. PHILIP RASCH, CHIEF SCIENTIST FOR CLIMATE SCIENCE, LABORATORY FELLOW, ATMOSPHERIC SCIENCES AND GLOBAL CHANGE DIVISION, PACIFIC NORTHWEST NATIONAL LABORATORY

Dr. RASCH. Thank you, Chairman Baird and the Subcommittee, for inviting me today.

I think I will start by just reminding you of what solar radiation management is. Scientists tend to loosely refer to light or heat or energy as radiation, and so when we speak of solar radiation management, we really mean managing the amount of sunlight reaching the surface of the earth. If we can reflect a little bit more sunlight back to space, then we will cool the planet.

Before jumping into some of the scientific issues, I am going to speak just for a second on funding issues. If you look at my assessment of funding in the written testimony, you will see that I think that the total grants from U.S. agencies today for geoengineering research amounts to about $200,000 a year. If you add in some invisible funding that comes from faculty members or scientists like myself donating their time, it might double. If you add in foundation money, it might come to a million dollars a year. If you contrast this with the kind of program like the Apollo program to put a man on the moon of $2 billion per year or total up all the climate research today of $1 billion per year, then you can see we are currently putting a tiny, tiny amount in, and maybe that is the right thing to do. That is really for policymakers like you to help us decide. But if you think it is important to do geoengineering research, then it would be very easy to make a big difference with a relatively small amount of money.

You asked me to talk about the solar radiation management techniques known as stratospheric sulfate aerosols and cloud whitening. I have worked in both of these areas. Scientists are interested in these two ideas because we already know they play a role in the real world. We see that when volcanoes produce sulfate aerosols high in the atmosphere, the planet cools. We see that when ships inject aerosols as pollution into clouds, that those clouds become whiter and reflect more sunlight—some of those clouds do—which should cool the planet a bit. We think we might be able to do the same kind of thing deliberately. In climate models when we brighten the clouds, we see that the planet cools. When we inject an aerosol like volcanoes do, we see that the planet cools. That is the good news, but that statement is far too simple. There are also undesirable things that happen. We see that even though we might make the average temperature of the planet about right, the rainfall patterns would change some from today, and some places become warmer and some places become cooler.

So there are going to be winners and losers in this geoengineering activity if we were to do it. But nevertheless, as David has said, there are reasons why we might consider doing it. We know that the models that we are using today are far too simple and incomplete. We know how to do better. There are many outstanding unresolved important issues that need to be addressed if one wants to understand geoengineering better. I have made some suggestions in my written testimony about ways we might use funding to strengthen the activity involving computer modeling, technology development, and lab and field research. There are a bunch of first-class research scientists and engineers in the United States and Europe now working for free in their spare time to think about this, but there are some things that take money to solve, and a much better job could be done if there was a funded program for geoengineering.

All the work that I have suggested doing essentially comes down to focusing on two questions: Can we actually create particles in the stratosphere or whiten clouds as we assumed in our first climate studies? We need technology development and we need fundamental research to understand this.

Then the second part would be: What would be the impact on climate if we did put the particles into the stratosphere or whiten clouds? This involves deployment, actually, at some level. I think I have to skip over, in the interest of time, my discussions of some of the subtleties of the ways we could focus on the cloud whitening or the stratospheric aerosols, but I would be glad to take questions about it.

You also asked me to address deployment issues. I feel very strongly we are not ready for deployment, if by deployment you mean trying to affect the climate. There are too many things that haven't been looked at yet, but there is a lot we can do with fieldwork that will help us understand geoengineering but won't change the climate. For the cloud whitening strategy, field and modeling studies would help us understand a critical feature of the climate system called the aerosol indirect effect, which is really critical for understanding climate change more generally as well. I don't have the time to talk to you about this now but I would love to address it if you ask me questions.

I think that if we managed to tighten up our work to the point that we think a geoengineering strategy looks viable, it would probably require a Manhattan Project, looking at it with a much larger group of stakeholders, checking the science, searching for flaws in our initial work and worrying about issues far beyond the scope of physical scientists.

Thanks for listening to me and I am happy to take questions.

[The prepared statement of Dr. Rasch follows:]

PREPARED STATEMENT OF PHILIP RASCH

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

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

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

Note that even if Solar Radiation Management succeeds, it will not cancel all the effects of increasing greenhouse gas concentrations. The increasing acidity of the oceans with its impact on ocean life is a good example of a consequence of increasing CO_2 that will not be treated by Solar Radiation Management.

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

Preliminary Remarks on Geoengineering Research Goals and Expected Outcomes: There are many uncertainties in geoengineering research. Identifying the consequences of geoengineering to the climate of the planet is at least as difficult as identifying the changes to the planet that will occur from increasing greenhouse gases. Just as scientists cannot be certain of all of the consequences of doubling (or more) the concentration of CO_2 to the planet, we cannot be certain of the outcome of any particular strategy for geoengineering the planet to counter that warming. What science can do is use the same tools and body of knowledge to identify likely outcomes from either class of perturbations to the planet.

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

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

- **Assessment, Integration:** to brainstorm, review suggested strategies, and identify obviously unsuitable suggestions. Only a little work has been done to evaluate proposed strategies for efficacy and costs (e.g. Royal Society report, 2009 and Lenton and Vaughan, 2009).
- **Computer Modeling:** There are a variety of kinds of modeling studies that are relevant to geoengineering.
    - Climate models and Earth system models are needed that provide a global view about interactions between many parts of the climate system over time scales as long a centuries.
    - "Process Models" that include a lot of detail about one specific feature of the Earth system are also needed. These kinds of models might describe how for example cloud drops might form, but they neglect anything that isn't central to that understanding, like what the rainfall was a thousand miles away. They do calculations that are generally far too expensive to be used for a global computer calculation but they are incredibly useful for understanding how a particular process operates. Science frequently uses global models to produce a broad view of geoengineering outcomes, but for those strategies that look promising, increasingly stringent levels of analysis are required to see whether the simple assumptions used in a climate model hold up. Process models are used to understand important details.
    - Other models may also be needed for a broader set of questions (for example the impact of geoengineering on ecosystems or the economy).
- **Lab and Fieldwork:** Lab and fieldwork are critical to assure a thorough understanding of the fundamental physical process important to climate and that computer models are reasonably accurate in representing that process. I think it is critical to distinguish between "small scale field studies" where we might introduce some particles into the atmosphere over such a small scale that they would have negligible climate impact, and "full scale deployment" where we expect to actually have a climate impact. *Field studies might try to induce a deliberate change to some feature of the earth system at a level with a negligible impact on the climate, but the change would allow us to detect a response in a component important to climate.* For example, with Cloud Whitening one might try to modify a cloud, or a group of clouds by introducing a change over a very small area, over and over again for a month, to see whether we really understand how that kind of cloud works, and whether models can reproduce what we see in the real world. With Stratospheric Aerosols one might envision devoting a few aircraft to trying to deliver the material needed to make aerosol particles in the stratosphere, and then look to see whether the right size particles form, and how long they last.
- **Technology Development:** to develop equipment and measurement strategies that might be used for process studies, for exploratory trials, or as prototypes for full deployment. Some work has been done to develop plans for the devices needed for the cloud whitening strategy, and the ships that could deploy the sea salt particles.
- **Deployment Activities:** Obviously, one can envision a gradation of experiments to the climate, ranging from those with no impact, to those having a

huge impact. **I am going to reserve the word "deployment" to refer to geoengineering designed to have a big impact on climate. I don't think scientists know enough today about geoengineering, and so I don't think we are ready for "deployment". I am going to avoid much discussion of full deployment scenarios for the rest of my testimony except to tell you what a climate model says might happen, and to acknowledge that when and if we think we understand geoengineering well enough to deploy it we must consider many new issues.** Monitoring, infrastructure, energy consumption, economic modeling, governance, and much else are needed if we reach a stage where deployment is viable.

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

In my opinion before a nation (or the world) ever decided to deploy a full scale geoengineering project to try to compensate for warming by greenhouse gases it would require an enormous activity, equivalent to that presently occurring within the modeling and assessment activities associated with the Intergovernmental Panel on Climate Change (IPCC) activity, or a Manhattan Project, or both. It would involve hundreds or thousands of scientists and engineers and require the involvement of politicians, ethicists, social scientists, and possibly the military. These issues are outside of my area of expertise. Early "back of the envelope" calculations estimated costs of a few billion dollars per year for full deployment of a stratospheric aerosol strategy (see for example, Crutzen, (2006) or Robock et al (2009b)). These numbers are very rough. I am not sure it is worth refining them much at this time, due to the many uncertainties that need to be resolved by exploratory research.

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

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

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

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

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

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

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

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

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

Now, on to your questions.

How does stratospheric sulfate aerosol achieve the necessary radiative forcing?

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

The geoengineering idea is to inject a "source" for aerosols into the same region of the atmosphere that volcanoes tend to inject the gas. I use the word "source" to refer to either a gas like sulfur dioxide (or another gas that will eventually react chemically and form sulfate aerosols), or to inject sulfuric acid (or some other particle type) directly. The expectation is that similar particles to those following a volcanic eruption will form from that source, and the earth will undergo a cooling similar to a volcano. The idea is to reduce the amount of energy reaching the surface of the earth to introduce just enough to balance the warming caused by increases in greenhouse gases. If the particles were like those that formed after Pinatubo we think that an amount like one quarter of that injected by Pinatubo per year would balance the warming that we expect from a doubling of CO_2 concentrations if it were injected at tropical latitudes. These numbers might change if the aerosols were injected in Polar Regions.

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

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

Over what time period would deployment need to take place?

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

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

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

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

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

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

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

1. **Assessment, Integration:** As mentioned above, the papers by Lenton and Vaughan (2008), and the report of the Royal Society (citation) provide some assessments of this strategy compared to others. Those studies are already somewhat out of date, given the additional information from studies over the last two years.
2. **Modeling:** A number of papers have appeared in the scientific literature exploring consequences of geoengineering with stratospheric aerosols using global models. These studies essentially frame the questions by assuming that it is possible to deliver a source gas to the stratosphere, and that gas will produce particles similar to the ones produced after the Mount Pinatubo eruption. Then they proceed to ask questions like "What would be the effect

of those aerosols on the Earth System?" using standard climate modeling techniques. The community is beginning to transition from the first "quick and dirty look" (e.g. Robock et al, 2008; Rasch et al, 2008). Each modeling group that explored stratospheric aerosol geoengineering did it a different way. Alan Robock has proposed that modeling groups try to compare their stratospheric aerosol geoengineering studies in a more systematic for the next IPCC assessment. Only one group (Heckendorn) has tried to understand the details of formation and aerosol size evolution, and they used a model framework with a number of very significant simplifications. It would be desirable to remove those simplifications. It is also time to begin assessing the evolution of the source of the aerosol from the time it is delivered from an aircraft until it spreads to a larger volume (like a few hundred km). Rasch et al (2008) revisited research performed during the 1970s and 1980s to estimate the aerosol formation and evolution after the source is released from an aircraft.

3. **Lab and Field Studies**: I am not aware of any efforts to conduct or plan lab or field studies to understand component processes important for this kind of geoengineering.
4. **Technology development:** I am not aware of any efforts to assess or develop technologies for producing the stratospheric aerosols.
5. **Deployment:** There has been one study that tried to assess the cost of just lifting various candidate compounds to the needed altitude using existing technology (Robock et al, 2009). There have been no studies yet published that explore what the optimal source gas or liquid is, how it should be injected into the atmosphere, or how to optimally deliver it. I know that David Keith, who is also testifying here, has thought about this, and he can do a better job briefing you on this activity than I.

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

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

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

1) **Research:** There are many opportunities for research. Here are a few ideas.

Detailed Models

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

Global Models

a. Global models indicate a number of positive and negative consequences to the planet from geoengineering. The first "quick and dirty" calculations described above produced different cooling responses, and different precipitation responses in different models. We don't yet know whether the differences are due to model differences, or different assumptions about emissions, particle size, etc. It would be good to systematize studies of geoengineering across multiple models to help in assessing uncertainty about the effect of geoengineering.

b. We need to make sure that the global models are producing similar pictures of aerosol formation, coalescence and removal to the picture provided by the detailed process models.

c. Very little work has been done in exploring sensitivity to injection scenarios. For example we don't know whether the geoengineering may have a different impact if we produce the aerosol at a constant rate over a year, or mimic a volcanic injection every other year.

d. There has been no assessment of the impact of the geoengineering aerosol on homogeneous nucleation of ice clouds

e. There has been no exploration of how changes in how geoengineering might affect ecosystems (plants and animal health)

2) **Field testing and Deployment**

a. How do we deliver the source to the region of release? A variety of delivery mechanisms have been proposed, but none have been tested, and no engineering details have ever been developed to the point that costs could be assessed.

b. Once we have a detailed idea of precisely what source we want, can we produce that source?

c. Plan an exploratory field experiment to help understand the formation and evolution of the particles for the first few weeks. After injecting the source in the stratosphere do particles form as models suggest? How do we track the plume? What instruments are required to measure the particle properties, the plume extent, and the reduction in sunlight below the plume. Do the particles coagulate and grow as our models suggest? Do the particles mix and evolve the way our models tell us they will (from source to the first scale, and from the first scale to the globe scale?).

3) **Monitoring**: We don't have much capability of monitoring the details of sulfate aerosol from space any more (we had better capability in the past before the NASA SAGE instrument died). This issue is documented in some of the contributions submitted by Allen Robock in the previous hearing. It would also be good to develop a "standing task force" that was capable of monitoring the detailed evolution of the aerosol plume following a volcanic eruption. This would allow us to gain significant understanding of plume evolution without the need to produce a source for the aerosol.

4) **Downscaling, cessation, environmental remediation.**

a. The only insight that we have about impacts of the geoengineering by sulfate aerosols come from that gained from the global climate model studies, and seeing the impact of climate changing volcanic eruptions. Both classes of studies suggest that if the source for stratospheric aerosols was turned off, the aerosols go away within a year or two, and the climate returns to a state much like it was before the stratospheric aerosols over a decade or so. The rapid return of temperature to the ungeoengineered state would probably produce significant stresses to society, and ecosystems, but no studies have been done to explore this.

5) **Environmental Impact:** There are a variety of possible environmental consequences, which have been described in the studies by Rasch and Robock submitted at the last hearing. Among them are a) changes in the ratio of direct to diffuse sunlight, with possible impacts on ecosystem, and solar electricity generation; b) changes in precipitation patterns; c) changes in El Niño.

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

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

How does marine cloud whitening achieve the necessary radiative forcing?

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

Clouds are enormously important to the climate of the earth. Everyone has experienced the cooling that results on a hot summer afternoon when a cloud goes by overhead and shades the earth. This occurs because the cloud reflects the sunlight that would otherwise reach the surface and heat up the ground. Clear winter nights will frequently be much colder than a nearby night when the sky is overcast. This is because high clouds "trap" heat that would otherwise escape to space. So it is warmer when high ice clouds are around.

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

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

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

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

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

The whitening phenomenon is believed to occur in many cloud systems, but the effect may be most important in marine clouds near the Earth's surface. Also clouds generally become more important in reflecting sunlight over oceans because the ocean surface reflects less sunlight than the land or snow even without clouds, so putting a bright cloud over oceans cools the Earth more than if you put the same bright cloud over already bright land or ice.

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

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

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

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

Scale and amount of materials needed: Latham et al (2008) and Salter et al (2008) have estimate that the total amount of aerosol that needs to be pumped into that atmosphere is about 30 m3 per second. They estimate that it might require X ships deployed over a large area (perhaps as much as 30% of the ocean surface) to distribute that sea.

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

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

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

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

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

If changing the cloud forcing was effective and it was ramped up to the point that it is influencing the climate then other issues must be considered. It ends up that the local changes in cooling patterns are likely to set up stronger responses in weather and ocean currents than the broader and weaker patterns seen with the stratospheric aerosols. Also, it is the case that the clouds that are believed to be most easily influenced by the cloud whitening reside in the subtropics, so the reduction in the amount of sunlight reaching the surface will tend to be strongest in those regions. Since the atmosphere and ocean distribute the heating and cooling through winds and currents the effect will eventually be distributed over the globe, but the difference in the weather or precipitation for example may still be more evident in the cloud whitening than the stratospheric aerosol strategy.

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

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

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

1. **Assessment, Integration:** The report of the Royal Society (2009) provides some assessments of this strategy compared to others.
2. **Modeling:**

Global Models

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

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

Process Models

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

3. **Lab and Field Studies:** No recent field studies have been done with cloud whitening. In 2008 a field experiment called VOCALS took place to study clouds and cloud aerosols interactions off the coast of Peru and Chile. This field experiment had no geoengineering component to it but the clouds systems in that region are of the type relevant to geoengineering, and the range of techniques and measurement strategies involved were very similar to those required for a limited-area field test of cloud whitening, and it could be used to estimate costs for limited field testing. There have been earlier field studies to measure cloud changes following ship tracks (for example, MAST, the Monterey Ship Track experiment), and I believe another similar study is being planned by B. Albrecht and J. Seinfeld.

4. **Technology Development:** Some exploratory work in developing spray generators to produce the appropriately sized sea salt particles for seeding the clouds has been done in two groups, one led by Armand Neukermans in California, and another led by Dan Hirleman at Purdue.

5. **Deployment:** I don't think we are ready to address this issue

6. **Interactions with other communities:** I don't have the expertise to provide guidance on this issue, but I am interested.

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

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

- Phase 1: Using Models, and extremely limited field experiments where there is no chance of significantly effecting to the climate to determine whether it is actually possible to whiten clouds in a predictable, controlled manner. Are there changes to other cloud properties (for example, cloud precipitation, cloud height, cloud thickness)
- Phase 2: Enlarge the scope of the geoengineering research and consider the consequences if we were to whiten cloud for long enough that it might actually make a difference to local climate. Look at the consequences to the local environment on short time scales (like less than a week). These consequence might matter to people, but they would be small compared to the kind of ways we already perturb the climate system (like the forest fires in Borneo, a Pinatubo, etc)
- Phase 3: Full scale deployment.

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

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

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

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

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

1. **Theoretical Research and Technology development:**

Process Models

a. The first studies by Wang (2009) using "Large Eddy Simulation" model for ship track research should be extended to explore the problem from a geoengineering point of view. Investigators could be tasked with exploring how to optimize the injection of the aerosols (how many ships per cloud region, whether it makes a difference if the cloud system has already formed or is expected to form soon, sensitivity to diurnal cycle of boundary layer clouds, sensitivity to levels of background aerosol (pollution levels). This would require simulations over larger domain, longer time frames, different cloud regimes, perhaps with more complex formulations of cloud and aerosol microphysics.

b. Very high resolution modeling studies should be performed of the evolution of the aerosol particles as they are emitted from the seed generator until they enter a cloud.

Global Models

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

Technology Development

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

2. **Deployment:** The knowledge and technology are not yet at a stage where deployment should be considered. The research program will change completely if research indicates it is possible to whiten clouds in a controllable and reproducible way.

3. **Monitoring:** During the first phase, while trying to establish whether cloud whitening is viable; monitoring should be consider part of the field campaign. The picture will change completely if deployment becomes viable and much more work is required to scope out a monitoring activity.

4. **Downscaling, cessation, environmental remediation.**

   a. During phase 1 there should be no impact on the climate.

   b. If a geoengineering solution were to be deployed, The only guidance we would have on this is research from global climate models. There are no analogues that come to mind in nature for cessation of geoengineering by cloud whitening. My suspicion is that climate models would show a recovery quite similar to that discussed in the section on stratospheric aerosols. This kind of study should be performed.

5. **Environmental Impact:** Because geoengineering has the potential for affecting precipitation patterns, and major circulation features like ENSO and monsoons, there are many ways in which it can have an environmental impact, with consequences to society and ecosystems. This issue will be very important in a "Manhattan" level activity if phase 1 research ever succeeds and deployment is seriously considered.

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

Closing Remarks:

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

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

1. I recognize that geoengineering is a very controversial and complex subject, and that there are many issues associated with it of concern to scientists and society. It can, for example, be viewed as a distraction, or an excuse to avoid dealing with greenhouse gas emissions. Scientists interested in geoengineering want to be responsible and transparent. We care about doing the science right, and in a responsible way. We believe that our energy system transformation is proceeding too slowly to avoid the risk of dangerous climate change from greenhouse gases, and that there has been little societal response to the scientific consensus that reductions must take place soon to avoid the risk of large and undesirable impacts.
2. Geoengineering should be viewed as a choice of last resort, It is much safer for the planet to reduce greenhouse gas emissions. Geoengineering would be a gamble. Just as there are many uncertainties associated with predicting the kind of changes to our climate from increasing greenhouse gases, there will be similar uncertainties to predicting the changes from geoengineering.
3. Current Climate models indicate that geoengineering would cool the planet and compensate for some, but not all of the consequences of increased greenhouse gases.
4. I don't think scientists know enough today about consequences of geoengineering to climate, and so I don't think we are ready for "deployment". Before anyone should consider full-scale deployment of a geoengineering strategy, lots of basic work (what I call phase 1 research) could be done to lay the groundwork for deployment. The basic work will help in eliminating unsuitable strategies, in identifying important issues to hone in on, to help us revise strategies to make them more suitable for deployment, and in some cases could help in revealing fundamental information critical for understanding climate change (I am thinking about information about the "Aerosol Indirect Effect" when I refer to the issue of critical understanding).
5. Right now, less than $1 million per year is spent on geoengineering research in the US. A viable research activity with a chance of making rapid, solid progress including field studies would probably require $20–40 million per year for either program.
6. I believe that if phase 1 research does come up with a promising strategy for geoengineering, and deployment is seriously considered, that the level of scrutiny and level of funding must increase very sharply to a level similar to that of a "Manhattan Project". Such a project would need to consider many issues beyond the physical sciences.

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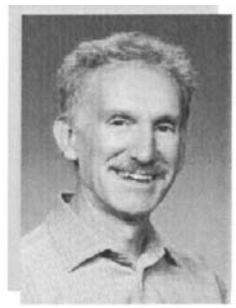
BIOGRAPHY FOR PHILIP RASCH



Dr. Philip Rasch serves as the Chief Scientist for Climate Science at the Pacific Northwest National Laboratory (PNNL), a Department of Energy Office of Science research laboratory. In his advisory role, he provides leadership and direction to PNNL's Atmospheric Sciences and Global Change (ASGC) Division. The Division conducts research on the long-term impact of human activities on climate and natural resources using a research strategy that starts with measurements and carries that information into models, with a goal of improving the nation's ability to predict climate change.

Dr. Rasch provides oversight to more than 90 researchers who lead and contribute to programs within a number of government agencies and industry. These programs focus on climate, aerosol and cloud physics; global and regional scale modeling; integrated assessment of global change; and complex regional meteorology and chemistry.

Dr. Rasch received a Bachelor Degree in Atmospheric Science and another in Chemistry from the University of Washington in 1976. He then moved to Florida State University for a Master of Science in Meteorology. He went to the National Center for Atmospheric Research (NCAR) in Boulder, Colorado as an Advanced Study Program (ASP) Graduate Fellow to complete his PhD (which was also awarded from Florida State University). Following his PhD, Rasch remained at NCAR, first as ASP Postdoctoral Fellow, and then as a scientist where he worked in various positions. He joined PNNL in 2008. Rasch also holds an adjunct position at the University of Colorado and is an Affiliate Professor in the Department of Atmospheric Science at the University of Washington.

Dr. Rasch is internationally known for his work in general circulation, atmospheric chemistry, and climate modeling. He is particularly interested in the role of aerosols and clouds in the atmosphere, and has worked on the processes that describe these components of the atmosphere, the computational details that are needed to describe them in computer models, and on their impact on climate. For the last five years, he helped to lead the technical development team for the next generation of the atmospheric component of the Community Climate System Model Project, one of the major climate modeling activities in the United States. He also studies geoengineering, or the intentional manipulation of the atmosphere to counteract global warming.

Dr. Rasch was a chair of the International Global Atmospheric Chemistry Program (IGAC, 20042008), and participates on the steering and scientific committees of a number of international scientific bodies. He was named a fellow of the American Association for the Advancement of Science, recognized for his contributions to climate modeling and connecting cloud formation, atmospheric chemistry and climate. He has contributed to scientific assessments for the World Meteorological Organization, NASA and the Intergovernmental Panel on Climate Change.

Chairman BAIRD. Thank you, Dr. Rasch.

Dr. Lackner.

STATEMENTS OF DR. KLAUS LACKNER, DEPARTMENT CHAIR, EARTH AND ENVIRONMENTAL ENGINEERING, EWING WORZEL PROFESSOR OF GEOPHYSICS, COLUMBIA UNIVERSITY

Dr. LACKNER. Chairman Baird, Mr. Inglis, Members of the Committee, thank you for inviting me. I am delighted to be here. It is a great honor.

I was a little bit puzzled though to start with why I would think of this, what I do, air capture and mineral sequestration as geoengineering. But then I started on reflection to think well, we have to stabilize the CO_2 in the atmosphere against 30 billion tons or more in the future of CO_2 emissions. That, by anybody's scale, would be considered geoengineering, and in my view, we will have to stabilize carbon dioxide in the atmosphere sooner or later, and it doesn't really matter whether we manage to do it right away or whether we fail and it takes a longer time and we stabilize at a higher level. As we reach stabilization, we have to balance out all emissions. We have to go to a net zero carbon economy, and I focus on capture and storage—these are capture and storage options—because I firmly believe that we have to solve the problem directly and not just mask the symptoms. We may have to do that for a short time but ultimately one has to solve the problem, which means managing that all the carbon which goes out is balanced against something else.

That means in turn we need comprehensive solutions for carbon capture and storage, and I would put air capture and mineral sequestration into that larger category. I would argue that carbon capture and storage has to be more comprehensive than just power plants, and we have to have the ability to store carbon anywhere and at the requisite scale because we have the ability to put out one or two Lake Michigans in terms of mass of CO_2 over the next century. We better find a way to put all of this away, and this is where in my view mineral sequestration comes in as an important part.

Let me begin briefly with the air capture and storage, and I would argue what makes this so nice is it separates the sources from the sinks. One of the side effects is, you will actually get a group of players who want to solve the problem and not just get dragged in because they must solve the problem. I think that is important, but most importantly, it allows us to rely on the future on liquid fuels. These fuels could come from oil, they could come from coal, they could come ultimately from biomass or from synthetically made processes which started with CO_2 in the first place and renewable energy, but whatever liquid fuel you had and burned in an airplane or a car will go into the atmosphere and will have to be taken back. Ultimately, CO_2 capture from the air allows you to reduce CO_2 levels in the air back down, and that makes it important.

The basic idea of the technology is actually quite simple. You can do it in a high school experiment. As a matter of fact, my daughter did just that. Really, the issue is cost and scaling. You have to build collectors, and what we found out, they are actually surprisingly small, and you then move them up to larger and larger scales. What we are working on right now is an attempt to go to roughly one-ton-a-day units, and I can show you here what we can do in the laboratory right now. This actually is sort of a synthetic pine branch, as people talk about it, as CO_2 capture devices. This guy is loaded with CO_2 because he has been in my briefcase all day, and he picked up the CO_2 while we were coming down here.

Ultimately, we have to get the large scale of one ton a day. These units as they are mass-produced would be like cars. You would need 10 million to make a real dent in the CO_2, 10 million of those, maybe 100 million if you wanted to solve the problem exclusively, but keep in mind, in order to have 10 million units running, you would need one million production a year, which is a tiny fraction of the world car production. Cars and light trucks add to roughly 750 million. Ultimately, it comes down to cost. We are predicting that once it is mass-produced, it would operate at about 25 cents per each gallon of gasoline, and that is the price for cleaning up climate and cleaning up after yourself.

Ultimately, let me say a few words about mineral sequestration. I view that as carbon storage version 2.0. It is bigger in scope. It can literally deal with all the carbon we ever have. It is definitely permanent. There is no question. It doesn't require monitoring because you did take the geological weathering cycle and you accelerated it artificially, and once you have done that, there is no way back. So you can break it into xenon tube where you mine the rock and then process it, which turns out is big, but is no bigger than coal-mining operations we have to produce the coal which produces the CO_2. And ultimately you also have *in situ*. I am involved in a project in Iceland where we put CO_2 underground for forming carbonates under ground, and the nice feature there is, you can come back in 25 years and say it actually is permanently stored. Monitoring beyond that time is not necessary.

The challenge here in my view is cost. We are roughly five times more expensive then we should be at this point, in my view, and I think that is an R&D challenge. If I look at the other sources of energy, I would argue a factor two is well within what can be done.

So to me, air capture and mineral sequestration provide a comprehensive solution. Under that umbrella will be better specific solutions. It makes no sense to not scrub a power plant and then go after it from the air. But I believe we ultimately have a big challenge that the energy infrastructure of the year 2050 is not yet understood, and I think therefore I have a can-do attitude, but you can only do by doing and you can only learn by doing and you have to do the research to make it happen. Energy is so central to our well-being that I think we should not take the risk of not knowing what to do in 50 years from now and put a reasonable large-scale research effort behind this. I thank you for your attention.

[The prepared statement of Dr. Lackner follows:]

PREPARED STATEMENT OF KLAUS LACKNER

Air Capture and Mineral Sequestration

Tools for Fighting Climate Change

Summary

Thank you for giving me the opportunity to express my views on air capture and mineral sequestration, two of the technologies that are included in this hearing as geoengineering approaches to climate change.

Together, air capture and mineral sequestration provide a comprehensive solution to combat climate change. Capturing carbon dioxide from the air and storing it safely and permanently as solid mineral carbonate provides a way to maintain access to plentiful and affordable energy, while stabilizing the carbon dioxide concentration in the atmosphere. Abandoning fossil fuels would seriously affect energy security. On the other hand, the continued emission of carbon dioxide would have harmful consequences for climate, oceans, and ecosystems. Air capture can extract unwanted carbon from the atmosphere, and mineral sequestration can provide a virtually unlimited and safe reservoir for the permanent storage of excess carbon.

Introduction

Stabilizing the concentration of carbon dioxide in the air requires reducing carbon dioxide emissions to nearly zero. Think of pouring water into a cup; as long as you pour water into the cup, the water level in the cup goes up. It does not matter whether the maximum level is one inch below the rim or one and half inches below the rim. In either case, you will eventually have to stop pouring.

Stopping or nearly stopping carbon dioxide emissions cannot be achieved with energy efficiency and conservation alone. These steps will slow the rate of increase but will not prevent us from eventually reaching the top of the glass, so to speak. Unfortunately, there are only a few choices for energy resources big enough to satisfy future world energy demand. Solar, nuclear and fossil energy are the only resources large enough to let a growing world population achieve a standard of living that we take for granted in the United States. Eliminating fossil fuels from the mix could precipitate a major energy crisis. Thus, it is critical for us to maintain all options by developing technologies that allow for the use of carbon-based fuels without leading to the accumulation of carbon dioxide in the atmosphere.[1]

The goal of a perfectly carbon neutral energy economy is only a slight exaggeration of what is needed; only a small and ever decreasing per capita rate of emissions is compatible with a constant concentration of carbon dioxide in the atmosphere. For the developed countries, this means reductions in the carbon intensity of their energy systems by much more than 90% by some point in this century. Without such reductions, the world would have to settle for far less energy, or an uncontrolled rise in the carbon dioxide concentration of the atmosphere. This is true whether the world succeeds in stabilizing the carbon dioxide concentration in the air at the currently suggested level of 450 ppm, or fails and ends up stabilizing at a much higher level some decades later. In my view, a transition to a carbon neutral economy is unavoidable. The question is only how fast we will be able to stabilize the carbon dioxide level in the atmosphere, and what pain and what risk the world will accept in exchange for a less rapid transition.

Capture of carbon dioxide from the air and mineral carbonate sequestration are two important tools in stabilizing carbon dioxide concentrations without giving up on carbon-rich energy sources and carbon-rich fuels like gasoline, diesel, or jet fuel. While this committee is considering air capture and mineral sequestration in the context of geoengineering, these technologies are very different from other geoengineering approaches like albedo engineering or ocean fertilization technologies. They involve far less risk, because they do not attempt to change the dynamics of the climate system, but simply return it to a previous state. Air capture and mineral sequestration simply work towards restoring the carbon balance of the planet that has been disturbed by the massive mobilization of fossil carbon. Their purpose is to capture the carbon that has been mobilized and to immobilize it again. Because they function within the existing carbon cycle, they also have far fewer unintended consequences than many other geoengineering approaches.

Air capture removes carbon dioxide directly from the air. It therefore can compensate for any emission, even emissions that happened in the past. We could theoretically reduce the atmospheric level of carbon dioxide to the pre-industrial level (280 ppm) while continuing to use fossil fuels. Mineral sequestration closes the natural geological carbon cycle and immobilizes carbon dioxide by forming stable and benign minerals. Both technologies fall into the broader category of carbon dioxide capture and storage. Among these technologies, they stand out because they are comprehensive. Air capture could cope with all carbon dioxide emissions; mineral sequestration could store all the carbon that is available in fossil fuels.

Without carbon dioxide capture and storage, the only way to stabilize the carbon dioxide concentration of the atmosphere is to abandon coal, oil and natural gas. As previously discussed, this option is, in my opinion, not viable or practical. Carbon

[1] For a more detailed discussion see Lackner, K. S. (2010), Comparative Impacts of Fossil Fuels and Alternative Energy Sources, in *Issues in Environmental Science and Technology: Carbon Capture, Sequestration and Storage*, edited by R. E. Hester, and R.M. Harrison, pp. 1–40.

dioxide capture and storage technology offers a way to maintain access to this plentiful and cost-effective energy source, while addressing the biggest environmental downside associated with their use.

In my view, carbon dioxide capture and storage pose two major challenges: how to catch the "fugitive" emissions that are not amenable to capture at the source of emission and how to deal with the vast amounts of carbon dioxide that will need to be stored safely and permanently.

Air capture can address the myriad emissions from small emitters including cars and airplanes and also deal with the last few percent of power plant emissions whose escape is expensive to prevent. Other capture options may be advantageous for particular situations, e.g., in the flue stack of a power plant, but air capture can assure that all emissions can be dealt with.

Storage of carbon dioxide is difficult. Since carbon dioxide is a gas, it will tend to escape from its storage site unless it is chemically converted to a mineral. Over this century, the mass of the carbon dioxide that will need to be stored will rival the amount of water in Lake Michigan. To avoid the escape of the carbon dioxide back into the atmosphere, it becomes necessary to maintain a physical barrier between the gas and the atmosphere, and to assure its efficacy for thousands of years. Given the large volumes involved, this raises serious questions about the safety and permanence of underground gas storage. These questions can only be answered by considering the specifics of each particular site. Quite rightly, the public will demand a careful risk analysis and detailed accounting, which will result in a gradual reassessment of the overall capacity of geological storage. I consider it likely that current estimates are too optimistic. Nevertheless there will be significant and adequately safe underground storage of carbon dioxide gas because there are some excellent storage sites available, and the technology to use them already exists. However, mineral sequestration may be required to complete the task of carbon sequestration on a longer time scale. Mineral sequestration converts the carbon dioxide chemically into a solid mineral that is common and stable in nature. There is no possibility of a spontaneous return of the carbon dioxide. Even though mineral sequestration may be more expensive up front, its long-term costs may prove to be more affordable.

Air Capture

The ability to capture carbon dioxide from the air is not new. Every submarine and every spaceship needs to remove carbon dioxide from the air inside in order to keep the crew healthy. The challenge is not to capture carbon dioxide from the air, but to do so in an economically affordable fashion and on a large scale.

I was the first to suggest that capture of carbon dioxide from the air should be considered as a promising approach to managing carbon dioxide in the atmosphere and hence to combating climate change.[2] Capture from the atmosphere has many advantages. First, it separates carbon dioxide sources from sinks, so it makes it possible to collect carbon dioxide anywhere in the world. Air mixes so fast and so thoroughly that capture in the Nevada desert could compensate for emissions in New York City, in Mali, in Ghana, or anywhere in the world. In a matter of weeks to months after starting to capture carbon dioxide in the Northern Hemisphere, the carbon dioxide reduction will have spread out over the entirety of this hemisphere.

Before starting research in this field, I was struck by two observations that suggested technical feasibility. First, the concentration of carbon dioxide in the air, although usually considered very small, is by some measure surprisingly large. To illustrate this point, consider a windmill, which can be viewed as an apparatus to reduce the human carbon footprint by delivering electricity without carbon dioxide emissions. For the same amount of electricity from a conventional power plant could be made carbon neutral with a carbon dioxide collector. The frontal area of this collector standing in the wind could be more than a hundred times smaller than that of a windmill. This convinced me that the cost of scrubbing the carbon dioxide out of the air is not in the apparatus that stands in the wind, but rather it is in the cost of "scraping" the carbon dioxide back off collector surfaces, so they can be used again. Fortunately, the binding strength of these sorbent surfaces need not be much stronger than the binding strength of the sorbent materials that would be used in a flue stack to scrub the carbon dioxide out of the flue gas. This fact, which follows from basic thermodynamics, is surprising considering the three hundred times higher initial concentration of carbon dioxide in the flue gas stream versus in the atmosphere. These insights—based on fundamental physics and thermodynamics—led me

[2] K.S. Lackner, H.-J. Ziock, and P. Grimes (1999), Carbon Dioxide Extraction from Air: Is It an Option?, presented at Proceedings of the 24th International Conference on Coal Utilization & Fuel Systems, Clearwater, Florida, March 8–11, 1999.

to start a large effort in air capture research, which has been funded by Gary Comer, the former owner of Lands End. Much of the work has been performed at a small research company (Global Research Technologies) of which I am member, a fact that I feel obligated for reasons of transparency to disclose. Much of the research effort is now housed at Columbia University.

This original R&D effort allowed us to go beyond theoretical arguments of what could be done with some ideal sorbent materials. We were able to demonstrate our ability to capture carbon dioxide from the air with real sorbents that require very little energy both in their regeneration and in the preparation of a concentrated stream of carbon dioxide ready for sequestration. We discovered a novel process, which we refer to as a moisture swing absorption system. We create air scrubbers that load up with carbon dioxide when dry and then release the carbon dioxide again when exposed to moisture.

We have demonstrated the capabilities of this sorbent in public and have published our results.[3] In short, our system requires water and electricity to collect carbon dioxide. The water can be saline and the energy consumption of the process is such that only 21% of the carbon dioxide captured would be released again at a distant power plant that produces the electricity required in the process.[4] Nearly 80% of the captured carbon dioxide counts toward a real reduction of carbon dioxide in the atmosphere. At this point we have demonstrated the system on the bench scale, and are moving toward a one-ton-per-day prototype. Just like a hand-made car will be expensive we expect a first of a kind version to capture carbon dioxide at approximately $200 per ton. This cost is dominated by manufacturing and maintenance cost and we see significant and large potential for cost reductions. We have set ourselves a long term goal of $30/ton of carbon dioxide, or roughly an addition of 25C per gallon to the price of gasoline. While we are not the only ones developing air capture technology, we were the first to get started, and we believe we are the closest to viable solutions.

Technical air capture, as opposed to growing biomass in fields, in forests and in algae ponds, can operate with a much smaller footprint. A "synthetic tree," our mechanical device to capture carbon dioxide from the air, collects approximately a thousand times as much carbon dioxide as a natural tree of similar size. It is for this reason that air capture is of practical interest.

Just as there are proposed side benefits to industry and the economy from biomass management of carbon dioxide, there are several immediate applications for carbon dioxide captured from the air. First, there is a small market of eight million tons per year for merchant carbon dioxide (i.e., carbon dioxide that is shipped by truck to its customers). Applications range from dry ice production to welding supply and carbonation of drinks. The price of merchant carbon dioxide depends on the distance from the nearest source and is often well above $100/ton. This market could provide a toehold for air capture technology where it could be tested before carbon regulations address climate change issues. Oil companies provide another potential market for air capture. In the United States some forty million tons of carbon dioxide are consumed annually in enhanced oil recovery.

In the future one can expect a large market for air-captured carbon dioxide in managing carbon for climate change. Total emissions in the United States are nearly six billion tons of carbon dioxide per year. Some fraction—currently nearly half—of all emissions comes from sources that do not lend themselves to capture at the point source. These include emissions from automobiles and airplanes. Indeed, practically all emissions from oil consumption fall into this category. As a result, air capture is the only practical option to maintain access to oil-based energy products. Indeed, mitigating the use of liquid hydrocarbon fuels is an important application for air capture. There is no good alternative to liquid fuels, e.g., gasoline, diesel or jet fuel. A pound of fuel contains about one hundred times as much energy as a pound of battery.

Air capture remains necessary as long as liquid carbon-based fuels are used in the transportation sector. Regardless of the carbon source in the fuel, the carbon will end up as carbon dioxide in the air, which will need to be captured. Rather than storing the carbon dioxide, it is also possible to recycle its carbon back into fuel, but this way of closing the carbon cycle requires renewable or other carbon-free energy inputs. Biomass fuels are a special example of closing the carbon cycle. Green plants capture carbon dioxide from the air by natural means and with the help of sunshine convert it into energy rich carbon compounds. However, the ability of biological systems to collect carbon dioxide from the air is slow. Thus, large-scale fuel production

[3] Lackner, K. S. (2009), Carbon of Dioxide Capture from Ambient Air, *The European Physics Journal: Special Topics*, *176*(2009), 93–106.

[4] The 21% is based on the average CO_2 emissions in U.S. electricity generation.

requires large swaths of land. Indeed, algae growth is limited by the innate ability of algae to collect carbon dioxide. And many companies have realized that they could improve performance by providing carbon dioxide from other sources. This could be carbon dioxide from a power plant, but ultimately one can only close the global carbon cycle if this carbon dioxide comes directly from the air. Air capture would be a natural complement to algae production of synthetic fuels.

Air capture can work for any emission of carbon dioxide, no matter where it occurs. Thus, it can provide the capture of last resort. For most power plants, capture at the site is the most economic approach, but in a number of older plants, it may be cheaper to collect carbon dioxide from the air or to install scrubbers that can only partially remove the carbon dioxide in the flue stack. The remaining fraction would still be released to the air and could be compensated for by an equivalent amount of air capture.

Finally, air capture provides one of the few options to drive the carbon dioxide content of the air back down. In a sense, here you are capturing carbon dioxide that was released decades ago. This is the ultimate separation of sources and sinks not only in space but also in time. This ability to turn the clock back, at least partially, is important, because it is very difficult to envision a scenario in which the world manages to stabilize carbon dioxide concentration so that the total greenhouse gas impact is less than that of 450 ppm of carbon dioxide. Adding up all greenhouse gases, including for example methane, the world is only seven years away from breaching this limit.

Managing global carbon dioxide emissions is a huge task, but air capture could operate at the necessary scale. Right now the technology is still in its infancy, but one can already see an outline of how it may work in the future. A collector that can produce one ton of carbon dioxide per day would easily fit into a standard forty-four-foot shipping container. While the first few of these containers will likely cost $200K each, we expect the price to come down to that of a typical automobile or light truck.

For the sake of argument, let us assume that air capture units stay at this scale, and that they are mass produced like cars. With ten million such units operating, air capture would make a significant contribution to the world's carbon balance. Ten million units would collect 3.6 billion tons annually or 12% of the world's carbon dioxide emissions. If these units last ten years, annual production would need to be 1 million. This is a tiny fraction of the world's annual production of cars and light trucks (approximately 70 million units). Thus, reaching relevant scales would certainly be feasible, although it would require a substantial commitment, and obviously a policy and regulatory framework that support such an effort.

Mineral Sequestration

Capturing carbon dioxide is just the first step in carbon management. After one has the carbon dioxide, it must be permanently stored to prevent it from returning to the atmosphere. Columbia University has an active research program on mineral sequestration, involving Juerg Matter, David Goldberg, Alissa Park and Peter Kelemen. Our group is also working on DOE-sponsored research on monitoring carbon dioxide in underground reservoirs.

Underground injection, or geological sequestration, is one option for carbon dioxide storage. It seems straightforward and simple, but it does not have an unlimited resource base, and it comes with the requirement of maintaining (virtually indefinitely) a seal to keep a gas that naturally wants to rise to the surface safely underground. By contrast, mineral sequestration has a much larger resource base, and it results in a stable, benign carbonate material that is common in nature and will last on a geological time scale. For all practical purposes, the storage of carbon dioxide in mineral carbonates is permanent. It requires energy to reverse the carbonation reaction. Therefore this reversal cannot happen spontaneously.

Mineral sequestration taps into a very large, natural material cycle on Earth. Volcanic processes push carbon dioxide into the atmosphere, and geological weathering removes it as carbonate. Carbon dioxide, which in water turns to carbonic acid, reacts with a base to form a salt. This happens every time it rains. There are plenty of minerals to neutralize carbonic acid, but this geological weathering process is very slow. Left to its own devices, nature will take on the order of a hundred thousand years to reabsorb and fixate the excess carbon that human activities have mobilized and injected into the atmosphere. The purpose of mineral sequestration in managing anthropogenic carbon is to accelerate these natural processes to the point that they can keep up with human carbon dioxide releases.

There are two fundamentally different approaches to mineral sequestration. The first is *ex situ* mineral sequestration.[5] Here one envisions a mine where suitable rock, usually serpentine and/or olivine is mined, crushed and ground up, and then in an industrial, above-ground processing plant, carbon dioxide is brought together with the minerals to form solid carbonates that can then be disposed of as mine tailings. Mining operations would be large, but no larger than current mining operations. It would take roughly six tons of rock to bind the carbon dioxide from one ton of coal. An above-ground mine producing coal in the Powder River Basin typically has to move ten tons of overburden in order to extract one ton of coal. Therefore, without wanting to minimize the scale of these operations, it is worth pointing out that current mining operations to produce coal already operate on the same scale.

The cost of *ex situ* mineral sequestration is directly related to the time it takes to convert base minerals to carbonates. In effect, the reactor has to hold an amount of minerals that is consumed during processing time. Thus, a reactor vessel which requires a day to complete the process is twenty-four times larger than a reactor vessel that finishes the job in an hour. Cost effective implementations must aim for a thirty to sixty minute processing time. There are very few minerals that are sufficiently reactive to achieve this goal. The only ones that exist in large quantities are serpentine and olivine. A recent study performed by the USGS and two of my students has shown that in United States, the resource base of these minerals is ample and could cope with U.S. carbon dioxide emissions.[6]

Worldwide, these minerals are sufficiently abundant to cope with all the carbon dioxide that could be produced from the entire fossil fuel resource.

Somewhat surprisingly the cost of mining and managing the tailings is quite affordable; estimates are below $10 per ton of carbon dioxide.[7] The cost that still needs to be reduced is the cost of the neutralization or carbonation reaction. In nature the chemical processes are slow and accelerating them either costs energy (which is self-defeating as it leads to more carbon dioxide emissions) or money. Today, total costs are estimated around $100 per ton of carbon dioxide, which makes costs roughly five times higher than they would need to be for a competitive process. Overcoming a factor of five in costs sounds challenging, but most alternative forms of energy still have high costs or started out with costs that were even further away from what would be required in a competitive market.

The second approach to mineral sequestration is *in situ* mineral sequestration. In this case the carbon dioxide is injected underground just as it is in geological storage, but for *in situ* mineral sequestration, the site has been carefully selected so that the carbon dioxide will react with the local mineral rock and form carbonates underground. The result will be carbonates that form solids, or in some case remain dissolved in the pore water deep underground. For this to be useful, the reactions will have to bind all or most of the carbon dioxide on a time scale that is suitable for human decision making. If it takes more than a few decades for the carbon dioxide to bind, the carbonation process comes too late to affect human decision making. Nevertheless, a few decades is a lot longer than thirty to sixty minutes, which is the time limit for an above ground reactor used for *ex situ* mineralization. As a result, a larger variety of minerals are available for *in situ* mineral sequestration than for *ex situ* mineral sequestration. Of particular interest are basalt formations. At Columbia University we have tested this in our own backyard on the Palisades along the Hudson River. On a larger scale in the U.S. North West, the Columbia River Basalts provide an inexhaustible resource base for *in situ* mineral sequestration. The Earth Institute is also involved in an *in situ* demonstration project in Iceland called the CarbFix project, as Iceland boasts some of the freshest and therefore most reactive basalt formations in the world.[8]

Mineral sequestration could play an important role in carbon management, if R&D could drive the cost down. First, mineral sequestration would provide a very different alternative for storing carbon dioxide that would provide a more permanent and potentially safer method than geological storage. The uncertainties in geological storage may well result in a general downgrading of the resource estimates,

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[5] Lackner, K. S., C. H. Wendt, D. P. Butt, J. E.L. Joyce, and D. H. Sharp (1995), Carbon Dioxide Disposal in Carbonate Minerals, *Energy*, 20(11), 1153–1170.

[6] For more information, see: *http://pubs.usgs.gov/ds/414/*.

[7] To set the scale, $10 per ton of CO_2 would add roughly 1 cent to the cost of the electricity from a 33% efficient coal fired power plant, it would add 8 cents to the gallon of gasoline.

[8] Matter, J. M. et al (2009), Permanent Carbon Dioxide Storage into Basalt: The CarbFix Pilot Project, Iceland, *Energy Procedia*, *1*(1), 3641–3646.

leaving only remote and particularly well characterized storage sites.[9] For example, underground storage of carbon dioxide in seismically active areas is almost certainly going to be challenged by nearby communities due to public safety concerns. Luckily, California has very large serpentine deposits and could entirely rely on mineral sequestration.

Second, particularly *ex situ* mineral sequestration may provide a virtually unlimited supply of carbon dioxide storage capacity and thus could act as an assurance that access to fossil fuels is not at risk. Mineral sequestration raises the value of the U.S. coal reserves because it assures that they could be used if they are needed. Otherwise, the resource limitations on fossil fuels may not be the carbon in the ground, but the capacity of the atmosphere to accept the carbon dioxide. The world resource base in coal, tars, shales, and, potentially, in methane hydrates is so large that the accumulation of carbon dioxide in the atmosphere will need to be addressed.

Third, mineral sequestration makes accounting simple and it provides a high degree of assurance that the carbon storage is, for all practical purposes, permanent. The environmental footprint is contained to the site and to the time window in which the mine operates.

Combining Mineral Sequestration and Air Capture

It has been suggested that one could combine mineral sequestration and air capture into a single process. For example, one could use olivine or serpentine minerals as soil enhancers and rely on the soils to remove additional carbon dioxide from the air in a typical geological weathering reaction. Alternatively, it is possible to spread these minerals into the ocean, and let the reaction between the ocean and the carbon dioxide from the air happen spontaneously to neutralize the additional base.

I do not advocate such an approach, because I see major challenges with distributing that much material over large distances. For the same reason, I believe that in *ex situ* mineralization the serpentine has to be processed at the serpentine mine. There are several options: the coal plant could be collocated with the serpentine mine with the coal would shipped in; the carbon dioxide could be pipelined from a remote power plant to the serpentine mine; or the carbon dioxide could be captured from the air directly at the mine site. In no case, would the heavy serpentine rock have to move over large distances, because the shipment of large amounts of solid material is too expensive.

Furthermore, I see unnecessary environmental complications with distributing finely ground rock in the environment. Mineral rocks, when ground finely, represent environmental and health hazards, which are better dealt with in the confines of a mining operation rather than in open fields of enormous extended areas. Finally, these soil enhancers or ocean fertilizers will, by their very nature, change the ecological balance in the areas to which they are applied.

One of the major advantages of air capture and mineral sequestration is that both operations can be performed on a well contained and relatively small footprint. Thus, one can limit the environmental impacts to small areas and keep them well contained.

The Research Agenda

One of the major challenges facing mankind is to provide ample energy without destroying the environment. The energy sector is exceptional in that the problems we face cannot be solved by simply promulgating the state of the art worldwide. With state of the art technology in water and food the world would be assured plenty fresh water and plenty of food. However, the state art in energy is based on fossil fuels without carbon management, and its continued growth would wreak environmental I havoc. While there is reason to believe that technologies for carbon management can be developed, they have not been developed yet, and thus it is necessary to create a large and ambitious research agenda.

Stabilizing carbon and providing energy is a century scale problem. It is not just about retrofitting existing plants, but it is about developing a brand new energy infrastructure. The power plant of the future will be different from conventional plants of today. Success will require a portfolio from basic research to commercial applications. Learning by doing will not happen until we actually do build a new infrastructure.

Most of the immediate research agenda does not fit with the goals and aspirations of a company in the private sector. Since there is no market for carbon reduction

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[9] Lackner, K. S., and S. Brennan (2009), Envisioning Carbon Capture and Storage: Expanded Possibilities Due to Air Capture, Leakage Insurance, and C-14 Monitoring, *Climate Change*, *96*(3), 357–378.

in the absence of regulation, it is difficult to appeal to a profit motive. However, since there is no accepted technology to solve the problem, it is difficult to force new power plant designs through regulation. Thus, public R&D must make major contributions to solve the problem of carbon dioxide emission and demonstrate feasibility.

There are very few resource pools for providing the amount of energy that the world will need in the second half of the twentieth century. The only sources big enough are solar energy, nuclear energy and fossil fuel energy combined with carbon capture and storage. In developing a sustainable energy platform, the world will need to place a big bet on all three options and hope that at least one of these bets pays off. In the unlikely event that all three resources fail to become sustainable and affordable energy resources, the world will be hit by an energy crisis of unprecedented proportions. Developing these alternatives will take a long time and the second half of the twentieth century is not that far away. The world has been working for more than fifty years on alternatives to fossil fuels—so far without success.

R&D will need to span the gamut from basic research to testing out new pilot plants, and from physics to health sciences. Nearly by necessity, research will span agencies from the National Science Foundation to the Department of Energy, from National Institute of Standards and Technology to the Environmental Protection Agency. Energy is important enough that it should be woven into nearly all aspects of technology development. Specific to air capture and mineral sequestration, research needs to focus on better sorbents, reaction kinetics, carbonate chemistry, and catalysts to speed up reactions. In applied research, we should consider applications in which carbonate disposal could become a byproduct of mineral extraction. We need to find better ways of producing carbonates from serpentines, and develop advanced capabilities of modeling the weathering of basalts in the presence of carbon dioxide. Demonstrations of the technology are necessary if they are ever to be introduced in the market. Altamont Pass was able to convince the world that wind energy has a future. Imagine what a large air capture park could do to convince the world that capturing carbon dioxide from the air is both possible and practical.

Biography for Klaus Lackner

Klaus Lackner is the Ewing Worzel Professor of Geophysics at Columbia University, where he is also the Director of the Lenfest Center for Sustainable Energy, the Chair of the Department of Earth and Environmental Engineering, and a member of the Earth Institute faculty. Lackner's current research interests include carbon capture and sequestration, air capture, energy systems and scaling properties (including synthetic fuels and wind energy), energy and environmental policy, lifecycle analysis, and zero emission modeling for coal and cement plants.

Lackner's scientific career started in the phenomenology of weakly interacting particles. While searching for quarks, he and George Zweig developed the chemistry of atoms with fractional nuclear charge. He participated in matter searches for particles with a non-integer charge in an experiment conducted at Stanford by Martin Perl and his group. After joining Los Alamos National Laboratory (LANL) in 1983, Lackner became involved in hydrodynamic work and fusion-related research. He was a scientist in the Theoretical Division, but also an active part of the Laboratory's upper management. He was instrumental in forming the Zero Emission Coal Alliance and was a lead author in the IPCC Report on Carbon Capture and Storage. In 2001, Lackner joined Columbia University and, in 2004, became a member of Global Research Technologies, LLC.

Lackner earned his degrees from Heidelberg University, Germany: the Vordiplom, (equivalent to a B.S.) in 1975; the Diplom (or M.S.) in 1976; and his Ph.D. in theoretical particle physics, summa cum laude, in 1978. He was awarded the Clemm-Haas Prize for his outstanding Ph.D. thesis at Heidelberg University. Lackner held postdoctoral positions at the California Institute of Technology and the Stanford Linear Accelerator Center before beginning his professional career, and he attended Cold Spring Harbor Summer School for Computational Neuroscience in 1985. Lackner was also awarded the Weapons Recognition of Excellence Award in 1991 and the National Laboratory Consortium Award for Technology in 2001.

Chairman BAIRD. Thank you, Dr. Lackner.

Dr. Jackson.

STATEMENTS OF DR. ROBERT JACKSON, NICHOLAS CHAIR OF GLOBAL ENVIRONMENTAL CHANGE, PROFESSOR, BIOLOGY DEPARTMENT, DUKE UNIVERSITY

Dr. JACKSON. Chairman Baird, Chairman Gordon and others, thank you for your attention today. Let me begin by stating that a wealth of evidence already shows our climate is changing and is a threat to people and organisms. As a scientist and citizen of our great Nation, I urge you to act quickly to reduce greenhouse gas emissions. So far today, you have heard about several approaches for geoengineering the earth's climate. My task is to discuss biological and land-based strategies.

My first take-home message is that some geoengineering on land is already feasible, including restoring or planting forests, avoiding deforestation and using crops to store carbon in soils and reflect sunlight. Plants are one of the cheapest ways to remove carbon from our air. Several limitations in land-based approaches are worth mentioning. One is that we need to apply these strategies over millions of acres to play a meaningful role.

The second is money. Private landowners will need incentives to apply geoengineering. How much will these incentives cost and how sustained will the landowners' responses be?

A third limitation is that geoengineering will surely alter other resources we value, including water and biodiversity. One difference for geoengineering on land is that carbon removal and sunlight reflections both change, never just one or the other. Geoengineering also alters other factors that affect temperature. We need a new framework that includes a full accounting for greenhouse gases and biophysics together. That long-term framework should include water evaporation, energy exchange and other factors in addition to carbon dioxide and sunlight.

Consider this example. Imagine providing incentives for tree planting on former croplands or pasture. This activity will remove carbon from air as the trees grow. What about the same activity viewed from the standpoint of solar radiation management? Trees tend to be darker than grasses or crops and to absorb more sunlight. The same plantation that cools the earth by removing carbon could warm it by reflecting less light. Your new plantation affects the earth's temperature in other ways too. Trees typically use more water than other plants. This increases evaporation, cools land locally, loads energy into the atmosphere and can produce clouds that absorb or reflect sunlight and produce rain. Overall, such biophysical changes can affect climate more than carbon removal does and sometimes in a conflicting way.

New research is needed on a full accounting system for greenhouse gases and biophysics, particularly in climate models. Some gaps in scientific understanding include the ways the models resolve cloud cover, melt snow, supply water for plant growth and simulate the planetary boundary layer. The fusion of real-world data and models is critical for reducing these uncertainties.

Our lands do more than store carbon and protect climate. They supply water, detoxify pollutants, support life and produce food. Geoengineering on land will alter the abundance of many things we value. We need research on its full environmental effects.

In the best-case scenario, geoengineering activities can help the environment. Restoring habitats or avoiding deforestation will store carbon, slow erosion, improve water quality and provide habitat for wildlife. In a worst-case scenario, geoengineering will harm ecosystems, such as proposals to cover deserts with reflective shields. In most cases, we will have to choose which services we value most. Returning to our plantation example, forests store more carbon than grasslands but also use more water. Yearly stream flow often drops by half after planting and streams can dry up completely. Which is worth more: carbon or water? The answer likely depends on whether you live in a water-rich area, as I do, or a water-poor one. Unfortunately, you can't have your cake and drink it too.

A new interdisciplinary research agenda for geoengineering drafted by a panel of experts is urgently needed. This process should be open and seek input from any stakeholders. Because no federal agency has the expertise to lead geoengineering alone, a coordinated working group is the best solution. I recommend that the U.S. Global Change Research Program [USGCRP], comprised of 13 departments and agencies, lead this effort.

In conclusion, although emitting less carbon dioxide and other greenhouse gases should remain our first priority, we do have short-term opportunities on land. In general, though, we need to study the feasibility, cost and environmental co-effects before applying geoengineering broadly. We need to get geoengineering right as a tool of last resort. Thank you.

[The prepared statement of Dr. Jackson follows:]

PREPARED STATEMENT OF ROBERT JACKSON

Biological and Land-Based Strategies for Geoengineering Earth's Climate

Chairman Baird and other members of the Science and Technology Committee, thank you for the chance to testify today. I appreciate the opportunity and your attention.

Let me first state that a wealth of scientific evidence already shows that climate change is happening and presents a grave threat to people and other organisms. We need to act quickly. The safest, cheapest, and most prudent way to slow climate change is to reduce greenhouse-gas emissions soon. No approach—geoengineering or otherwise—should lead us from that path.

Unfortunately, the world has so far been unable to reduce greenhouse-gas emissions in any substantive way. We therefore need to explore other tools to reduce some of the harmful effects of climate change. That is why we are discussing what was once purely science fiction—the remarkable possibility of geoengineering Earth's climate.

For my testimony, you asked me to discuss biological and land-use-based strategies for geoengineering. Here are **four take-home messages** of my testimony:

1) Some biological and land-use strategies for geoengineering are already feasible, including restoring or planting forests, avoiding deforestation, and using croplands to reflect sunlight and store carbon in soils.
2) Biological and land-based geoengineering alters carbon uptake, sunlight absorption, and *other* biophysical factors that affect climate together.
3) Geoengineering for carbon or climate will alter the abundance of water, biodiversity, and other things we value.
4) A research agenda for geoengineering is urgently needed that crosses scientific disciplines and coordinates research across federal departments and agencies.

Let me begin by describing some of the most common biological and land-use-based strategies for geoengineering and their relative effectiveness and feasibility.

Biological and Land-Based Options for Geoengineering

As described in the recent Royal Society report, *Geoengineering the Climate*, many geoengineering options are possible. One set of activities focuses on carbon dioxide removal. The other examines how to manage systems to reflect sunlight and cool the planet, termed solar radiation management. I will call these approaches "carbon" and "climate", respectively. For biological and land-based sequestration, what constitutes "geoengineering" instead of "carbon mitigation" or "offsets" is sometimes unclear. I will try to focus on strategies that are usually placed in the realm of geoengineering. An example of a land-use strategy that is not usually considered as geoengineering is the production of biofuels (in the absence of carbon capture and storage). I do not have the space to consider biofuels in this brief discussion.

Biological Carbon Dioxide Removal

Biological and land-based strategies provide a meaningful opportunity to remove carbon from the atmosphere and to store it on land. Since 1850, human activities accompanying land-use change have released at least 150 gigatons (10^{15} g) of carbon to the atmosphere, roughly one fifth of the total amount of carbon in the atmosphere today.

Plants and other photosynthetic organisms (hereafter "plants") provide one of the oldest and most efficient ways to remove carbon dioxide from our air. For this reason, they provide a feasible, relatively cheap way to reduce the concentration of carbon dioxide in the Earth's atmosphere—at least in the short term.

Several biological and land-based approaches are possible for removing carbon dioxide from air. Because carbon is lost when a forest is cut or disturbed, *restoring* forests is an important tool for placing carbon back in lands. *Afforestation*, or planting trees in places that were not previously forested (or have not been for many years) is another way to remove carbon from the atmosphere. *Avoided deforestation* is a third tool that improves the carbon balance and is sometimes considered to be geoengineering. If a policy incentive keeps a rainforest in Amazonia or Alaska from being cut, carbon that would have moved to the atmosphere is "removed" from the atmosphere.

Restoring and enhancing *soil organic matter* is another tool for carbon management and removal. Because agriculture tends to release soil carbon to the atmosphere, typically soon after land conversion, incentives to restore native ecosystems or to improve agricultural management are two ways to remove carbon from the atmosphere. Restoring or enhancing the amount of organic matter in soil has many benefits, including improved fertility and crop yield, reduced erosion, and better water-holding capacity.

Three issues or limitations in biological or land-based geoengineering are important. One is the scale of the approach needed to reduce the amount of carbon in our air. For any given project, a single acre of land can be managed or manipulated to remove carbon. Nationally, however, we need to implement these strategies over *millions of acres* if they are to play a meaningful role in policy (remembering that we already manage millions of acres). Otherwise, their net effect will be too small compared to the amounts of carbon entering the atmosphere through fossil fuel emissions.

A second issue is landowner behavior. Land is a valuable commodity, and private landowners will need financial incentives to make geoengineering a reality. How much will these incentives cost, and under what conditions, financial or otherwise, might they change their minds?

A third issue is that biological and land-based management will inevitably alter other resources that we care about, including water and biodiversity. I will return to this point after exploring solar radiation management as a second type of geoengineering.

Solar Radiation Management

Managing solar radiation directly is an alternative to removing carbon dioxide from air. In effect these approaches manipulate "climate" directly, or at least temperature. The most common approach for cooling is reflecting sunlight back into space. You only have to reflect a small percentage of the sun's rays to counterbalance the temperature effects of a doubling of atmospheric carbon dioxide. Managing solar radiation is thus the basis for many geoengineering strategies, including stratospheric dust seeding and whitening clouds over the oceans.

Biological and land-based strategies can also employ solar radiation management. One approach is to select crops, grasses, and trees that are "brighter" in color, reflecting more sunlight into space. This strategy can cool plants locally and save water but will likely reduce plant yields in some cases. The option may be especially valuable in sunny, dry areas of the world.

Like strategies for carbon removal, solar radiation management will need to be applied across large areas to be effective, probably millions of acres, at least. One smaller-scale exception may be when solar radiation manipulations reduce the energy needed to heat or cool buildings. Urban forestry, white buildings, and "green roofs" are examples. The energy savings are local but could play a small but meaningful role in reducing our national energy budget.

A disadvantage of solar radiation management is that it offsets only the climate effects of increased greenhouse gases but does not reduce greenhouse gas concentrations. It does nothing for the pressing problem of ocean acidification, for instance, caused by increased carbon dioxide dissolving into our oceans. Also, changing the amount of sunlight alters not just temperature but atmospheric circulation, rainfall, and many other factors. Less sunlight will almost certainly mean less rainfall globally and is likely to reduce global productivity of plants and phytoplankton.

Geoengineering on Land is Carbon *and* Climate Management

As just discussed, geoengineering strategies are typically lumped into two categories, those that remove carbon from the atmosphere and those that manage solar radiation ("carbon" and "climate", respectively). Unlike some geoengineering strategies, however, every biological and land-based approach will alter carbon storage *and* sunlight absorption. Moreover, sunlight is not the only factor that changes the temperature and energy balance of an ecosystem.

We need a new framework for geoengineering that includes a full radiative accounting for greenhouse-gas and biophysical changes together. That long-term framework should include not just reflected sunlight but water evaporation, energy exchange, and other important biophysical factors. Such a framework will then help us make best-practice recommendations for if, when, and where to promote geoengineering activities.

To demonstrate the need for better accounting, consider the following example. Imagine providing landowners with incentives to plant trees on lands that were previously croplands or pasture. Under a carbon management framework, this activity will almost certainly remove carbon dioxide from our air (assuming that planting and management practices do not increase net greenhouse gas emissions). That is what trees do—they grow.

What about the same activity viewed from the standpoint of solar radiation management or "climate"? Trees tend to be darker than grasses or other crop species and thus reflect less sunlight (Figure 1; Jackson et al. 2008). The same plantation that cools the Earth through carbon removal may warm it by absorbing more sunlight. Planting dark trees in snowy areas could cause substantial warming, for instance.

Your new plantation in Figure 1 also affects the Earth's temperature in more ways than just storing carbon and reflecting less sunlight. Trees typically evaporate more water than the grasses or other crops they replace do. This increased evaporation (the blue arrows in Figure 1) cools the land locally. It also loads more energy into the atmosphere and can alter the production of convective clouds that absorb or reflect sunlight and produce rain. Trees also alter the roughness or unevenness of the plant canopy, transmitting more heat into the atmosphere (the red arrows in Figure 1). Overall, such biophysical changes can affect local and regional climate much more than the accompanying carbon sequestration does—and sometimes in a conflicting way.

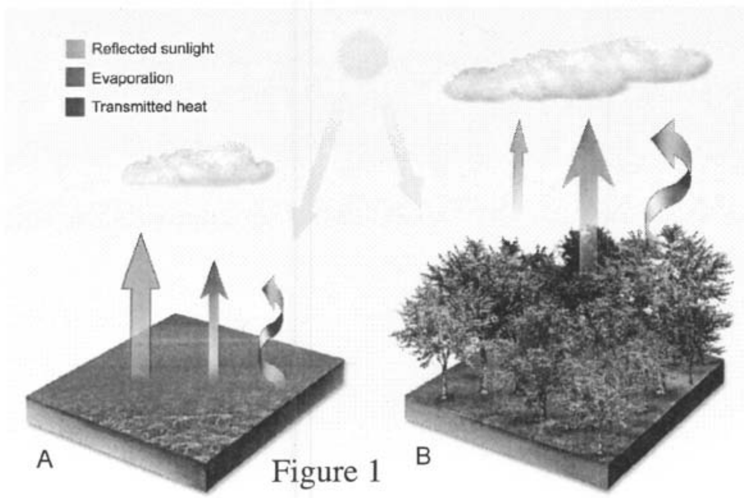


Figure 1

New research is needed to provide a full radiative accounting for greenhouse-gas changes and biophysics together. Some examples of gaps in scientific understanding include the ways that climate models do (and don't) resolve cloud cover, melt snow, supply water for plants to grow, and simulate the planetary boundary layer. The fusion of observations and models is critical for reducing these uncertainties.

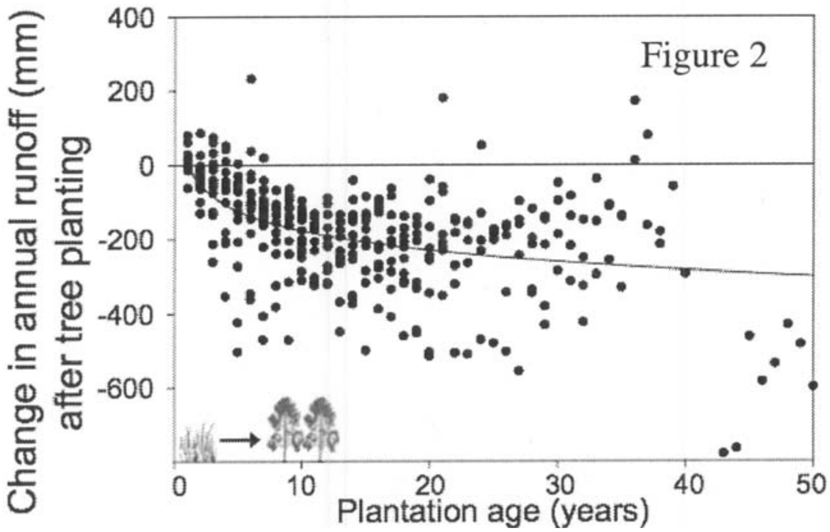
Geoengineering for Carbon or Climate Will Alter Other Valuable Resources

As just described, our lands do many things for us. They store carbon and protect our climate. They also supply and purify water, detoxify pollutants, support a treasure of biodiversity, and produce the food we need to survive. Geoengineering strategies to remove carbon from our air or to reflect sunlight will inevitably change the abundance of these resources. **We need immediate research on the full environmental effects of geoengineering.**

In a best-case scenario, managing lands to store carbon or reflect sunlight will provide additional ecosystem benefits. An example of this win-win scenario is restoring degraded lands. Restoring forests or native grasslands on lands that have been over-used will not just store carbon in plants and the soil; it will slow erosion, improve water quality, and provide habitat for many species. Similarly, avoiding deforestation in the tropics keeps carbon out of the atmosphere, preserves biodiversity, and provides abundant water for streams and for the atmosphere to be recycled in local storms.

In a worst-case scenario, blindly managing lands to store carbon or reflect sunlight will harm ecosystem goods and services. Covering hundreds or thousands of square miles of deserts with reflective surfaces, as has been proposed, may indeed cool the planet. It would also harm many other ecosystem services we value.

The more common reality will lie somewhere in between. One example of a tradeoff in services that I have studied is carbon storage and water supply. Continuing the analogy in Figure 1, most trees store carbon for decades after planting. Because they grow quickly, however, trees also use more water than the native grasslands or shrublands they replace (Figure 2; Jackson et al. 2005). These losses are substantial. Yearly streamflow typically drops in half soon after planting. In about one in ten cases the streams dry up completely.



In many real-world scenarios, we will have to choose which ecosystem services we value most. In the specific case of our plantation, which currency should we value more—carbon or water? The answer probably depends on whether you live in a relatively water-rich area or a water-poor one. Unfortunately, you can't always have your cake and drink it, too.

Research into the environmental co-effects of geoengineering is critical for successful policy and for avoiding surprises. In the final section of this testimony, I present a few ideas for designing and coordinating geoengineering research.

Which U.S. Agency Should Lead Geoengineering Research?

Because of the range of geoengineering activities and their environmental consequences, *no single agency has the expertise needed to lead all geoengineering research*. A more feasible approach would build on a model that is sometimes used successfully—a coordinated, interagency working group. One example of such a group is the U.S. Global Change Research Program comprised of thirteen departments and agencies.

Choosing a single U.S. agency to lead the research effort is appealing administratively but would duplicate efforts. The Environmental Protection Agency might be one home for geoengineering research, particularly if the EPA is to regulate carbon dioxide emissions. The Department of Agriculture, including its Forest Service and Agricultural Research Service, has a long history of expertise in managing our forests and agricultural lands. The Department of Energy leads federal agencies in life-cycle and energy analysis on the global carbon cycle. The National Aeronautics and Space Administration (NASA) coordinates satellite-based research needed to understand global processes and feedbacks. Many other agencies, including the National Science Foundation, the National Oceanic and Atmospheric Administration, and the Department of the Interior, play important roles in research.

Geoengineering research is most likely to succeed if research agencies agree on a joint research agenda. **The agencies should therefore immediately convene a multi-disciplinary panel of experts to outline an agenda for geoengineering research.** This process must be open and should seek input from the broader research community and from stakeholders outside that community.

Conclusions

To discuss the possibility of engineering the Earth's climate is to acknowledge that we have failed to slow greenhouse gas emissions and climate change. Emitting less carbon dioxide and other greenhouse gases should remain our first goal.

Because our climate is already changing, we need to explore every tool to reduce the harmful effects of those changes. Geoengineering is one such tool. We have some valuable, short-term opportunities at hand, including restoring ecosystems and avoiding deforestation. Overall, though, we need to study the feasibility, cost, and environmental co-effects of geoengineering broadly *before* applying it across the United States and the world. We need to get geoengineering right—as a tool of last resort.

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BIOGRAPHY FOR ROBERT JACKSON

Robert B. Jackson is the Nicholas Professor of Global Environmental Change at Duke University and a professor in the Biology Department. His research examines how people affect the earth, including studies of the global carbon and water cycles and climate change.

Jackson received his B.S. degree in Chemical Engineering from Rice University (1983). He worked four years for the Dow Chemical Company before obtaining M.S. degrees in Ecology (1990) and Statistics (1992) and a Ph.D. in Ecology (1992) at Utah State University. He was a Department of Energy Distinguished Postdoctoral Fellow for Global Change at Stanford University and an assistant professor at the University of Texas before joining the Duke faculty in 1999. He is currently Director of Duke's Center on Global Change. In his quest for solutions to global warming, he also directs the Department of Energy-funded National Institute for Climate Change Research for the southeastern United States and co-directs the Climate Change Policy Partnership, working with energy and utility corporations to find practical strategies to combat climate change.

Jackson has received numerous awards, including a 1999 Presidential Early Career Award in Science and Engineering from the National Science Foundation (honored at the White House), a Fellow in the American Geophysical Union, and inclusion in the top 0.5% of most-cited scientific researchers (*http://www.isihighlycited.com/*). His trade book on global change, *The Earth Remains Forever*, was published in October of 2002. He has also written two children's books, *Animal Mischief* and *Weekend Mischief*, both published by Boyds Mills Press, the trade arm of *Highlights* Magazine. Jackson's research has been covered in various newspapers and magazines, such as the *Boston Globe*, *Washington Post*, *U.S.A. Today*, *New York Times*, *Scientific American*, *Economist*, and *BusinessWeek*, and on national public radio. He conceived and organized the Janus Fellowship, an annual undergraduate award to encourage the study of an environmental problem from diverse perspectives; 1999's first recipient traveled down the Nile River to examine water use and water policy in Egypt.

DISCUSSION

Chairman BAIRD. Thank you, gentlemen. I commend you for keeping your comments in the time period. That enabled us to hear all of your initial testimony. We have about probably seven or eight minutes until we need to leave. Then what we will do is, we will proceed with questions. I will probably ask the first one and I imagine we will have to break after that.

ECONOMIC COSTS OF GEOENGINEERING

I think your points are well taken about that we need to prepare for this, but it also well taken that we don't want to have people believe oh, hey, we don't have to do anything to reduce, and you have spoken a lot about carbon. Obviously there are many other greenhouse gases of great concern, some much more potent in their efficacy and greenhouse warming. The cost issue seems to me to be so prohibitive relative to all the other things we could do more promptly to reduce carbon. If you look at conservation, for example, if you look at development of alternative energies, if you look at the CCS cost curve, and I know carbon sequestration is different than what you are talking about, but it would seem to me that your technology may be fairly more expensive than carbon capture and sequestration. Educate me. Is it or is it not more expensive, and if so, why or why not?

Dr. KEITH. I think it is crucial to distinguish these two completely different kinds of things. Carbon removal is inherently expensive. We can disagree about exactly how much but it is expensive. Putting sulfates in the stratosphere is potentially so cheap that costs are irrelevant. In the same sense as when you think about security strategy, the actual cost of nuclear warheads is not a big driver in security strategy. Costs are so cheap that the richest people on the planet could perhaps afford to buy an Ice Age and that individual small states could act alone. So essentially that doesn't mean you should do it but it means that this will be a risk——

Chairman BAIRD. How cheap is that? Educate us on that.

Dr. KEITH. Pardon?

Chairman BAIRD. You are saying it is so cheap. What is it that makes it so cheap?

ATMOSPHERIC SULFATE INJECTIONS

Dr. KEITH. The underlying physical fact that makes it so cheap is that a couple of grams of sulfur in the stratosphere offsets a ton of CO_2 in the atmosphere, not in terms of all the environmental effects, but in terms of the crude radiative forcing. So I am working with one of the leading contractors of high-altitude aircraft in the United States, Aurora Flight Sciences. We are in the middle of a contract they have with us looking at the cost of doing this, and the costs are, as we thought, small.

Chairman BAIRD. Would you add it to the fuel or would it——

Dr. KEITH. No, no, no, that doesn't work at all. That is in the blogosphere. No, you build custom aircraft that would fly at about 65,000, 75,000 feet. They would put the appropriate sulfur or whatever it is in the atmosphere. And the costs of doing that really work out to be low enough that costs don't matter. We are talking about a cost offset the entire effect of doubled CO_2. That is an order of just billions a year, so that is 100 to 1,000 times cheaper than the cost——

Chairman BAIRD. When you say offset the entire effects of CO_2——

Dr. KEITH. In terms of gross rate of forcing. As I have said and we all have said, it can't solve all the problems.

Chairman BAIRD. Only on the radiative side?

Dr. KEITH. Yes.

Chairman BAIRD. This would have—my guess, I may be wrong—would have no impact on ocean acidification.

Dr. KEITH. None at all.

Chairman BAIRD. And I think it is really important to understand that.

Dr. KEITH. Absolutely. So this is inherently imperfect. It can't compensate for CO_2 in the air completely but it can provide an extraordinarily fast-acting thing, and this business of it being cheap I think is pretty much a fact, and it is not necessarily a good thing. The downside is, it allows unilateral action.

Chairman BAIRD. How long does it last up there?

Dr. KEITH. The lifetimes are years, a couple years.

Chairman BAIRD. And then it, what, precipitates out or——

Dr. KEITH. Yeah, that is correct.

Chairman BAIRD. No toxic side effects that we know of?

Dr. KEITH. The thing we always wonder about is the unknown unknown, so if you are thinking about, say, the acidification, it is clear that is not a problem in several studies that showed that. But of course, the concern here is with so little research there may be some unknown unknown that comes out of left field that bites us.

LAND-BASED GEOENGINEERING

Dr. JACKSON. There may be. There are issues that have come up in the literature including interactions with the ozone layer, the water cycle and things like that, and I agree with David: more research is necessary. In my group, we do work on both geologic sequestration, CCS sequestration and land-based, and I would say it is useful to remember the land-based strategies are much cheaper than carbon capture and storage strategies. The issue with land-based strategies is that on a 50- to 100-year time frame, the bucket is not big enough to solve this problem. So my answer would be, there are some shorter term options that we can do some good and we can also do some harm, but there are relatively low-cost options that we can use to help us get started. Long term, we need these bigger-picture solutions like others here have talked about.

Chairman BAIRD. Dr. Lackner?

CARBON AIR CAPTURE AND MINERAL SEQUESTRATION

Dr. LACKNER. Let me make a case for the more expensive carbon capture and storage options, which all of them are. My point in a way is that air capture is probably more expensive than any other capture, but not much more expensive so they are all in the same ballpark. Yes, it is correct that it is cheaper to put some conservation in place, to drive efficiency up and all of this. But consider I came from New York this morning and I could have said, it is much cheaper to walk so maybe I should buy myself some running shoes and get going. But in the end I broke down and said the distance is so large, I will buy myself an airplane ticket and fly down here. And so I would argue the same is true here too. We can make a difference by efficiency, by conservation and doing all of these things, but in the end, if you want to keep the level in the atmosphere constant at any number, once you got to that number you really have to drive emissions close to zero, and keep in mind with the rest of the world growing, basically you have to come down by factors of 20 to 30 in order to hold things in a semblance of stability and that requires more drastic solutions. They in the end will cost a little more, and you are closing the carbon loop by adding another third to it.

Chairman BAIRD. Thank you. We are going to recess at this point. My belief is, we have most likely at least an hour of votes, so we will resume the hearing at 11:30 and with the indulgence of our guests and our panelists, I apologize for the interruptions but we don't get to set that part of the schedule. Thanks. We will see you in an hour.

[Recess.]

PUBLIC OPINION AND EDUCATION

Chairman BAIRD. I thank you for your indulgence on this hour break. I will recognize Mr. Inglis in a minute. I will share with you, though, this idea of placing particles in the upper atmosphere. Are any of you familiar with the conspiracy theory known as chemtrails? Have you heard of this? It is a rather interesting phenomenon. I was at a town hall and a person opined that the shape of contrails was looking different than it used to, and why was that? I gave my best understanding of atmospheric temperature and humidity and whatnot, but the theory which is apparently pretty prevalent on the Net is that the government is putting psychotropic drugs of some sort into the jet fuel and that is causing a difference in appearance of jet fuel and allowing them to secretly disseminate these foreign substances through the atmosphere via our commercial jet airline fleet. Thanks to Dr. Keith, I know that is true. The blogs will have your name, Dr. Keith. I am just kidding.

But it does—on a more serious note, it does highlight that if we are going to do this, we are going to have to be very clear with the public about what we are doing and how we are doing it and why we are doing it and unintended consequences, because legitimate scientific research must not get tied up into these kind of things. Dr. Keith?

Dr. KEITH. I think it is really crucial to do it in a transparent way. One of the reasons I think we need a small government program now is to inject some transparency because right now we have got a hodgepodge, including private money, and that increases the risk that people are very fired up about this. I have voice mails from people who told me I am going to burn in a lake of fire and I don't love my kids and I am a murderer.

Chairman BAIRD. You too?

Dr. KEITH. Oh, yeah.

Chairman BAIRD. We must be on the same mailing list.

Dr. KEITH. So I think that it is—the only cure for that is transparency.

Chairman BAIRD. Mr. Inglis.

POLITICAL, SCIENTIFIC, AND ECONOMIC CHALLENGES

Mr. INGLIS. Thank you, Mr. Chairman.

It strikes me what we are talking about here is something that is very difficult to do because there is no profit to be made in it, and if you think about it, the other way of cutting off the CO_2 has a real profit motive in it, and the way that you can really get things done in a free-enterprise society like ours is to give people an opportunity to make money. They will move quickly if they can make a buck. What you are talking about here, I think just involves government expenditures because I don't know of any customer who would buy these things. So it means if you are doing appropriations to support this with, A, some real questions about the science of it, and B, selling people on the idea of using their tax money to spend money on something that they can't see any tangible result from. It is a little bit like putting padding in a car to avoid injuries with DUI or something. I mean, maybe what you should do is stop the people from being DUI rather than putting padding in the car. And I am also aware that the Committee had an opportunity to be in Greenland and we heard about an earlier idea several decades ago of putting coal dust out on the glaciers in order to help heat up the glaciers. Gee, I am glad we didn't do that. And we heard too, though, about the good thing of getting lead out of gasoline and the result is that real improvement in the situation in the glaciers. So it meant sort of a picture. I mean, one, we are thinking about putting out coal dust. In the other, we are just removing a noxious substance, and the result was really good.

So you have to be real certain of the science and then you have to figure out how you sell a constituency on it, and the thing I am looking for always when dealing with climate change is some way of getting a two-fer or a three-fer, and this is a one-fer. I mean, you just get one thing, CO_2 out of the air and you have a problem finding a constituency, you have real questions about the science. If you think about it, if you can incentivize people to really go after reducing emissions and make money at it, then you can create jobs, you can improve the national security of the United States, especially by breaking the addiction to Middle Eastern oil and you can clean up the air. It is a three-fer and it is driven by profit motive. Wow, what a deal. Because, you know, this thing, if we had done this by appropriations, we would be dragging behind our cars in a trailer, you know, with two technicians figuring out how to get an e-mail across but because this was profit motive, look at this incredible thing. They made a bazillion dollars making these things. So that is what we are after, right? And so I realize I am really panning the idea here, so does anybody want to defend it since I have totally panned it? Who wants to go? Dr. Rasch, you still look like you want to tell me.

Dr. RASCH. Sure, I am happy to respond. I guess the first thing to say is that I think probably all of us agree with you on 99 percent of what you said. I think the first thing to say is that the only reason that we are considering doing geoengineering—it is going to cost money that we wish we didn't have to spend—is because the consequences of not doing anything might be more costly. That is the first thing. Then the second thing to just mention is that of course we also want to find a way of changing our energy technology so that we are not emitting the CO_2 or other greenhouse gases, and the best way is to do it the way that you are talking about. We are a bit concerned that it is going to take a while both to convert the technology to reduce or zero out emissions, and also even if we were to do that, it is going to take a while for the planet to come to some equilibrium with respect to the emissions that we have already made and those that are coming. There are also difficulties with respect to continuing emissions for things like transportation sectors, which were also mentioned earlier this morning. So we don't really like the idea of doing geoengineering, but we can't see any way around it. We see that we may need to do geoengineering.

Mr. INGLIS. I see that my time is up. I hope we may come back to it but, you know, it reminds me of the Malthusian predictions too about the manure in New York City. It really undercuts, I think, our efforts to do something about climate change to have Malthusian predictions. I mean, the reality is that Henry Ford created the car and made a bazillion dollars on it and the result was, we didn't have horse manure piling up to second-story levels in New York City or however deep is was supposed to get. And so I really think that when those of that are out there trying to say let us take responsible action or sort of hear the chorus of a Malthusian prediction, then it really undercuts our effort of trying to get people to buy into this and say gee, we can make a buck, we can improve the national security of the United States, and if you care about it, you don't have to care about it but if you care about it, we can clean up the air too. That is how to sell change.

The other thing is, it is really hard to sell. I can tell you in the 4th District of South Carolina, it would be extremely hard to sell. I yield back.

Chairman BAIRD. Apparently Dr. Keith would like to speak about euphemistic Malthusian predictions, which may be a euphemism for horse pucky, but Dr. Keith?

Dr. KEITH. I think profit motive and entrepreneurialism are just fantastic and I think it is vital that we actually talk about this in a positive way. We have solved an enormous number of pollution problems over the last 100 years. We made huge progress on cleaning up air and water and there was a lot of innovation that came about. I run a little company that is trying to innovate, and we don't think we should make that money, in the long run, by government appropriations. We think what we need is a clean, transparent law where government doesn't pick winners but does restrict the amount of CO_2 going in the atmosphere, and we want to and intend to compete and win in that world.

Chairman BAIRD. Mr. Rohrabacher.

SKEPTICISM OF CLIMATE CHANGE

Mr. ROHRABACHER. Thank you very much, Mr. Chairman. You know, I come to this. I actually waded through the snow coming here, and noticing how miserable I would be without global warming would be even worse. Actually the snow we have had and the temperatures we have had in the last nine years totally are contrary to what we were told in this Committee for about 10 years, all the predictions of the people who came here to talk to us about global warming. I know they have changed it now to climate change because the climate doesn't seem to be doing what they said it would do, but in this Committee, testimony after testimony about what was going to be happening. We were going to reach this turning point. It was going to get hotter and hotter until it would reach some point and then it would really get hotter, and it has been just the opposite. We come into this hearing today—just in the last month we have heard not only the revelations that came out of these hacked communications which indicate a lack of scientific credibility behind certain issues that have been brought up in the global warming debate but we also have found that there was in the IPCC report itself that the Himalayan glaciers that were predicted, that prediction was not based on any scientific research. Just last week it was indicated that and found out that the guesstimate on the Amazon rain forestation, the elimination of the rain forest in the Amazon had no scientific research and basis, and we also heard just recently a statement from the Russian Academy of Sciences that the information they had provided the IPCC was cherry-picked before it was put into the computer model to have an outcome that was not a scientific outcome but an outcome that was predetermined by the people who were putting the project together. These things would cause us reason to doubt the premise which your request for the spending of billions of dollars to remediate a problem is based on.

For the record, Mr. Chairman, I would like to place in the record, out of—there are thousands of such scientists, and you know them, who disagree with this theory that your proposals are based upon but I would like to put a list of at least 100 of those thousands of scientists who are prominent scientists who agree with the case for alarm regarding climate change is grossly exaggerated. Surface temperature changes over the past century have been episodic and modest. There has been no net global warming for over a decade. The computer models forecasting rapid temperature change abjectly fail to explain recent climate behavior. And finally, characterization of the scientific facts regarding climate change and the degree of certainty informing the scientific debate is simply incorrect. I would like to place for the record the list of 100 prominent scientists who agree with those statements.

Chairman BAIRD. If it doesn't exceed the requisite page limit——

Mr. ROHRABACHER. Well, we will squeeze them down into a little——

Chairman BAIRD. Because that is an issue.

Mr. ROHRABACHER. —one page if you would like, Mr. Chairman.

Chairman BAIRD. If you want to submit one page, then without objection.

Mr. ROHRABACHER. Otherwise we would be wasting all of that carbon the paper.

Chairman BAIRD. Well, it has happened before that we have sought to do that on our side with objections——

[The information follows:]

Submission from Rep. Rohrabacher

List of more than 100 Scientists Who Agree That:

- The case for alarm regarding climate change is grossly overstated;
- Surface temperature changes over the past century have been episodic and modest;
- There has been no net global warming for over a decade;
- The computer models forecasting rapid temperature change abjectly fail to explain recent climate behavior; and
- Characterization of the scientific facts regarding climate change and the degree of certainty informing the scientific debate is simply incorrect.

1. Syun Akusofu, Ph.D
   University of Alaska
2. Arthur G. Anderson, Ph.D
   Director of Research, IBM (Retired)
3. Charles R. Anderson, Ph.D
   Anderson Materials Evaluation
4. J. Scott Armstrong, Ph.D
   University of Pennsylvania
5. Robert Ashworth
   Clearstack LLC
6. Ismail Baht, Ph.D
   University of Kashmir
7. Colin Barton
   CSIRO (Retired)
8. David J. Bellamy, OBE
   The British Natural Association
9. John Blaylock
   Los Alamos National Laboratory (Retired)
10. Edward F. Blick, Ph.D
    University of Oklahoma (Emeritus)
11. Sonja Boehmer-Christiansen, Ph.D
    University of Hull
12. Bob Breck
    AMS Broadcaster of the Year 2008
13. John Brignell
    University of Southampton (Emeritus)
14. Mark Campbell, Ph.D
    U.S. Naval Academy
15. Robert M. Carter, Ph.D
    James Cook University
16. Ian Clark, Ph.D
    Professor, Earth Sciences, University of Ottawa, Ottawa, Canada
17. Roger Cohen, Ph.D
    Fellow, American Physical Society
18. Paul Copper, Ph.D
    Laurentian University (Emeritus)
19. Richard S. Courtney, Ph.D
    Reviewer, Intergovernmental Panel on Climate Change
20. Uberto Crescenti, Ph.D
    Past-President, Italian Geological Society
21. Susan Crockford, Ph.D
    University of Victoria
22. Joseph S. D'aleo
    Fellow, American Meteorological Society

23. James Demeo, Ph.D
University of Kansas (Retired)

24. David Deming, Ph.D
University of Oklahoma

25. Diane Douglas, Ph.D
Paleoclimatologist

26. David Douglass, Ph.D
University of Rochester

27. Christopher Essex, Ph.D
University of Western Ontario

28. John Ferguson, Ph.D
University of Newcastle Upon Tyne (Retired)

29. Michael Fox, Ph.D
American Nuclear Society

30. Gordon Fulks, Ph.D
Gordon Fulks and Associates

31. Lee Gerhard, Ph.D
State Geologist, Kansas (Retired)

32. Gerhard Gerlich, Ph.D
Technische Universitat Braunschweig

33. Ivar Giaever, Ph.D
Nobel Laureate, Physics

34. Albrecht Glatzle, Ph.D
Scientific Director, INTTAS (Paraguay)

35. Wayne Goodfellow, Ph.D
University of Ottawa

36. James Goodridge
California State Climatologist (Retired)

37. Laurence Gould, Ph.D
University of Hartford

38. Vincent Gray, Ph.D
New Zealand Climate Coalition

39. William M. Gray, Ph.D
Colorado State University

40. Kenneth E. Green, D.Env.
American Enterprise Institute

41. Kesten Green, Ph.D
Monash University

42. Will Happer, Ph.D
Princeton University

43. Howard C. Hayden, Ph.D
University of Connecticut (Emeritus)

44. Ben Herman, Ph.D
University of Arizona (Emeritus)

45. Martin Hertzberg, Ph.D.
U.S. Navy (Retired)

46. Doug Hoffman, Ph.D
Author, The Resilient Earth

47. Bernd Huettner, Ph.D

48. Ole Humlum, Ph.D
University of Oslo

49. Neil Hutton
Past President, Canadian Society of Petroleum Geologists

50. Craig D. Idso, Ph.D
Center for The Study of Carbon Dioxide and Global Change

51. Sherwood B. Idso, Ph.D
U.S. Department of Agriculture (Retired)

52. Kiminori Itoh, Ph.D
Yokohama National University

53. Steve Japar, Ph.D
Reviewer, Intergovernmental Panel on Climate Change

54. Sten Kaijser, Ph.D
Uppsala University (Emeritus)

55. Wibjorn Karlen, Ph.D
University of Stockholm (Emeritus)

56. Joel Kauffman, Ph.D
University of the Sciences, Philadelphia (Emeritus)

57. David Kear, Ph.D
Former Director-General, NZ Dept. Scientific and Industrial Research

58. Richard Keen, Ph.D
University of Colorado

59. Dr. Kelvin Kemm, Ph.D
Lifetime Achievers Award, National Science and Technology Forum, South Africa

60. Madhav Khandekar, Ph.D
Former Editor, Climate Research

61. Robert S. Knox, Ph.D
University of Rochester (Emeritus)

62. James P. Koermer, Ph.D
Plymouth State University

63. Gerhard Kramm, Ph.D
University of Alaska Fairbanks

64. Wayne Kraus, Ph.D
Kraus Consulting

65. Olav M. Kvalheim, Ph.D
Univ. of Bergen

66. Roar Larson, Ph.D
Norwegian University of Science and Technology

67. James F. Lea, Ph.D

68. Douglas Leahy, Ph.D
Meteorologist

69. Peter R. Leavitt
Certified Consulting Meteorologist

70. David R. Legates, Ph.D
University of Delaware

71. Richard S. Lindzen, Ph.D
Massachusetts Institute of Technology

72. Harry F. Lins, Ph.D.
Co-Chair, IPCC Hydrology and Water Resources Working Group

73. Anthony R. Lupo, Ph.D
University of Missouri

74. Howard Maccabee, Ph.D, MD
Clinical Faculty, Stanford Medical School

75. Horst Malberg, Ph.D
Free University of Berlin

76. Bjorn Malmgren, Ph.D
Goteburg University (Emeritus)

77. Jennifer Marohasy, Ph.D
Australian Environment Foundation

78. Ross Mckitrick, Ph.D
University of Guelph

79. Patrick J.Michaels, Ph.D
University of Virginia

80. Timmothy R. Minnich, MS
Minnich and Scotto, Inc.

81. Asmunn Moene, Ph.D
Former Head, Forecasting Center, Meteorological Institute, Norway

82. Michael Monce, Ph.D
Connecticut College

83. Dick Morgan, Ph.D
Exeter University (Emeritus)

84. Nils-Axel Mörner, Ph.D
Stockholm University (Emeritus)

85. David Nowell, D.I.C.
Former Chairman, NATO
Meteorology Canada

86. Cliff Ollier, D.Sc.
University of Western Australia

87. Garth W. Paltridge, Ph.D
University of Tasmania

88. Alfred Peckarek, Ph.D
St. Cloud State University

89. Dr. Robert A. Perkins, P.E.
University of Alaska

90. Ian Pilmer, Ph.D
University of Melbourne (Emeritus)

91. Brian R. Pratt, Ph.D
University of Saskatchewan

92. John Reinhard, Ph.D
Ore Pharmaceuticals

93. Peter Ridd, Ph.D
James Cook University

94. Curt Rose, Ph.D
Bishop's University (Emeritus)

95. Peter Salonius M.Sc.
Canadian Forest Service

96. Gary Sharp, Ph.D
Center for Climate/Ocean
Resources Study

97. Thomas P. Sheahan, Ph.D
Western Technologies, Inc.

98. Alan Simmons
Author, The Resilient Earth

99. Roy N. Spencer, Ph.D
University of Alabama—Huntsville

100. Arlin Super, Ph.D
Retired Research Meteorologist,
U.S. Dept. of Reclamation

101. Eduardo P. Tonni, Ph.D
Museo De La Plata (Argentina)

102. Ralf D. Tscheuschner, Ph.D

103. Dr. Anton Uriarte, Ph.D
Universidad Del Paisvasco

104. Brian Valentine, Ph.D
U.S. Department of Energy

105. Gosta Walin, Ph.D
University of Gothenburg
(Emeritus)

106. Gerd-Rainerweber, Ph.D
Reviewer, Intergovernmental Panel
on Climate Change

107. Forese-Carlowezel, Ph.D
Urbino University

108. Edward T.Wimberley, Ph.D
Florida Gulf Coast University

109. Miklos Zagoni, Ph.D
Reviewer, Intergovernmental Panel
on Climate Change

110. Antonio Zichichi, Ph.D
President, World Federation of
Scientists

Mr. ROHRABACHER. So now to the questions based on some of the reading that I obviously have had on this. What percentage of the atmosphere is CO_2? I have asked that question, by the way, of numerous people, and after hearing all of the various proposals about the importance of CO_2, most novices think it is 10 percent or 20 percent of the atmosphere. What percentage is it?

Dr. JACKSON. Three hundred and ninety parts per million.

Mr. ROHRABACHER. It is .0395 something. It is less that one tenth of 1 percent of the atmosphere. As a matter of fact, it is less than one half of one tenth percent of the atmosphere. Is that correct?

Dr. KEITH. Yes, and maybe it is useful to think about where the knowledge that that could cause a problem came from. It came from the Air Force geophysics lab in the 1950s. So one thing that you lose in all the hype, and IPCC has overhyped, and all the hype on both sides is the stability of the core science. So the original modeling that showed that surprisingly—it is surprising that that small amount of CO_2 could have a big effect on climate. That modeling was first done accurately by the U.S. Air Force and it wasn't——

Mr. ROHRABACHER. The point is not accurate. There are many scientists who disagree that that small amount of CO_2 has anything to do with the changes in the climate, especially—now, is it your contention that this tiny, miniscule amount, and of course, mankind's investment into that is only 10 to 20 percent of that. Eighty percent of it comes from natural sources. That makes it even more miniscule. That that is a more important factor to the change in our climate than solar activity? The biggest source of power in our universe but this little tiny thing is more important than that?

Dr. LACKNER. I would say yes, and I don't come at it as a climate scientist. I would be happy to stand away from this. I am a harmless physicist when it comes to this. But Joseph Fourier understood this in 1812. And really nothing much has happened new since Svante Arrhehius in 1900, and yes, if you were to take the CO_2 out, the United States would be very much colder than it is today. It is a simple greenhouse gas, and what we are talking about are fine details of what happens if you make small changes to that admittedly small number. Nevertheless, it is important. If you take it out, you also have no photosynthesis. Your ocean would be a hydroxide solution. So there are lots of things which make this important. Nobody argues about argon, which is comparable in content, because it is inert. It doesn't do anything.

Mr. ROHRABACHER. At that time in the early——

Dr. RASCH. Those 100 scientists that you mentioned would not disagree with anything that Dr. Lackner just said.

Mr. ROHRABACHER. But let me try——

Dr. LACKNER. Let me try to——

Mr. ROHRABACHER. Let me ask you this specifically. Has there been a time when the CO_2 in this planet's history, when the CO_2 level was much greater but that we had abundant plant life, oceans that flourished.

Dr. KEITH. Absolutely. So 50 million years ago there was 1,000 or 2,000 parts per million CO_2 in the air, several times what it is now, and there were alligators in the high Arctic and there is nothing wrong with that whatsoever. The problem is about pace of change. It took 10 million years for CO_2 levels to come down from where they were, and we are planning to put them back up to that level in one human lifetime. That is 100,000 times faster. There is nothing inherently wrong with a warmer climate, but that argument is fallacious because it neglects the issue of rate of change. When things came 100,000 times faster, you have a problem.

Mr. ROHRABACHER. Well, except, of course, if the earth has several volcanoes that erupt, right, and that might do as much change as what we do in a full year or two. Isn't that right?

Dr. RASCH. If you get a big enough volcano, it can have a catastrophic effect on the atmosphere.

Mr. ROHRABACHER. So volcanic activity really has something to do with this as well that may even override what human beings do.

Dr. LACKNER. It certainly will override a year or two. The point which convinced me to work on it, because I had to go through the same sort of questions 10, 15 years ago when the climate science was far less certain, and whether it is worth spending time on these issues. What convinced me is we can have a long and learned debate what precisely is the right number to stop at, but once we reach that number, we have to stop emitting, because to a very good approximation, this is like pouring water in a cup. As long as I keep pouring, it goes up, and so we could have an argument whether 450 is the point to stop and there are some people who are of a different opinion than I am on that, but——

Mr. ROHRABACHER. A lot of scientists, for example, suggest that the baseline that you are using to claim that there is a temperature change going on starts in 1850, and we all know that 1850 represented the bottom of a 500-year decline in temperatures, which is what they call I think the Little Ice Age or something, which the scientists that I am talking about point to that and say there has not been any change, even though we have this supposed increase in CO_2.

Dr. JACKSON. It discourages me a bit, I must confess, to still be debating things like whether greenhouse gases are increasing and whether the earth is warming. The earth's temperature is warming. In 1998—the only reason that there is some discussion about the warming slowing is the 1998 weather was off the charts in terms of warmth. It was unprecedented in terms of warmth, and it was so high that the bouncing around since then, it may have slowed a little bit. My suspicion is that in five years it will be back to the same——

Mr. ROHRABACHER. So you are saying that this 1850 argument, that using that as the baseline really isn't accurate because we have actually grown a lot more than what would have normally been throughout the 1,000-year, 2,000-year history of humans.

Dr. JACKSON. I am just saying that it is not an 1850 discussion, it is a million years and longer discussion through different methods. I am just saying that the knowledge base is quite strong. I guess I would also like to add that when we think about changing the earth's climate, I would like—as a climate and environmental scientist, I would also like to remind people that there are millions of other species that we share this planet with, and for 50 million years those species were free to migrate and move. That is no longer the case, so we have to think about human adaptation and human cost but also the ability of the other species that we share the planet with to move in the kind of lifetime that David Keith was talking about——

Mr. ROHRABACHER. Well, the CO_2 argument—and I certainly agree that we have a footprint but it is not just a carbon footprint, and thank you very much. I see my time is up. Thank you for indulging me, Mr. Chairman.

THE SCIENTIFIC BASIS OF CLIMATE CHANGE

Chairman BAIRD. I thank the gentlemen for their responses and want to commend you. Some of the arguments that Mr. Rohrabacher has made have been offered previously to panels of climate scientists without response, and I commend you for the response.

I want to drill down a little bit on one of these issues, and Dana and I are very good friends and we disagree on the conclusion here, but there is a premise that seems to be that if something appears to be a small quantity, that it then assumes it cannot have a large effect. My understanding is, ricin in microscopic quantities can be dreadfully fatal. I take a little tiny pill each day called Lipitor, which relative to my body mass is pretty darn small, and it seems to extend my life. If I were to put a thin, thin, thin film of plastic over your mouth, you would die. If I hold it under the sun, it will warm you up a lot. A thin film of plastic which relative to thickness of atmosphere is far smaller than the parts per million we are talking about, and yet it could—you know, nobody would dispute you lay a piece of plastic on the ground, sun comes through it, things get hot. So this fundamental core argument that because CO_2 is a small percentage of our total atmosphere it cannot have dramatic effects is—we can illustrate countless examples in nature where apparently tiny quantities have dramatic impact. So I think we would do well to reject that as a line of argument.

But beyond that, my understanding of the recent temperature data from this year suggests this past year was a pretty warm year in spite of the fact—I think proponents of climate change make an egregious mistake when there is a tornado somewhere or a hot day somewhere and they say oh, look, it must be climate change. The opponents are guilty of the same problem. And my understanding is the pattern of temperature last year was actually pretty warm year. Is that your understanding? And my understanding also is that IPCC and NASA itself have looked at the solar radiation issue and largely refuted the notion that solar radiation increases. I mean, they modeled it elsewhere and they said solar radiation increases are not believed to be responsible for the apparent temperature increase. Is that your understanding? The record will show that these four distinguished gentlemen all say yes on that.

I think there is a need to—you know, the temptation is to say well, there is one thing or a few things that point maybe in the opposite direction or questions of doubt, and there is no question in my mind that if doubt is distorted on either side of an argument, that—as a scientist and someone who has introduced legislation to promote ethical scientific conduct, that is a problem. But a few bad examples don't seem to me to overwhelm the abundant evidence that I think you gentlemen are citing.

CHEMICAL & GEOLOGICAL CARBON UPTAKE

So back to the issue at hand of geoengineering. Let us talk about solar radiation management a little bit. I want to talk about that and also about the carbon uptake. We will start with carbon uptake. The white pine tree that you gave us, give us some costs, both carbon costs, you know, and what does it cost to produce that in terms of carbon and cost to manufacture? You mentioned, I think, 25 cents a gallon.

Dr. LACKNER. Well, this is once we are in a mass manufacturing mode. We are still in a research phase so we have developed this material which is an anion exchange resin. If it is dry, it absorbs CO_2 out of the air. If it is wet, it gives it back. So around that we built a cycle which allows us to collect the CO_2, compress it, and we will pay energy for that, and so the main energy consumption is the compression. Figure that we roughly give 20 percent of the CO_2 we collected back because some distant power plant is generating electricity in order to feed that system, so that is the order of magnitude of what you have to give back. The cost of the electricity is small and would be well within that 25 cents.

Chairman BAIRD. So you are able to—once that thing draws the carbon out of the air, you are able to then draw the carbon off of that?

Dr. LACKNER. Exactly. So this is like a sponge to soak it up and then I squeeze the sponge out and then I can do with the CO_2 whatever is necessary. I can put it to mineral sequestration, I can use geological sequestration or you could just happen to want some CO_2 for a fizzy drink. I can sell you that CO_2 for that purpose. Clearly, I have no carbon impact if I do that.

Chairman BAIRD. But if we burp, we screw up the cycle.

Dr. LACKNER. Yeah, you would have kept the cycle going. But for a small company, again, that actually gives you the profit motive because in the beginning those are the markets and quite clearly in the beginning I am not down to $30 of ton of CO_2. We estimate that the next round where we go to a one-ton-a-day unit, we are at about $200 a ton on the first try.

Chairman BAIRD. How about the carbon costs of producing the material?

Dr. LACKNER. The carbon cost of that is nearly negligible to the total, because in a matter of a week or two this machine will have collected its own weight in CO_2 multiple times over. Roughly speaking, without doing a careful lifecycle analysis, you have collected a few times your own weight, in the CO_2 emitted that you have produced. Furthermore, the material is a polymer so at the end of the day it becomes fuel to close the cycle.

Chairman BAIRD. And my understanding is, we are getting—there was an article in *Science* a couple weeks ago about how we are making some new developments in terms of molecules that may be able to—and catalysts that may be able to more efficiently strip carbon out as well. Is that——

Dr. LACKNER. Yes. There are a variety of options. We believe what we did here, we discovered actually a brand new way of doing it and we will pursue this further and try to drive the costs down, and one of the things we can do is just make the material finer. Therefore, we use less of it, and therefore the cost is coming down. That is why I am optimistic that mass production—I don't just have to appeal to the world's learning curves for other things when you say things get cheaper if you make more, but I can point my finger to things here and here and here. I can make it much cheaper.

ALTERNATIVES TO FOSSIL FUELS

Chairman BAIRD. And one last point on this and then I will recognize Mr. Inglis. My understanding is that a portion of the energy demand, it will be very possible to meet it through renewable energies, particularly in off-peak times.

Dr. LACKNER. Certainly, and——

Chairman BAIRD. So we are not having to burn more coal, for example, to power our carbon cleansing mechanism. We can use renewables to do that?

Dr. LACKNER. You could certainly do that, and we actually have developed ways where we can wait for the electricity demand when you don't need it so that we can fit in that way. But overall, I would argue you can also get away from fossil fuels, and the dream of the hydrogen economy is to use renewable energy to make hydrogen as a fuel. If I can give you CO_2 and hydrogen, you can make any fuel you like with technologies we have developed in the 1920s. So it seems to me this opens the door both ways to carbon sequestration if you want to go that route, and if renewable electricity or, for that matter, nuclear electricity, becomes cheap enough to make it worthwhile. You can get independent of oil by making your own synthetic fuels.

Chairman BAIRD. Thank you.

Mr. Inglis.

THE SUCCESSES OF PROTERA LLC AND THE NEED FOR INNOVATION

Mr. INGLIS. So Dr. Keith, thank you for that answer for Mr. Rohrabacher. I think it is a very helpful explanation because if it is a pace of 100,000 times faster, that really helps people to understand why it is that it is a problem, and that is the kind of thing that really builds our credibility as we try to address the issue, and I am with Chairman Baird, I thank you for answering the question because quite often those questions do go—or those assertions go unchallenged and so very cogent explanation there. It is 100,000 times faster. I think we can all understand that, that is fast.

So right now I have to sort of celebrate something happening in our district that is relevant to this. Protera, which is an electric bus company, is announcing that they are coming to Greenville, South Carolina, at Clemson University's Center of Automotive Research, where they are going to begin building these buses. The bus has a number of advances. It is made out of balsa wood that is infused with resins that make it as strong as steel. It has got a fiberglass case on it that is very light. It is about a third shorter but carries as many people as an average bus, a city bus, because it doesn't have big diesel engines in the back, and it runs on 3,000 pounds of batteries, heavy batteries. It is a lot of batteries. They are quick charge and quick discharge, 6-minute charge, which means—the physicists here can explain to us that that means they discharge quickly too, right? But they figure that by going around from stop to stop, and stop and have an extended stop, maybe a minute and a half, they can actually recharge the battery enough to get to several more stops. And so around the city that uses such a bus, there won't be any emissions from the diesel. The electric bus goes faster than a diesel because you can go lickety split. I drove one right up the hill here several months ago, and we beat a city bus off the line, and all you do is put the accelerator down and that thing moves. It doesn't have the grinding of the diesel and it doesn't have the smoke coming out the back. And it has regenerative braking too so when you let off the accelerator, the thing slows down as it is recapturing that energy. What an exciting thing. These people have decided that the economics work right now, and I wish I were there now to celebrate this with them but I did a recording yesterday to celebrate it, and what I pointed out is, if we get action on climate change, those economics will look even better, so the amazing thing is that they have something that works right now but imagine them in the catbird seat if we do actually insist on accountability and say incumbent fuels, consider all of your externalities, force a recognition of all the negative externalities and suddenly Protera is going to be—wow, everybody is going to be asking for one of those buses or many of those buses and we are going to have jobs in South Carolina. We are going to have an improved national security because we are going to be saying to the Middle East, we just don't need you like we used to. And we will clean up the air.

Now, of course, that assumes a clean way of producing electricity, but if you insist there on internalizing the externals associated with the cheap coal, then we will fix that one too. We will be building IGCC machines in Greenville, South Carolina, at General Electric, creating a lot of jobs there. We will be creating windmills. They are building wind turbines at General Electric in Greenville. And so we will be building nuclear power plants with a whole high concentration of engineers in the upstate of South Carolina.

Now, you see I have a parochial interest in this. I want to make a lot of people very wealthy out of figuring out a way to fix this problem, and we can create jobs in the process. We are going to say to the Middle East, we just don't need you as much, and we are going to clean up the air. So what an exciting thing. So I just had to celebrate this Protera announcement, Mr. Chairman. Can I hear a cheer for Protera?

Chairman BAIRD. Go, Protera. All I care about is you driving buses.

Mr. INGLIS. Yes, I shouldn't have admitted that. I don't have a CDL.

Dr. JACKSON. May I comment briefly? I think that is a wonderful example, and one way or another, one of the things that we clearly need is some sort of carbon price, and the reason I think for having a carbon price down the road is that you don't pick winners and losers in terms of technology. You let the private sector and markets drive the innovation and the energy savings and all the technologies including perhaps things like capturing CO_2 from the air but we must have a carbon price and we must figure out a way to do it smartly and efficiently to protect our jobs and business but that is what we need to drive exactly the kind of innovation that you are talking about. That is fantastic.

Mr. INGLIS. And can I pass one on to you? How about this? Art Laffer, one of Reagan's economic advisors, is a neighbor of Al Gore's in Tennessee. They agree on a 15-page bill that I have introduced. It reduces payroll taxes and an equal amount shifts those taxes to emissions. So it is a revenue-neutral bill. It is also border adjustable tax so it is removed on exports, and it is imposed on imports.

Dr. KEITH. That is beautiful. May I comment on the need for innovation?

Mr. INGLIS. Yes.

Dr. KEITH. I think private money can do great, and both Klaus and I are, in a friendly way, competing, and we both have private money to work on air capture. And in the long run prices are absolutely necessary to allow clean competition but we also have to find ways, and government has a role. It is not easy to figure out exactly how to do it right in incentivizing innovation because we just are not putting enough energy into energy innovation. The U.S. electric power industry puts as much money into R&D as a fraction of gross sales as the pet food industry does. I didn't make that number up. We checked that number. It is a very small amount, and we need to find a way to make this economy more innovative, and private money is necessary but we need ways for government to encourage innovation both through specifics of tax policies and direct funding for basic R&D. I think that is crucial.

Mr. INGLIS. You know, I found that out actually visiting the utility that is subject to a Public Service Commission. They are sort of proud of the fact they didn't have an R&D department, and the reason is that they can't figure out how to pass those costs along through the PSC, and so they took it as a point of pride that they weren't charging the consumer with those. So it is a real chicken and egg kind of thing. You have to figure out how to—but if you establish a clear price and you insist on accountability, which I believe, by the way, is a very conservative concept. I mean, I am a conservative Republican and I am here to tell you that if you allow people to be not accountable for what they do, well, then you get market distortions. But if you insist on accountability, then those incumbent technologies lose to new technologies.

Dr. LACKNER. Let me 100 percent agree with you on that point. We do need some way of holding people accountable for the carbon. My view is, this has to be somehow built into the price, ideally, as high upstream as you possibly can. And then we move on and say all these various options can compete. Your electricity-driven bus I think is a great idea. I am 100 percent behind that. It is a little harder for my sports car to have all of those batteries in it, and so maybe the 100 times higher concentration in the liquid fuel, which could be synthetic, is another option, but let the market figure that out, and what I am driving towards is that we shouldn't close options off. Air capture is an option. Electricity is another option. Which of the two will win? I tell my students, I can't tell you today. The markets will have to figure this out and it is too close to call with 50 years ahead trying to work this out, but we do need the market to sort this out.

INCREASING STRUCTURAL ALBEDO

Chairman BAIRD. Thanks, Mr. Inglis.

I want to ask two more quick questions and then, Mr. Inglis, we may finish at that point. It seems to me that the most basic form of—you folks have been very informative here and it makes sense to me that we ought to look at this much more than we are. The most basic form of geoengineering that I have heard about is paint your roof white, which actually is very little cost and dramatic benefit. Is that your understanding, that if we could move, you know, towards lighter colored shingles—in fact, I understand people are making photovoltaic shingles now. What are your thoughts on that?

Dr. KEITH. Huge local benefits, such huge potential benefits——

Chairman BAIRD. In this city——

Dr. KEITH. —cooling loads and city-level loads, but I think it is pretty clear that as a method of changing he global climate, it is both too small of a matter and actually not cheap. But locally to help cities and to help reduce cooling loads, it can be very effective.

Chairman BAIRD. And dramatic—not dramatic but noticeable impact on cooling loads especially.

Dr. RASCH. If I could respond, it doesn't have much effect on the brightness of the planet but it does have a big effect on the energy.

Chairman BAIRD. So we are not going to change planetary albedo by painting our roofs white, but the city of Washington, D.C., could substantially reduce its load, and that means less air conditioning, that means less carbon burning for the air conditioning.

Dr. RASCH. Yes, absolutely.

ALTERNATIVE FUELS AND CONSERVATION PRIORITIES

Chairman BAIRD. In terms of research dollars, one of my concerns—I was just at the World Economic Forum and there is a lot of discussion about CCS, carbon capture and sequestration. We are building an enormous base infrastructure right now. We already have one in coal but we are building—China, particularly, and other nations, are continuing to expand on the bet basically that we are going to have some sort of CCS that is economically viable. And the projections we have heard in this committee previously suggest there is a real question about that, and on top of that, if you are adding more carbon, the efficacy of reducing the existing carbon that you are just trying to keep up with an ever-fleeing target. It would seem to me that we would be much better to do a couple of things, to make a large investment right away in conservation because that is your quickest and most immediate return on investment. Then put money into disruptive technologies like distributed photovoltaics or wind or like Dr. Daniel Nocera is doing at the Massachusetts Institute of Technology [MIT], some form of better hydrogen and fuel cell rather than letting the money go into these big coal plants that just commit us to a coal path and then make all your clever devices, Dr. Lackner, not reducing down to 350, which we are already above 350 parts per million but trying to keep up with this fleeing target. What are your thoughts on this? If we throw so much money into new coal capacity versus—what does that do to us?

Dr. LACKNER. I think we should do what you just said because it is important to go after the low-hanging fruit, but I come back to where I started, particularly if you talk about what other countries are getting into, you are talking in the end about a world of 10 billion people who strive to have a style of living we take for granted, and I think we should do everything we can to allow that to happen. Now you need an awful lot of energy, probably four or five times as much energy as we are using today. So I started to ask myself the question, where could all that energy possibly come from? There are very few resources which are big enough to do that. I would argue one of them is solar energy. There is no question we have enough sunshine and we should have a big, big program there.

Secondly, I think nuclear energy with all its problems is a second one which is actually large enough to solve this problem and can play as a truly big player. Thirdly, you have fossil fuels. We may be running out of oil. We are not so likely running out of gas and we are certainly not running out of coal in the foreseeable future. So in my view, we have some 200 years there to keep banking on that fuel, provided you have carbon capture and storage in place. So that has to be part of the bundle because otherwise you simply couldn't dare to use all of this carbon. So in my view, standing back a little, there are three major resources and we better place three big bets, making sure that at least one of them pays out. And I am optimistic that each one of the three has a fair chance of getting through, but if we were to fail on all three, we would have an energy crisis of unprecedented proportion no matter how well we do in terms of conservation or improved efficiency. Those can help but they cannot solve the problem, and I would argue the other energy sources we are talking about on that scale are too small. So those three I would view as in a special category, and we have to pay attention that they work. And then the market has to figure out whether it is 30, 35, 40 or whether it is one winner takes all in 50 years. I cannot predict that. But we better not close the door on any one of those.

Dr. JACKSON. May I add wind to that list as well? I agree with all of that. I can't pass up an opportunity to say thank you for emphasizing the need for conservation and renewables. Those are things that we can do now. When we are discussing geoengineering, we are talking about things that work at best 10, 20 years and perhaps and hopefully never if we don't get to that point, but it is increasingly likely that we will get to it because of the increasing use of fossil fuels. So anything that we can do now, and there are many things we can do now to improve efficiency and provide incentives for renewables like wind and solar, I wholeheartedly support, and the market is the best way to do that. On top of that, though, when we build a coal plant, that coal plant is on the ground for 40 or 50 years perhaps, so I do believe, as strongly as I feel about conservation and renewables, that we have to pursue at least economic and feasibility analyses of CCS. Perhaps carbon capture and storage directly from the atmosphere is another example. These are not—it is not an either/or situation. In my view, these are backup plans because we are not doing the job we should be doing as quickly as we should be doing it.

COAL AND CARBON CAPTURE AND SEQUESTRATION

Dr. KEITH. CCS has become a bit of an orphan child, so I think we should do everything we can to stop building any new coal plants without CCS. I would be happy to see a ban. But I think it is tempting to say, and I agree very much with the idea that solar and nuclear and coal with capture are the big players in the long run, wind to a lesser extent. But I think it is important to be clear about the politics of CCS right now. It is an orphan child. The NGOs at best are lukewarm and the coal companies' preferred strategy, in many ways, would be to have it be R&D forever so they don't get regulated. And so it is sort of caught in between the two. Yet nevertheless, it looks to those of us who spent a lot of time on it that you could actually build gigawatt-scale power using coal with capture today, and the costs of doing that would be much lower than, say, the cost of solar today, much meaning factors of several.

Chairman BAIRD. With respect, there is substantial dispute of that.

Dr. KEITH. I actually don't know any serious dispute. I have served on the IPCC panels.

Chairman BAIRD. About the cost curve?

Dr. KEITH. Here is a simple way to say it. The feed-in tariffs that we need to make solar happen are of order 30, 40 plus cents a kilowatt hour in places where we are really doing it. I helped to get in Alberta, where I come from, one of the first—probably what will be the first megaton-a-year scale plant happen. I helped to recommend and was involved in the contracting for that. Those costs are substantially lower. So they will be done in three years for a million-ton-a-year effort and that is baseload power. It is ugly. Nobody likes it. It is not sexy. It is something that sort of nobody wants but it is something you can actually do and provides low CO_2 electricity at a cost that is reasonable, and I think we would be very foolish to throw it out.

Chairman BAIRD. I will not stipulate to that, having heard Mr. Heller's comments in Davos last week.

Dr. JACKSON. I am not sure I agree completely with that either.

Dr. LACKNER. It is indeed a complicated story, but if you look back to the sulfur discussions, the sulfur dioxide discussions in the 1980s, the estimate right before it happened where typically an order of magnitude larger. I think in the absence of economic incentives, prices tend to escalate and so I would argue there is a complicated story. If you want my intuitive feeling, and it is no more than that, these costs will come down to somewhere around $30 a ton in power plants.

Chairman BAIRD. I also wanted to say, to say that it is an orphan child, the energy bill that passed the House had $100 billion over time into CCS. That is a hell of an orphan. You were saying, Dr.

Rasch, the best you could get was $1 billion. Was it even a billion? It was a million.

Dr. RASCH. A billion dollars for climate, and we are currently at a million dollars per year for geoengineering.

Chairman BAIRD. A million for geoengineering, so we are—order of magnitude.

Dr. RASCH. Many orders of magnitude.

Chairman BAIRD. Three orders of magnitude.

Dr. LACKNER. Five.

Chairman BAIRD. Five orders. Yes, right, five orders of magnitude. And so I don't think it is an orphan child by any means, and I think as an orphan child, it is a darn expensive child when you are putting $100 billion in. So if you are going to say that yes, the cost of CCS may come down, well, what if you put $100 billion in alternative technologies?

And one last note on this and I will get to Mr. Inglis. The coal cost is not just the carbon cost. Five thousand miners a year die in China. It is a centralized system with a very inefficient transmission. We lose a tremendous amount of power across the transmission. There are all the other eminent domain issues, whether it is pipelines to transport the carbon or transporting the energy through those lines. I am very much, personally, much more of a distributed energy person with backups of the kind of thing you are doing, but I worry greatly about the big investment in coal, and $100 billion is a lot of darn money that could go somewhere else.

Mr. Inglis.

Mr. INGLIS. Thank you, Mr. Chairman.

ECONOMICALLY VIABLE ENERGY SOURCES

Just briefly. I don't know, Dr. Rasch, whether—you referenced $1 billion for a year in climate research. Our numbers show it is $2.5 billion.

Dr. RASCH. I tried to cite the location for the information that I used to assess that, but I could be off by a factor of two. You can also correct me if I am not looking at the right numbers. I am glad to be educated on that.

Mr. INGLIS. Which is a fair amount of money. The thing I just go back to is, what we see in this Committee quite often is some things that work and we know they work. For example, wave energy works. It has obviously got to work. I mean, you can do it all kinds of waves. The question is whether it works economically, and the way to get things—I believe a basic rule of government is to basic research. I mean, it is an important function we do. But then once it gets into the applied range, what you are looking for is just economics at work, and when those economics start working, things happen quickly. So the internet came from defense research that then saw real opportunities in the private sector, and wow, what an opportunity it was.

By the way, I might point out this 15-page bill, do another commercial for it. It starts out at $15 a ton, gets to $100 a ton over 30 years. But we can go steeper than that if you want to. Just give me a tax cut somewhere else. In other words, how low do you want to go on taxes? How low do you want to go on reducing those FICA taxes? I will go all the way down and then we will shift them on to something else. So the idea of the curve is, it gives a period of time for innovation and it starts going more steeply. But the process is—I just want to point out, the bill, as I said, that Art Laffer, Ronald Reagan's economic advisor, and Al Gore both support this. It is 15 pages compared to the 1,200-page cap-and-trade monstrosity. And so—which is a tax increase, decimates American manufacturing and is a trading scheme that Wall Street brokers would blush about. And so we have to find something simpler and something that people can say oh, I see, we are just going to—you are going to give me money in my pocket so I can go buy these wonderful shingles that Chairman Baird was just talking. We are getting ready to need to replace shingles on our house in several years. I want to replace them with solar-collecting shingles. But I need some money in my pocket, so reduce my FICA taxes and I got some money now to innovate. If you just give me a tax, I am stuck, I don't have money to innovate. And the cap-and-trade folks who go around saying oh, it is not going to increase energy cost, well, then why do it? I mean, it is disingenuous. Of course it is going to increase energy cost. Otherwise you wouldn't be doing it.

But in my case, what I am saying is, I have money for you in your pocket. Then we are going to increase energy cost but I admit that energy costs will go up under what Art Laffer, Al Gore and I are talking about. But we have got a tax cut. If Art Laffer is on the scene, you can be assured that it starts with a tax cut. And so you have money in your pocket. It is just a small fair tax. It is one sector fair tax.

Anyway, enough of my commercial, Mr. Chairman. Thank you.

Chairman BAIRD. I am actually a supporter of the commercial product.

CLOSING

I want to thank our witnesses. We could go on for a great length here but you have been very generous with your time and your expertise, and it has been most informative to us. As is customary, the record will remain open for two weeks for additional statements for the Members and for answers to any follow-up questions the Committee may ask of the witnesses. And with that, the witnesses are excused with our great gratitude and appreciation for your work.

[Whereupon, at 12:25 p.m., the Subcommittee was adjourned.]

Appendix 1:

Answers to Post-Hearing Questions

ANSWERS TO POST-HEARING QUESTIONS

Responses by David Keith, Canada Research Chair in Energy and the Environment, Director, ISEEE Energy and Environmental Systems Group, University of Calgary

Questions submitted by Chairman Brian Baird

Q1. Why does the rate of change of carbon dioxide concentration suggest climate risk?

A1. Several independent lines of evidence suggest that carbon dioxide concentrations reached about 1000 parts per million (ppm) during the beginning of the Eocene about 55 million years ago, these carbon dioxide levels then declined to about one third of that value over a few tens of millions of years. The Eocene climate was far warmer than today's. Crocodilians walked the shores of Axel Heiberg Island in the present-day Canadian Arctic. While there is lots of scientific uncertainty about the precise amount of climate change that will arise from increasing carbon dioxide levels, there is no doubt that carbon dioxide levels are currently being driven by combustion of fossil fuels and that were we to continue increasing our combustion of fuels at the current rate we would drive concentrations to roughly 1000 ppm by the end of the century.

This increase in atmospheric carbon dioxide over a century would be, therefore, roughly as large as the declining carbon dioxide over the few tens of millions of years that followed the Eocene thermal maximum, that is a human driven rate of change perhaps 100,000 times larger than the average rate in nature.

There is nothing wrong with the Eocene climate; there is no inherent reason we should prefer our crocodiles in the Florida Keys rather than on Axel Heiberg Island. The climate risks come from the rate of change, not because the current climate is some magic optimum for life. Our infrastructures, our crops, the very locations of our coastal cities have evolved for the current climate. The slow adaptation that has anchored us to the current climate puts us at risk if climate changes fast. The climate has varied for billions of years, and would keep changing without us, but on our current high-emissions path, the rate of climate change over the next century will likely be many times faster than humanity has experienced in the past millennia.

While it is beyond the ability of science to predict the exact consequences of this increase in carbon dioxide, both our understanding of the physics of carbon dioxide and climate developed over the last century and with our understanding of the geological record suggest that the resulting climate changes will be dramatic. While the consequences of climate change may be somewhat worse or somewhat less severe than our models that predict, there is simply no scientific line of argument that concludes that we should expect no climate response to this increase in carbon dioxide.

Q2. Is it possible to somewhat confine the impacts of atmospheric geoengineering strategies?

A2. The climate throughout the whole world is coupled together by winds and ocean currents that move heat and moisture between distant locations. This means that the whole world's climate is strongly coupled together as an interacting system. This strong coupling is not a one-to-one link. Its possible for one area of the world to cool, or to be cooled by some external influence such as geoengineering, while other parts warm. Nevertheless, in general and on average, any manipulation of solar radiation that substantially alters the climate over a large area, such as that of India or the continental United States, will necessarily involve the alteration of climate over much larger areas. Future research might find some particular locations or methods that reduced this coupling, but I suspect that the physics of the atmosphere makes it practically impossible to control climate of different parts the world in a completely independent fashion.

So, to answer the specific question, geoengineering that focused on cooling the Arctic and thus increasing the extent of Arctic sea ice, could not be completely localized, and would necessarily have influences that would be felt over much of the northern hemisphere.

That said, it's completely possible that geoengineering could be used both help cool the Arctic and help reduce the severity of climate change over the areas covered by the South Asian monsoon. It is not correct to assert that these two objectives are necessarily in opposition.

Q3. Will adding sulfur in the stratosphere increased acidification the ocean?

A3. Sulfur added to the stratosphere will be returned to the earth as sulfuric acid in rain. However the amounts of sulfur now being contemplated are sufficiently low that there are no serious concerns about acidification of surface waters.

Combustion of fossil fuels, most importantly coal, currently adds about 50 million tons of sulfur to the atmosphere each year. The resulting air pollution impairs the health and shortens the life of millions around the world, and also increases the acidity of surface waters, a phenomenon called "acid rain". The worst environmental effects come from concentrated sources that overwhelm the buffering capacity of local lakes causing them to become acidified. Because of the way the oceans are chemically buffered, this addition of sulfur is not a substantial contributor to ocean acidification which is primarily caused by carbon dioxide.

Most discussion of sulfate geoengineering proposes adding a few million tons a year of sulfur to the stratosphere. At first glance, one might assume that the impact of this geoengineering on acidification of surface waters would thus be about a tenth as bad as the current impact of sulfur from fossil fuel combustion. However because the sulfur injection in the stratosphere would be deposited much more evenly around the world the rate of acid deposition would be far lower (e.g., 100 times lower) than the concentrated acidic deposition that causes acidification of lakes by overwhelming their natural buffering capacity. The overall impact of these sulfur emissions on acidity of surface waters are therefore thought to be vanishingly small.

While it seems unlikely that addition of sulfur in the stratosphere will be a significant contributor to acidification of surface waters, it's important to remember that there a host of other potential environmental problems that might arise from the injection of sulfur into the stratosphere, and that these can only be evaluated by a research program which enables scientists to quantify these risks.

Q4. How much funding for geoengineering is appropriate?

A4. I think it's important to start with a relatively small amount of funding for Solar Radiation Management, and then to gradually increase the funding as the community of active scientists and engineers grows. I would suggest starting with about $5 million per year and then ramping the funding up towards $25 million per year over about five years.

I suggest starting small because research programs (however important) can fail if too much money is spent too quickly. This seems to me a particular concern here because the topic is (justifiably) controversial and there is a relatively small community of serious scientists who seem currently inclined to work on the topic. Under these circumstances a sudden "crash" research program with a lot of funding would inevitably find some research which was ill considered and controversial raising a chance at the entire program would be killed. It's important to learn to walk before one runs.

The agencies best positioned to begin funding research are likely the NSF and DOE's office of science, but many other agencies including, for example, NOAA, NASA and EPA clearly have capabilities that will be important as a research program grows.

I don't believe, however, that agency funding alone will be sufficient for the program to thrive. There is a vital need for a crosscutting role which articulates the broad objectives of the research program, minimizes duplication, and provides a forum for within which interested parties, including nongovernmental civil society groups such as representatives of major environmental and industry organizations can advise on the programs scope and progress. I suspect that the Office of Science and Technology Policy will be best positioned fill this role. I suspect that the presence of broadly representative advisory panel would serve as a place for parties to air their differing views about the merits of this research area and that that would in turn increase the chance of establishing a stable and sustainable research program that serves the public interest.

Finally I want to emphasize the need to begin research program quickly. Research programs are starting in Europe and in private hands as are international efforts to ban all such research through existing treaties. The absence of a U.S. federal research program means that the U.S. government is unable to play an effective role in shaping the direction of research on solar radiation management in the public interest.

Q4. How to coordinate SRM and CDR?

A4. As I said in my opening testimony: SRM and CDR each provide a means to manage climate risks; but they are wholly distinct with respect to (a) the science and technology required to develop, test and deploy them; (b) their costs and environmental risks; and, (c) the challenges they pose for public policy and regulation.

Because these technologies have little in common, I suggest that we will have a better chance to craft sensible policy if we treat them separately.

As research programs, I don't believe they require more coordination with each other than either of them do with other areas of climate related research such as research into low carbon energy systems or adaptation to climate change. All of these (and others) need to be woven into a coherent national strategy for managing climate risk. But I see no special reason for tight coordination between SRM and CDR research. I don't believe one should attempt to avoid use of the word *geoengineering*, as attempts to avoid controversy by avoiding use of controversial terms are rarely, if ever, well advised; but in crafting a research program should one should treat SRM and CDR independently and used the word *geoengineering* primarily in association with SRM.

ANSWERS TO POST-HEARING QUESTIONS

Dr. Philip Rasch, Chief Scientist for Climate Science, Laboratory Fellow, Atmospheric Sciences & Global Change Division, Pacific Northwest National Laboratory

Questions submitted by Chairman Brian Baird

Q1. In your testimony you suggested employed field and modeling studies to examine the aerosol indirect effect, which is critical to understanding the marine cloud whitening strategy, and climate change more generally. Please describe what is lacking in our understanding as it applies to geoengineering?

A1. As a reminder, the term "aerosol indirect effect" refers to the response of clouds to the presence of aerosols. Aerosols affect clouds in many ways. They can act to "whiten" clouds or make them more extensive, or more persistent, all of which will make the clouds more reflective to sunlight, and thus cool the planet. But aerosols can also act to trigger precipitation, depleting the cloud of condensed water, reducing cloud amount, and reducing the cloud lifetime, making the clouds "less white". These processes can act simultaneously, with some effects essentially counteracting others. This makes the effect of aerosols on clouds very uncertain (this is thoroughly discussed in the Assessment of the Intergovernmental Panel on Climate Change report). Science currently believes that on balance that aerosols tend to make clouds whiter, and that increasing aerosols will tend to cool the planet.

Key points regarding this feature of the climate system as it applies to geoengineering include:

1. The "cloud whitening" geoengineering strategy depends upon the "more aerosols→ more/brighter clouds→ cooler planet" effect to work. **We need to be sure that this aspect of the aerosol indirect effect is the dominant one for this geoengineering strategy to work.**
2. Equally important, the aerosol indirect effect is critical to our understanding of climate change in the past, and in the future. Scientists believe that aerosols have increased dramatically over the last 150 years. If our understanding is correct, then **the aerosols will have tended to cool the planet, partially compensating for the warming arising from increasing greenhouse gas concentrations**. We believe that in the future the warming from more and more greenhouse gases will eventually "win out" over the cooling from aerosols, especially if we continue to clean up our emissions of aerosols. But in the past we think both effects played a role. **Our lack of precision in knowing how much aerosols acted to cool the planet in the past also interferes with our ability to identify how much the greenhouse gases warmed the planet in the past and will warm the planet in the future.**

The same research on the aerosol indirect effect that will help us evaluate the positive and negative consequences of geoengineering will help us understand how much aerosols have been compensating for the warming arising from greenhouse gases. Our lack of understanding confounds our ability to interpret the past temperature record, and to predict the changes that will occur in the future.

What kinds of studies would be most useful for exploring the aerosol indirect effect?

One very good way of understanding the aerosol indirect effect is to try to deliberately change a cloud system for a short time period. One would try to measure the cloud properties in an "unperturbed environment" and then do the same kind of measurement for the same type of clouds after deliberately and carefully trying to change the clouds to see whether our models can predict the changes that we see in the cloud system. The desired perturbation would be introduced for a relatively short period of time, over a small area. *Mankind changes clouds all the time through pollution, but we don't do it in a way that makes it easy to measure, or to identify the response of the clouds*.

The best way to do this is in the context of a scientific field experiment. The field experiment should be designed to deliberately change the local cloud system for a short time. It would introduce a local change far smaller than the kinds of changes to aerosol amounts introduced by, for example, emissions from a large city, or a large forest fire, and thus the field experiment would be expected to have much less effect on climate than those already produced by many other situations.

Our models suggest that the cloud systems most susceptible to the "cloud whitening effect" are those called "marine stratocumulus". These cloud systems are also very important climatically, so it would be an obvious cloud system to study first. Marine Stratocumulus clouds were recently studied in the VOCALS field experiment. The difference between VOCALS and a study designed to understand the aerosol indirect effect would be that the study would attempt to deliberately change the cloud system for a short time.

Q2. In your testimony you explain that lab and fieldwork are critical to assure that the physical processes that are critical to climate are understood. What scale would ultimately be needed to field test these SRM technologies to develop the technology and to test its effects?

A2. I advocate conducting scientific research to understand approaches to and implications of geoengineering, particularly as they relate to a deeper understanding of the dynamic processes and interactions of aerosols and cloud systems. Lab and Field tests are required at a variety of scales to explore the relevant issues. I describe a sequence of studies in the next few paragraphs.

1. At the smallest time and space scales it is important to see whether we can produce the sea salt particles that are suggested to be used to seed the clouds. The first steps would involve production of the particles on a laboratory bench scale for a few seconds.
2. If engineers were able to produce the particles for a few seconds then the next stage would be to study how those particles interact with each other and their environment after they are produced. Do the particles bump into each other and stick to each other growing big enough to sediment out from gravity? Do they mix rapidly with surrounding air or stay confined near the surface like the particles from a fog machine? Some of these tests could be done in a big warehouse, others off the end of a pier for a few minutes, to a few hours.
3. If the previous tests are positive then larger scale field tests become informative that require studies of over areas of the ocean the size of a few tens of city blocks for a few hours to answer questions like the following. How rapidly would the salt particles mix into the surrounding air? How long would they last? Does it matter whether they are produced during the day or at night? Do they go into the clouds as our models suggest? Does it matter what kind of a cloud environment the particles are near? (our models suggest that it would matter). How many particles survive after they are produced. How rapidly do they mix with their surroundings? All of these studies would take place for such a small area and over such a small amount of time that they would be indiscernible a few kilometers away, or a few hours after they were stopped.
4. The next set of field tests would reach the scale where the sea salt particles might actually influence cloud system for a short period of time. Stage 1 (involving a single small research aircraft nearby a single emitter of salt particles) would be to see whether scientists could produce a "ship track" like the ones that are seen regularly in satellite pictures as a result of ship pollution, and to try to construct experiments where the effects of the sea salt particle emissions could produce a measurable effect on the cloud. Stage 2 studies on a larger scale (maybe a box a hundred kilometers on a side, involving 2–3 aircraft and a ship to make measurements above multiple sources of sea salt particles) would look at: a) how many particles are needed to brighten a particular kind of cloud; b) the influence of the seeding on surrounding clouds; c) how many sources that emit particles are required to influence a particular type of cloud over a small region (say a square a few tens of kilometers on a side). One would then be in a position to use that kind of a perturbation to answer the question of whether our models are able to predict the evolution of a cloud and its response to a perturbation. Various strategies could be employed by turning the sea salt particle source on and off for a few hours, or by seeding patches of clouds adjacent to unseeded regions, and contrasting the behavior of the cloud in both regions to explore how the salt particles influence that particular cloud type. This kind of field experiment should be performed at a variety of locations to see whether scientists are able to predict the response of models to such a perturbation for different situations.

Larger scale studies: All of the previous field tests would be designed to introduce a local change that is far smaller than the kinds of changes to aerosol amounts introduced by, for example, emissions from a large city, or a large forest fire, and the emissions would take place for only a brief time. Because the sea salt particles, and the clouds themselves persist for only a few hours to a few days the field experiment effects would disappear rapidly, and one would not be able to detect the effects of the experiment itself a few days after sea salt emissions were terminated.

If the previous studies indicated that it were possible to introduce measurable and predictable changes in clouds, then more intrusive studies on the climate system would need to be considered. The next level of field experiments could have possible (temporary) effects on the climate system, and such studies would require a much more intensive level of scrutiny, governance and planning. These type of field experiments would attempt to introduce significant changes in clouds for a sufficiently long time over a broad enough region that they would temporarily cool an small area of the ocean surface, and possibly introduce small shifts in winds or precipitation patterns. While the study is taking place, it could have an equivalent effect to that introduced by the pollution from a city on clouds. It would still have a much smaller impact on climate than many major features like ENSO, but it could be large enough to actually be detectable days or weeks after the field experiment had taken place. It will take a dedicated and coherent research program to understand how one would design such field experiments to maximize the possibility of detecting temporary changes in surface temperature, winds and precipitation. One wants to make changes that are large enough to be detectable, but small enough that they will disappear soon after the field experiment is over. It is difficult to outline a complete and appropriate strategy at this scale without more research.

Field experiments at scales larger than this, for longer time periods would have more and more impact on the climate, and thus require more and more caution.

Q3. Is it possible to somewhat confine the impacts of atmospheric-based geoengineering strategies, marine cloud whitening or stratospheric injections, to protect geographically-specific areas?

A3. The Earth system is interconnected in many ways, and all geoengineering strategies will probably affect all parts of the planet, but the effects will be felt most strongly near the area where the sunlight shading is strongest. The marine cloud whitening strategy should have a much more "localized influence" than the stratospheric aerosol strategy because the aerosols near the surface and the clouds they affect have a much shorter lifetime than the stratospheric aerosols. Climate models suggest that the cloud whitening strategy will maximize the cooling in local regions, although the effects will gradually spread away from a local area as the planet adjusts to the local cooling and that cooling effect is transmitted to other areas by the winds and ocean currents. This aspect of geoengineering research requires more study.

For example could SRM be localized specifically for the protection of polar ice?

It may in principle be possible to apply either the cloud whitening strategy, or the stratospheric aerosol strategy to protect polar ice. Computer model studies by Caldeira and colleagues suggest that if it were possible to shade the Arctic by reducing sunlight reaching the Arctic surface by 10–20% then polar ice could be preserved to the current ice extent and thickness, but Robock and colleagues have shown that stratospheric aerosols introduced over the Arctic will spread to lower latitudes and influences features there also. It may also be possible to use the cloud whitening strategy to maintain sea ice extent and thickness, because there are many low clouds in the Arctic during the summertime. There are a number of relevant studies that could be made to explore these issues:

1. It would be useful to understand how stratospheric aerosols introduced in the polar regions evolve. This would include knowing how rapidly the aerosols propagate to lower latitudes, and how rapidly they are removed from the stratosphere by sedimentation and mixing. Both computer models and field experiments should be used in these kinds of studies.
2. It would be useful to explore how susceptible low-level polar clouds are to whitening by using aerosol particles. Most of the focus to date has been on whitening clouds at subtropical latitudes and little or no studies have been done in polar regions. Literature reviews, computer models studies, and fieldwork would help in identifying the efficacy of whitening polar clouds.
3. It is worthwhile noting that very little work has yet to be done in studying the influence of geoengineering on ocean features (boundary currents, deep water formation and features like ENSO) or ecosystems. The changes to these features will occur only if geoengineering techniques are applied for

months or years, so they may not be critical for the very earliest studies but these features are very important to the planet, and work should be done to understand the impact of geoengineering on them.

If it is unclear whether or not localized geoengineering is possible, what types of research could help inform the answer?

More work can be done in each of the areas mentioned above with computer modeling. As technology becomes available to produce the particles needed to explore a given geoengineering strategy it would make sense to develop small scale field programs to verify the behavior predicted by the computer models. As discussed above, the initial field studies would not be designed to understand the consequences of geoengineering to the planet, but only to explore our understanding of the effect on components of the climate system at the process level by answering such questions as: 1) how rapidly do stratospheric aerosol particles grow? 2) how quickly are they flushed out of the stratosphere? 3) can we produce stratospheric aerosols in sufficient numbers that they might shield the planet? 4) how do sea salt particles mix near the ocean surface in polar regions? 5) Is there special chemistry taking place on those sea salt particles that influences for example ozone concentrations in the Arctic? 6) do the sea salt particles act to effectively whiten Arctic clouds in summer? These are just examples of the questions that need to be considered.

Q4. In your testimony, you stated that geoengineering research receives about $1M per year in funding, and roughly $200,000 of that is from federal sources. What initial funding levels would you recommend for a federal program authorizing atmospheric sulfate injection and marine cloud whitening research?

A4. I think a minimal funding level of $5–10M/year from federal sources for scientific research would help progress in geoengineering research, and also provide reassurance to society that the research is being done in an objective and unbiased manner. This level would allow some exploratory work to take place with strategies that have already been thought of. The work could involve computer modeling studies, and some support for lab and bench studies to explore the technology needed to produce aerosol particles for either the stratospheric aerosol, or the cloud whitening to be done. That funding level might also allow some support for as yet unidentified strategies to be fleshed out.

As our understanding of a particular approach increases more money would be required. A single ambitious field study for cloud whitening would involving multiple aircraft, a ship for a month, support for satellite studies and scientific research would require $20–30M to see whether one could actually produce a measurable effect on the reflectivity of the planet locally. More money would be needed for planning the field experiment and analyzing the results.

It would probably take another factor of 10 in funding if one were to then start considering measuring the consequences to the planet (by for example looking for the impact on ecosystems, or on ocean features) for geoengineering that might actually have a measurable effect on the planet.

Which agencies and or national labs would be best equipped to initiate such modeling and laboratory and field-based research?

NASA, DOE, NOAA, and NSF all have a mandate to study various relevant components of the earth system and climate change science. I believe firmly that each of these agencies can and should participate in research in stratospheric aerosol and cloud whitening strategies. Here is a quick list of some of the relevant labs by agency and their particular expertise. Each of these agencies also funds university and other research entities and they should also play a part.

Agency	Laboratory	Expertise
NASA	Goddard, JPL,	Remote sensing relevant to clouds, aerosols, and climate
	(aircraft research managed via Johnson, Wallops)	aircraft field measurements relevant to clouds, aerosols, and climate
DOE	PNNL, BNL, LLNL	Field studies, lab studies, and modeling relevant to clouds, aerosols and climate
NOAA	ESRL Chem. Sci. Div, GFDL	Field and Lab studies, cloud and aerosol models, climate models
NSF	NCAR	Field and lab studies, cloud models, climate models

These Agencies also have a great deal of relevant expertise in CDR, but I did not testify on that topic and will not make recommendations on how research in that area should be conducted.

Q5. The science and technology committee has held three geoengineering hearings and each witness at each hearing has emphasized the deep distinctions between the two types of geoengineering: solar radiation management) SRM) and carbon dioxide removal (CDR). If legislation were developed to facilitate geoengineering research, how should these distinctions be dealt with or accommodated? For example should CDR research initiatives be sited amongst existing activities at federal agencies while SRM research is authorized separately under the umbrella of "geoengineering research?"

A5. I agree that CDR and SRM techniques should be treated separately, both at the funding level, and in terms of their oversight, and research goals. I see no reason why CDR research could not be accommodated within the existing activities involving managements of CO_2 and the Carbon Cycle. I do believe that SRM should be authorized separately.

ANSWERS TO POST-HEARING QUESTIONS

Dr. Klaus Lackner, Department Chair, Earth and Environmental Engineering, Ewing Worzel Professor of Geophysics, Columbia University

Questions submitted by Chairman Brian Baird

Q1. The mineral sequestration technologies you describe are certainly distinct from the technologies being researched through existing CCS programs at the Department of Energy, such as the Clean Coal Power Initiative (CCPI). In your testimony, however, you described mineral sequestration as "Carbon Storage 2.0."

a. Should mineral sequestration research be sited among the existing CCS activities within the federal agencies?

b. Alternatively, should mineral sequestration research activities be undertaken in a newly established, separate research program?

c. Which federal agency(s) would be best suited to carry out mineral sequestration research activities?

A1. Mineral sequestration is a particular form of CCS, so it could well be sited among existing CCS programs. However, most funded CCS technologies are further down the development path. Mineral sequestration and other more innovative technologies would benefit from an institutional home that looks at a longer development horizon. A stronger role of basic sciences and the USGS would be very welcome.

Q2. The Science and Technology Committee has held three geoengineering hearings, and each witness at each hearing has emphasized the deep distinctions between the two types of geoengineering: solar radiation management (SRM) and carbon dioxide removal (CDR).

a. If legislation were developed to facilitate geoengineering research, how should these distinctions be dealt with or accommodated?

b. For example, should CDR research initiatives be sited among existing activities at federal agencies, while SRM research is authorized separately under the umbrella of "geoengineering research?"

A2. Solar radiation management and most carbon dioxide removal have very little in common. Specifically, the technical capture of carbon dioxide from the air is certainly a form of CCS and naturally fits under this umbrella. It is very different from technologies that aim to modify natural geodynamic systems.

ANSWERS TO POST-HEARING QUESTIONS

Dr. Robert Jackson, Nicholas Chair of Global Environmental Change, Professor, Biology Department, Duke University

Questions submitted by Chairman Brian Baird

Q1. You noted in your testimony that reflective materials over deserts would be an undesirable geoengineering strategy because of its harmful effects on ecosystems. Please elaborate upon this statement.

A1. This suggestion strikes me as a poor idea, environmentally and scientifically. Deserts are 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 deserts (and other comparable manipulative strategies) 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.

Examined from a different perspective, consider the recent public opposition to solar-thermal power facilities in California, Nevada, and other states. If siting relatively limited power facilities in desert ecosystems is difficult, how likely is the public to accept such a disruptive shield for thousands of square miles in the United States? Taxpayers in the United States deserve better solutions than proposals such as this one.

Q2. You described in your testimony the interrelated, and sometimes conflicting, impacts on atmospheric carbon concentration and surface albedo caused by large-scale afforestation. While new forests sequester atmospheric carbon through photosynthesis, the dark growth can also decrease the local reflectivity, causing more sunlight to be absorbed. One article written by scientists at Lawrence Livermore National Lab,[1] among others, suggests that because of this relationship, tropical afforestation would be very beneficial, but afforestation in temperate regions would be marginally useful.

a. Do you agree with this assessment?

b. What geographic areas are, in general, most appropriate for afforestation, and what types should be avoided?

A2. My response below is a summary based on the information in Jackson et al. 2008 (Jackson RB, JT Randerson, JG Canadell, RG Anderson, R Avissar, DD Baldocchi, GB Bonan, K Caldeira, NS Diffenbaugh, CB Field, BA Hungate, EG Jobbágy, LM Kueppers, MD Nosetto, DE Pataki 2008 Protecting Climate with Forests. Environmental Research Letters 3:044006).

Based on decades of research in carbon sequestration and biophysics, we (the authors of the above paper) suggest that avoided deforestation, forest restoration, and afforestation in the tropics provide the greatest value for slowing climate change. Tropical forests combine rapid rates of carbon storage with biophysical effects that are beneficial in many settings, including greater convective rainfall. Forestry projects in warm-temperate regions, such as the southeastern US, can also help reduce warming, but large uncertainties remain for the net climate effects of forestry projects in temperate regions. Forestry projects in boreal systems are less likely to provide climate cooling because of the strong snow-cover feedback. Thus, incentives for reforesting boreal systems should be preceded by thorough analyses of the true cooling potential before being included in climate policies.

Policies could also be crafted to provide incentives for beneficial management practices. For instance, urban forestry provides the opportunity to reduce energy use directly; in temperate regions deciduous trees block sunlight in summer, reducing the energy needed to cool buildings, but they allow sunlight to warm buildings in winter. In addition to choosing appropriate deciduous species, foresters could also select trees that are 'brighter', such as poplars, with albedos relatively close to those of the grasses or crops they replace. Additionally, forest planting and restoration can be used to reclaim damaged lands, reducing erosion and stabilizing streambanks.

[1] Bala, Govindasamy et al."Combined Climate and carbon-cycle effects of large-scale deforestation." PNAS, Volume 104, no. 16. April 17, 2007. Archived online at: *http://www.pnas.org/content/104/16/6550.abstract* as of April 27, 2010.

It is important to remember that trade-offs and unintended consequences are possible when forests are included in climate policies. The choice of tree species matters. Eucalypts, for instance, grow quickly and have a fairly bright albedo, but they are fireprone, can be invasive, and typically use more water than native vegetation. Because forestry projects can appropriate scarce water resources, they may be poor choices in drier regions. Applying fertilizers in forest sequestration projects helps trees grow more quickly but also increases the emissions of nitrous oxide, a potent greenhouse gas. Finally and perhaps most importantly, forests provide a wide range of important services, including preserving biodiversity, wildlife habitat, and freshwater supply. To the greatest extent possible, policies designed for climate change mitigation should not jeopardize other key ecosystem services.

Q3. In your testimony you recommended that the U.S. Global Change Research Program lead domestic geoengineering research efforts.

a. Is one or more of the existing interagency working groups within the USGCRP equipped to absorb geoengineering research? Or should one or more new working groups be created within the USGCRP to work on geoengineering?

A3. Aspects of the *science* of geoengineering cut across many of the working groups within USGCRP, including atmospheric composition, global carbon cycle, ecosystems, human contributions and responses, and land use and land cover change. For that reason, a new crosscutting working group may be needed. Complicating matters further, coordination with the U.S. Climate Change Technology Program (CCTP) on the *technology* of geoengineering will be equally important.

Q4. The Science and Technology Committee has held three geoengineering hearings, and each witness at each hearing has emphasized the deep distinctions between the two types of geoengineering: solar radiation management (SRM) and carbon dioxide removal (CDR).

a. If legislation were developed to facilitate geoengineering research, how should these distinctions be dealt with or accommodated?

b. For example, should CDR research initiatives be sited among existing activities at federal agencies, while SRM research is authorized separately under the umbrella of "geoengineering research?"

A4. The federal government's first priority for geoengineering research should be to provide incentives for carbon dioxide removal. The sooner we invest in, and make progress on, reducing greenhouse gas emissions today and promote ways to restore the atmosphere through carbon-removing technologies in the future, the less likely we are ever to need much riskier global sunshades. Our goal should be to cure climate change outright, not in treating a few of its symptoms.

In a new paper in Issues in Science and Technology (Jackson and Salzman 2010 Pursuing Geoengineering for Atmospheric Restoration), I coin the term "atmospheric restoration" as a guiding principle for prioritizing geoengineering efforts. The goal of atmospheric restoration is to return the atmosphere to a less degraded or damaged state and ultimately to its pre-industrial condition. Our climate is already changing, and we need to explore at least some kinds of carbon-removal technologies because energy efficiency and renewables cannot take carbon dioxide out of the air once it's there.

In response to your last question about where to place research initiatives, I have already stated that coordination through the USGCRP (and CCTP) is needed. If a different option is needed, some CDR activities could be sited within the Department of Energy. However, ocean fertilization is just one example of a CDR strategy that does not fit well in DOE and would be better placed in a different department or agency.

I do not believe that a separate umbrella of "geoengineering research" should be authorized specifically for SRM activities. Such a stand-alone structure would give SRM greater visibility (and priority) than it deserves compared to CDR. It would also be counter-productive scientifically. Splitting CDR and SRM research may be desirable administratively; I simply take exception to the suggestion that CDM belongs in current agencies but SRM doesn't and deserves its own structure.

Appendix 2:

Additional Material for the Record

Transcript of Discussion Prior to the Formal Hearing Opening

Chairman BAIRD: I will explain to our guests and witnesses that we are expecting a vote at about – a series of votes, I wish it were just one – at about 10:15. The way the votes work is that we have about 15 minutes to get over there but that never is real, so you have 25 minutes to get over there. The theory then being that with four witnesses at five minutes ea, we can actually hear your testimony before we have to run and vote and then give you all a bit of time to go have a break.

But I'd rather go ahead and start. We're waiting for our Ranking Member on the Republican side to join us, so what we'll do, I'll forgo any opening comments as hopefully will Mr. Inglis and I think the Chairman Mr. Gordon has agreed to do that. So as soon as Mr. Inglis gets here, which we hope will be soon, we'll proceed and we'll proceed with alacrity. I think I may just introduce our witnesses before we call the hearing to order unless there's some procedural reason we can't do that. Is there any problem with that?

[No]

That is very kind of you since it is now 10:03. I will introduce our witnesses and there will be additional information about them in the record. Dr. David Keith is the Canada Research Chair in Energy and the Environment at the University of Calgary. Dr. Philip Rasch is a Laboratory Fellow of the Atmospheric Sciences & Global Change Division and Chief Scientist for Climate Science at Pacific Northwest National Lab. Dr. Klaus Lackner is the Ewing Worzel Professor of Geophysics and Chair of the Earth and Environmental Engineering Department at Columbia University, and Dr. Robert Jackson is the Nicholas Chair of Global Environmental Change and a professor in the Biology Department at Duke University. So we'll hear from them shortly as soon as we can officially start.

Mr. GORDON: Mr. Chairman while you are --- I was going to rope-a-dope a little bit while we're waiting for Mr. Inglis.

Chairman BAIRD: Unless we can start with Mr. Rohrabacher. Oh, here is Mr. Inglis.

Mr. GORDON: What I'll just quickly say while Mr. Inglis gets in place, is that I think probably you know that we're having parallel hearings with the Science and Technology Committee in the UK. We are looking more at the areas of potential research; they are looking at treaties. We hope that we are going to be able to come together later with a joint report. We have talked with the similar committees in the other EU parliaments, and I think that we will have other countries that will join us. As you know, if we are going to do anything in this area it needs to be global.

GEOENGINEERING III: DOMESTIC AND INTERNATIONAL RESEARCH GOVERNANCE

THURSDAY, MARCH 18, 2010

HOUSE OF REPRESENTATIVES,
COMMITTEE ON SCIENCE AND TECHNOLOGY,
Washington, DC.

The Committee met, pursuant to call, at 12:06 p.m., in Room 2318 of the Rayburn House Office Building, Hon. Bart Gordon [Chairman of the Committee] presiding.

BART GORDON, TENNESSEE
CHAIRMAN

RALPH M. HALL, TEXAS
RANKING MEMBER

U.S. HOUSE OF REPRESENTATIVES

COMMITTEE ON SCIENCE AND TECHNOLOGY

SUITE 2321 RAYBURN HOUSE OFFICE BUILDING
WASHINGTON, DC 20515–6301
(202) 225–6375
http://science.house.gov

Committee on Science and Technology
Hearing on

Geoengineering III: Domestic and International Research Governance

Thursday, March 18, 2010
12:00 p.m. – 2:00 p.m.
2318 Rayburn House Office Building

Witness List

Panel I

The Honorable Phil Willis, MP
Chair
Science and Technology Committee
United Kingdom House of Commons

Panel II

Dr. Frank Rusco
Director of Natural Resources and Environment
Government Accountability Office (GAO)

Dr. Scott Barrett
Lenfest Professor of Natural Resource Economics
School of International and Public Affairs and the Earth Institute
Columbia University

Dr. Jane Long
Deputy Principal Associate Director at Large
Fellow
Center for Global Strategic Research
Lawrence Livermore National Lab

Dr. Granger Morgan
Professor and Head
Department of Engineering and Public Policy
Lord Chair Professor in Engineering
Carnegie Mellon University

HEARING CHARTER

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

"Geoengineering III: Domestic and International Research Governance"

THURSDAY, MARCH 18, 2010
12:00 P.M.
2318 RAYBURN HOUSE OFFICE BUILDING

Purpose

On Thursday, March 18, 2010, the House Committee on Science and Technology will hold a hearing entitled "*Geoengineering III: Domestic and International Research Governance*." The purpose of this hearing is to explore the governance needs, both domestic and international, to initiate geoengineering research programs. Specifically, discussion will focus on governance to guide potential geoengineering research projects and which U.S. agencies and institutions have the capacity or authorities to conduct such research.

Witnesses

Panel I

- **The Honorable Phil Willis, MP** is the Chair of the Science and Technology Committee in the United Kingdom House of Commons.[1]

Panel II

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

Background

Geoengineering can be described as the deliberate large-scale modification of the earth's climate systems for the purposes of counteracting climate change. Geoengineering has recently gained recognition as a potential tool in our response to climate change. However, the science is new and largely untested and the international implications of research and demonstration are complex and often novel in nature. For these reasons, a pressing need for governance of geoengineering research has emerged. Geoengineering can be controversial because of the potential for environmental harm and adverse socio-political impacts, uncertainty regarding the effectiveness and cost of the technologies, the scale that may be needed to demonstrate the technology, and concern that the prospect of geoengineering may weaken current climate change mitigation efforts.[2] These issues highlight the potential barriers to research as well as the need for governance of these emerging technologies. Experts are calling for a governance model or set of models that will allow the field to develop in an adaptive manner that facilitates development and explo-

[1] *Chairman Willis will testify via satellite.*
[2] The Royal Society (2009). Geoengineering the Climate: Science, Governance and Uncertainty. Edited by J. Sheperd et al., New York.

ration of effective technologies that are environmentally and socially acceptable while being relevant for both domestic and international policy solutions.

There is broad consensus among geoengineering experts that expansive reductions in greenhouse gas emissions must be made to limit the effects of climate change. However, political inertia and trends in greenhouse gas emissions indicate that traditional mitigation efforts may not provide an adequate response to mitigate the effects of climate change.[3] Tools other than emissions reductions may be therefore needed. Proponents claim that geoengineering technologies, compared to traditional mitigation techniques, offer faster-acting, politically palatable, and cost-effective solutions. Only through research and testing can these assertions be validated or refuted. That said, greenhouse gas mitigation strategies alone may ultimately prove insufficient and the lead times that will be needed for sufficient geoengineering research, should it become necessary for deployment, may be years long.

Today's hearing is the third in a series of hearings that is intended to provide a forum for an open discussion of the merits and disadvantages of geoengineering research. These hearings are not intended to be an endorsement of geoengineering deployment.

Collaboration with the U.K. Science and Technology Committee

The U.S. and the U.K. Science and Technology Committees have successfully built upon each other's efforts to advance the international and domestic dialogues on the need for international collaboration on regulation, oversight, environmental monitoring, and funding of geoengineering research. In April of 2009, Chairman Gordon met with the Science and Technology Committee[4] of the U.K. House of Commons, chaired by the Honorable Phil Willis, MP. The chairmen agreed that their committees should identify a subject for collaboration. The U.K. Committee had recently published a report, *Engineering, Turning Ideas into Reality*, recommending that the government develop a publicly-funded program of geoengineering research. Given the international implications of geoengineering research and the authorities and interests of each committee, geoengineering emerged as an appropriate subject for collaboration by the chairmen.

The chairmen coordinated the research and both committees have been in close communication throughout. The U.K. Committee established its terms of reference for its inquiry into the regulation of geoengineering, issued a call for evidence in November 2009, and is issuing a Committee report on the topic in March 2010. This report will be submitted as written testimony on behalf of Chairman Willis at today's hearing. The official agreement between the U.S. and U.K. Committees, outlining the terms of work and collaborative agreement, will be included in the final hearing record.

In the first session of the 111th Congress the U.S. Science and Technology Committee began a formal inquiry into the potential for geoengineering to be a tool of last resort in a much broader program of climate change mitigation and adaptation strategies. To initiate this, Chairman Gordon requested information on geoengineering from the Government Accountability Office (GAO) on September 21, 2009. Dr. Frank Rusco, Director of Natural Resources and Environment at GAO will present the draft response to this request as his written testimony at today's hearing. The Committee formally introduced the topic of geoengineering research in Congress on November 5, 2009 with a Science and Technology Full Committee hearing, "*Geoengineering: Assessing the Implications of Large-Scale Climate Intervention*." On February 4, 2010 the Energy and Environment Subcommittee held the second hearing in the series, "*Geoengineering II: The Scientific Basis and Engineering Challenges*." Together with today's hearing, this series of hearings serves as the foundation for an inclusive and transparent dialogue on geoengineering at the Congressional level.

Definition of Geoengineering

Geoengineering technologies aim to intervene in the climate system through large-scale and deliberate modifications of the earth's energy balance in order to reduce temperatures and counteract the effects of climate change.[5] Most proposed geoengineering technologies fall into two categories: Carbon Dioxide Removal (CDR) and Solar Radiation Management (SRM). The objective of SRM methods is to reflect a portion of the sun's radiation back into space, thereby reducing the amount of

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[3] Lenton and Vaughan (2008). A review of climate geoengineering options. Tyndal Centre for Climate Change Research, UEA.

[4] *Formerly the U.K. Innovation, Universities, Science and Skills Committee.*

[5] The Royal Society (2009).

solar radiation trapped in the earth's atmosphere and stabilizing its energy balance. CDR methods propose to reduce excess CO_2 concentrations by capturing, storing or consuming carbon directly from air, as compared to direct capture from power plant flue gas and storage as a gas. CDR proposals typically include such methods as carbon sequestration in biomass and soils, modified forestry management, ocean fertilization, modified ocean circulation, non-traditional carbon capture, sequestration, distribution of mined minerals over agricultural soils, among others.[6]

The above definition of geoengineering may need to be modified going forward to create a more productive discourse on our response to climate change. CDR technologies remove excess amounts of CO_2 from the air, thus presenting different hazards and risks than SRM technologies. In fact, many CDR technologies could be categorized with traditional carbon mitigation strategies, especially if they were undertaken at a small scale. For example, a mid-scale program for avoided reforestation does not carry the same risks as large-scale atmospheric sulfuric injections. In fact, such a program's risks and challenges may not be greatly divergent from some traditional carbon management proposals, such as carbon credits. CDR technologies may not invoke the need for international governance instruments either. SRM approaches, on the other hand, call for the introduction of technologies into the environment; therefore, presenting novel challenges to governance and larger hurdles for basic research and risk assessment. Some experts suggest that the term "geoengineering" encompass fewer of the more benign technologies discussed above. Coming to a resolution on appropriate terminology for this field may be a key step to increasing public understanding of geoengineering and assist the field in moving forward.

Domestic Research

Although formal research in Federal agencies has been largely limited to a small number of National Science Foundation (NSF) grants to study closely-scoped issues related to geoengineering,[7] it is clear that a number of Federal agencies have jurisdiction over one or more areas imbedded in geoengineering research. It is as yet unclear how Federal geoengineering research programs could be organized or allocated among Federal research bodies, as well as how non-governmental research consortia might contribute. The location of existing expertise in pertinent scientific and engineering fields, and the ability to execute comprehensive plans for interdisciplinary, inter-agency coordination would be key considerations in structuring domestic research in this area. Furthermore, it should be recognized that many of the developments and research activities needed for a formal geoengineering research program are also desirable for non-geoengineering purposes, such as general climate science research.

The following are examples of how existing research capacities in Federal agencies could be engaged in geoengineering research from the basic science and engineering behind the technology, to quantifying its effectiveness, and to understanding the risk of such hazards as environmental impacts.

The National Science Foundation (NSF) supports basic foundational research that may assist in the identification of the most promising geoengineering technologies. The Biological and Environmental Research program (BER) at the Department of Energy's (DOE) Office of Science houses key expertise related to various elements of atmospheric and land-based geoengineering strategies. Satellite capabilities sited within the National Aeronautics and Space Administration (NASA) and the National Oceanic and Atmospheric Administration (NOAA) could help identify potential locations for land-based carbon management, inform atmospheric geoengineering approaches, and monitor large-scale land use changes. Climate modeling tools at NOAA, the Environmental Protection Agency (EPA) and DOE's Office of Science could potentially be used to monitor large-scale demonstration projects. Such resources could also be used in a basic research setting for reverse climate modeling activities to project the potential impacts of decreased solar radiation and atmospheric carbon levels. High-end computing capabilities within the Office of Science at DOE, e.g., facilities located at Oak Ridge National Lab, may be suited to provide such highly detailed climate projections.

For all CDR geoengineering strategies, a robust carbon accounting and verification program would be needed to ensure program effectiveness. Existing expertise in programs at EPA, the National Institute of Standards and Technology (NIST), and the Ameriflux and Atmospheric Radiation Measurement (ARM) pro-

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[6] *See the draft CRS report (2010) that is attached to this charter for descriptions of CDR and SRM technologies.*

[7] For example, researchers at Rutgers University received a grant in 2008 to model stratospheric injections and sun shading.

grams within the BER program at DOE could contribute to such a program. In addition, monitoring and verification tools such as NOAA's Carbon Tracker and the Advanced Global Atmospheric Gases Experiment (AGAGE) at NASA could also be useful. More advanced and comprehensive tools may be needed, however.

More specifically, the Forest Service and National Resource Conservation Service at the Department of Agriculture (USDA), the United States Geological Survey (USGS) at the Department of Interior, and DOE's BER program could contribute expertise and management experience to land-based carbon reduction strategies such as afforestation, avoided deforestation, and biochar. NOAA's expertise in oceanography at offices such as the Geophysical Fluid Dynamics Laboratory (GFDL) could contribute to ocean fertilization research. DOE's Office of Fossil Energy (FE) and the National Energy Technology Laboratory (NETL) could leverage their capacity from such initiatives as FutureGen and the Clean Coal Power Initiative for air capture and non-traditional carbon sequestration research activities. And the Office of Basic Energy Sciences (BES) at DOE could inform the geological materials side of non-traditional carbon sequestration.

The U.S. State Department would coordinate activities and agreements with foreign ministries for some geoengineering technologies. State Department involvement would depend, as noted, upon which activities are determined to impede upon existing international agreements or be associated with trans-boundary impacts. In addition, the involvement of more cabinet-level departments and Federal agencies may be useful for effective development of geoengineering research given the potential for associated agricultural, economic, international security, and governance effects.

Criteria for Governance Development

Criteria to consider regarding the impacts of geoengineering technologies include: whether they are international or trans-boundary in scope; whether they dispense hazardous material into the environment or create hazardous conditions; and whether they directly intervene in the status of the ecosystem.

Governance needs for geoengineering research will likely differ based on the technology type, the stage of research, the target environment (e.g., the high seas, space, land, atmosphere), and where potential impacts may occur. As noted above, SRM and CDR technologies may have differing regulatory needs. CDR technologies that are similar in scope to most of those proposed today could be governed by existing U.S. laws and institutions. An exception to this would possibly be enhanced weathering in oceans and ocean fertilization techniques (both are CDR technologies), which may require international governance structures due to the potential for trans-boundary ecosystem impacts. SRM technologies, on the other hand, are more likely to require international governance for research. For example, two proposed SRM technologies, marine cloud whitening and atmospheric injections of sulfur particles would likely take place in an area governed by the international community, disperse trans-nationally, and have trans-national effects. Other SRM technologies such as land surface albedo modification may have lesser need for international governance.[8] Different governance needs will also become apparent as research develops from modeling, to assessments, and finally to field trials. Built-in flexibility and feedback mechanisms throughout the research process will assist in the effective development and governance of these emerging technologies. Lastly, different environments for research and demonstration are likely to require different governance strategies. Activities that take place in or affect the high seas or space versus the lower atmosphere, terrestrial, and near-shore areas will fall under different jurisdictions with different legal authorities.

Governance Options

Possible options for governance are outlined below. Please refer to the attached draft Congressional Research Service (CRS) report[9] and The Royal Society's study[10] for further information.

No Regulation

Governments could fully refrain from all governance of geoengineering, allowing the field to develop at will under existing frameworks. Advocates of this approach see private efforts as the best avenue to pursue research and development. Advocates of the "no regulation" approach may see government involvement as a stamp

[8] *For example, the deployment of genetically engineered plants with increased albedo could invoke treaties such as the Convention on Biological Diversity of 1992.*
[9] CRS (2010).
[10] The Royal Society (2009).

of approval for potentially unfavorable technologies. It is important to note that this approach essentially results in an unregulated research environment for largely new and unproven technologies, whose impacts are uncertain and may be unevenly distributed, even from small demonstration projects.

International Treaties and Agreements

At this time, no international treaties or institutions exist with sufficient mandate to regulate the full suite of current geoengineering technologies.[11] Although no existing international agreements or treaties govern geoengineering research by name, existing institutions could theoretically be modified to incorporate this field. For example, the U.N. Framework Convention on Climate Change (UNFCCC) may serve as a potential governing body for geoengineering. Another suggestion is that the Intergovernmental Panel on Climate Change (IPCC) could establish a technical framework to determine where the research should be focused and what technologies are scientifically justified.

Treaties for geoengineering research governance may be inappropriate at this time as the field encompasses many emerging technologies. In such a situation, treaty discussions could lead to a moratorium on research because nations often negotiate based on what their capacity for research, development, deployment and assessment is today, which in most cases is limited. Proponents of a moratorium argue that the potential risks of these technologies are just too great. Alternatively, some suggest that a research moratorium would be ill-advised because it would prematurely inhibit the generation of scientific knowledge and fail to discourage potentially dangerous experimentation by less responsible parties. It could limit society's ability to gather the information necessary to make informed judgments about the feasibility or acceptability of the proposed technologies. A moratorium could also deter responsible parties while failing to dissuade potentially dangerous experimentation by less responsible parties.

International Research Consortia

Given how little is understood about the scientific, technical, and social components of proposed geoengineering technologies, crafting appropriate governance through new or existing treaties may be difficult. International research consortia such as the World Climate Research Program (WCRP) could be used effectively to safely advance the science while building a community of responsible researchers. This would essentially provide a middle ground between the *no regulation* and *international treaty* options. Past experiences show that international research consortia (e.g., the Human Genome Project and the European Organization for Nuclear Research) can succeed at prioritizing research for emerging technologies, developing effective and objective assessment frameworks, providing independent oversight of evolving governance needs, and developing voluntary codes of practice to govern emerging technologies.

Conclusions

Some geoengineering technologies appear to be technically feasible; however, there is high uncertainty regarding their effectiveness, costs, environmental effects, and socio-political impacts. Appropriate governance structures that allow for an iterative exchange between continued public dialogue and further research are needed to determine if such technologies are both capable of producing desired results and socially acceptable. Climate change is a global problem that impacts people and ecosystems at the local scale. If traditional mitigation efforts are not effective on their own,[12] we will need alternatives at the ready. In the next decade the debate over geoengineering will intensify. Research will lead to increasingly plausible and economically feasible ways to alter with the environment. At the same time, political and social pressure will grow—both to put plans into action (whether multi- or unilaterally), and to limit the development of geoengineering research. These issues led the U.K. and U.S. Science and Technology Committees to jointly consider the role for potential governance structures to guide research in the near term and to oversee potential demonstration projects in the long term.

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[11] *See the draft CRS report (2010) that is attached to this charter for descriptions of CDR and SRM technologies.*

[12] Lenton and Vaughan. (2008).

Chairman GORDON. Good morning and welcome to this hearing on and discussion with domestic and international research governance of geoengineering. And let me give a little preface, particularly to our guest, Chairman Willis. We are going to be having votes around our time, 12:30 or 1:00. You know what that is like, when the bells go off, so it is our hope to move forward with your first part of this hearing, and as we go along, we will have a little better understanding.

Our changing climate has been the topic of sometimes heated discussion by some of our committee's hearings. It is understandable. As with any field of science, climate service, or climate science, will continue to evolve over time to provide an ever-greater level of accuracy for findings and forecasts.

However, in my opinion, one thing is now clear. The overwhelming preponderance of data indicates that global climate is changing, that humans are at least partially responsible, and that we can best mitigate the damage by reducing our emissions of greenhouse gases such as carbon dioxide.

Additionally, I am concerned that the impacts of climate change could outpace the world's political, economic, and physical ability to avoid them through greenhouse gas reductions alone. Therefore, we must know what other tools we have at our disposal. Certain proposals for deliberate modification of the climate, otherwise known as geoengineering, represent one option. But we cannot know until we have done the research on the full range of impacts of global engineering.

It will take substantial time and research to determine whether these new technologies can develop appropriately, whether there is an appropriate governance structures, and to test them, to see what potential benefits and hazards may be posed.

As the Chairman of the committee of jurisdiction, my interest is to provide a forum for open and honest discussion of geoengineering, just as we will have on nuclear power, on carbon capture and sequestration, other energy sources, as well as other types of mitigation.

And today, we are here to discuss the matters of domestic and international governance of geoengineering research programs. With that, I would like to thank our excellent witness, Chairman Willis, for appearing before this committee, and I yield to the distinguished Ranking Member, Mr. Hall, for his opening remarks.

[The prepared statement of Chairman Gordon follows:]

PREPARED STATEMENT OF CHAIRMAN BART GORDON

Good Afternoon. I want to welcome everyone to today's hearing to discuss the Domestic and International Research Governance of Geoengineering.

Our changing climate has been the topic of sometimes heated discussion at some of our Committee's hearings.

It is understandable—As with any field of science, climate science will continue to evolve over time to provide an even greater level of accuracy in its findings and forecasts.

However, in my opinion one thing is clear now—the overwhelming preponderance of data indicates that the global climate Is changing, that humans are at least partially responsible, and that we can best mitigate the damage by reducing our emissions of greenhouse gases such as Carbon Dioxide.

Additionally, I am concerned that the impacts of climate change could outpace the world's political, economic, and physical ability to avoid them through greenhouse gas reductions alone.

Therefore, we must know what other tools we have at our disposal, and if certain proposals for deliberate modification of the climate, otherwise known as geoengineering, represent an option.

But we cannot know until we have done the research on the full range of impacts of geoengineering.

It will take substantial time to research these new technologies, to develop appropriate governance structures, and to test them to see what potential benefits and hazards they may pose.

As the Chairman of the Committee of jurisdiction my interest is in providing a forum for an open and honest discussion of geoengineering, just as we will do for nuclear engineering, carbon caption sequestration, and other complex engineering subjects.

Today we are here to discuss matters of domestic and international governance for geoengineering research programs.

Mr. HALL. Thank you, Mr. Chairman, and but for my respect for you, I would have a lot longer opening remark here, but I would just say that I believe this is the third hearing our committee has held on geoengineering.

As I have expressed on previous occasions, I have significant reservations about pursuing this line of research. With that, in the interest of time and courtesy to our very distinguished guest, I will just put this in the record.

You can read it later, if you would like to.

[The prepared statement of Mr. Hall follows:]

PREPARED STATEMENT OF REPRESENTATIVE RALPH M. HALL

Thank you, Mr. Chairman. I believe this is the third hearing our Committee has held on geoengineering. As I have expressed on previous occasions, I have significant reservations about pursuing this line of research.

The debate about climate change is far from over. This statement is even more true today given the several admissions by the Intergovernmental Panel on Climate Change, or IPCC, since the end of last year, regarding mistakes, miscalculations and the use of non-peer reviewed science in the 4th Assessment Report. Despite many assurances that the base science has not been compromised, our faith in the scientific community when it comes to climate change research has been severely shaken. We are now facing an onslaught of regulations that could severely harm our economy based upon this science that has now come into question.

Today's hearing focuses on domestic and international research governance of geoengineering. Although I think it is premature to be wading into this aspect of geoengineering—we have yet to agree on whether or not we should pursue this—there are several hurdles that would need to be overcome in order to implement any type of governance structure. On the domestic side, there is no way to truly verify the science without conducting experiments. Like every other test that could potentially effect the environment, an Environmental Impact Assessment would have to be conducted in order to comply with current law.

Since a geoengineering experiment is supposed to affect the environment, I am not sure that such an Assessment could successfully meet current standards under the National Environmental Protection Act (NEPA), as this law has been interpreted over time to ensure that any impact on the environment is minimized or eliminated.

Internationally, I find it hard to believe that there would be any kind of consensus on this issue.

And, as we witnessed with the Copenhagen conference last December, when a larger consensus breaks down, a small group of nations may try to work out a deal amongst themselves. If world leaders decide to come together and seriously discuss geoengineering, it could force a situation where some nations feel justified embarking on their own program. Geoengineering could have global repercussions, so it is especially troubling that one or more nations could band together to produce an outcome that could have global implications, such as attempting to mimic a volcanic eruption.

So, Mr. Chairman, while I am interested in the testimony of our witnesses today, I must state that I am skeptical of this research and wary of the potential diplomatic minefield we may be stumbling into if we pursue this. I look forward to hearing from our distinguished witnesses.

[The prepared statement of Mr. Costello follows:]

PREPARED STATEMENT OF REPRESENTATIVE JERRY F. COSTELLO

Good Afternoon. Thank you, Mr. Chairman, for holding today's hearing to discuss the governance of potential geoengineering research projects in the U.S. and abroad.

Global climate change is an international issue that will require an international response. For this reason, I am pleased to welcome our colleagues from the United Kingdom with whom this Committee has worked to explore the potential of geoengineering as a means of reducing greenhouse gas emissions.

Geoengineering could have a global impact on our atmosphere, oceans, and land. Because these techniques have the potential to change the chemical make-up of the earth, international cooperation and governance of the research will be necessary. In particular, it will be important to have the involvement of as many international partners as possible. I would like to hear how all countries, including less developed countries that have been reluctant to work on climate change mitigation in the past, may engage in geoengineering research. Further, I would like to know what international organizations would best be suited to take the lead in governing this research.

In addition, geoengineering remains in its earliest stages of research and development, but there are significant concerns about the safety and reliability of geoengineering. I would like to know how the international community may address these safety risks should geoengineering research move forward.

I welcome our two panels of witnesses, and I look forward to their testimony.

Chairman GORDON. Without objection. Thank you, Mr. Hall. And now, it is my pleasure to introduce our witness at this time. Member of Parliament Phil Willis is the Chairman of the United Kingdom's House of Commons Science and Technology Committee.

Chairman Willis has represented the constituency of Harrogate and Knaresborough in the Parliament since 1997. Before his election to the House of Commons, Chairman Willis served as a distinguished educator in U.K. schools for over 35 years, 20 of those years as head teacher at a large comprehensive school.

During his tenure in Parliament, Chairman Willis has been a champion for inclusive childhood education, vocational training, and affordable university tuition. I am honored to have or embarked upon these joint activities with your committee during each or our last terms.

We thank you for your commitment to this inquiry and appearing before us today.

And let me remind everyone here today, this is a very historic and unique hearing that we are having. To the best of my knowledge, it is the first time that two committees, similar committees, in this case, the Science and Technology Committee within Congress and the U.K., have agreed to have a joint hearing, or I guess I should say parallel hearings on a topic from which there will be brought back information, not as a legislative proposal, but rather, as a potential recommendation.

So, again, this is historic, and Chairman Willis, I appreciate you being a part of this. Your written testimony will be included in the record, and now, we welcome you to begin your oral testimony.

Let us see. Mr.—Chairman Willis, do you hear us now? Hold your hand up if you can hear us. Well, we know we have a time delay, but not that much? Larry, what do you think? Let us—once again, Chairman Willis, can you—raise your hand if you can hear me.

Well, again, do we have Larry around, or has he escaped? I can understand him trying to get away. I see Chairman Willis' lips, but I can't read them. So, let me suggest to the staff—are we having a parallel telephone conversation with them, or internet conversation? Okay.

Well, I am going to try one more time. Mr. Willis, if you could hear me, raise your hand. I don't see it. So, why don't I suggest that our other—our Panel II come forward, and whatever—I wish there was a way that we could—we don't have any kind of parallel communication?

Okay, Larry, what do you think? Okay. Chairman Willis, can you hear me? Raise your hand if you can.

Chairman WILLIS. I certainly can.

Chairman GORDON. Oh, good. Good.

Chairman WILLIS. Barely hear you.

Chairman GORDON. Well, you may have missed the well-deserved glorious introduction that I had given you earlier, as well as the statement of the uniqueness and historic aspect of this hearing. There is another historic matter going on right now, and that is a healthcare debate in Congress.

Our phone lines are being jammed, we had 40,000 yesterday, so it is making all communication difficult, but as we pointed out earlier, if we could get to the Moon, we should be able to complete this hearing.

And so, with that, I welcome you to begin.

STATEMENT OF HON. PHIL WILLIS, MP, CHAIRMAN, SCIENCE AND TECHNOLOGY COMMITTEE, UNITED KINGDOM HOUSE OF COMMONS

Chairman WILLIS. Well, first of all, thank you very much indeed, Chairman Gordon. I was making the comment that if we can't get this to work, then geoengineering is a long way off the agenda.

But may I commence by saying how honored I am to appear before the U.S. House of Representatives Science and Technology Committee. And this, as I am probably—I am sure you said in Washington, is a first for our Committees, and I trust that the level of cooperation between our Committees can be continued after our general election, which occurs in, probably, May of this year.

This inquiry really began right in April 2009, when we visited Washington, D.C., and your Chairman, Bart Gordon, and we discussed the possibility of a joint inquiry. My fellow Committee Members and I are delighted that we have managed, within the constraints of procedure, to undertake something that approached a joint inquiry.

I state in the record that our staff have found your staff to be absolutely superb to work with, highly professional, exceedingly helpful, and knowledgeable. And we, as a committee, have thoroughly enjoyed the process of dovetailing our inquiry on geoengineering specifically to fit into your larger inquiry into the wider issues of geoengineering. I would very much hope that this relationship between our two committees is something that can outlast my, and indeed your, tenure.

Today, we published in London our report, *The Regulation of Geoengineering*, and geoengineering is a topic that, as a committee, we have been interested in for a while. We were, I believe, the very first legislature to examine geoengineering, which we did as part of a larger report on engineering itself.

In that report, we urged the U.K. government to consider the full range of policy options for managing climate change, and that includes various geoengineering options as potential Plan Bs, in the event that Plan A, mitigation and adaption, was not sufficient.

We divided geoengineering into technologies that reduce solar radiation, SDM or SRM, as I think you call it, that is, to keep the Earth cooler by reflecting more of the Sun's energy, and carbon sequestration, that is, taking carbon out of the atmosphere to reduce the greenhouse effect.

We cautioned against mass roll-outs without extensive research, and suggested that our U.K. Research Council fund research on modeling the effects of geoengineering and to start a public debate on the use of geoengineering techniques, both of which, I am pleased to say, are now underway.

Following that inquiry, the Royal Society produced a report on geoengineering, an excellent report that details the scientific and technological issues and options, and I believe that you took evidence from Professor John Shepherd, who was Chairman of the Royal Society's geoengineering panel.

One of the key recommendations from the Royal Society's report was that the regulation of geoengineering required careful consideration. We decided, as part of a dovetailing exercise with your committee, to take on that challenge and move the debate on the regulation of geoengineering a little further.

The first question in our terms of reference for this inquiry was, is there a need for international regulation of geoengineering research and deployment? And if so, what international regulation mechanisms need to be deployed? We discovered two things. First, such geoengineering techniques are already subject to regulation. In fact, there is a lot of regulation in this field. For example, ocean fertilization is being managed by the London Convention on Ocean Dumping under the London Protocol, and existing international regulatory arrangements, such as the U.N. Framework Convention on Climate Change, could relatively easily incorporate some geoengineering techniques, particularly carbon dioxide removal technologies.

Second, with regard to remaining techniques, such as stratospheric aerosols or space mirrors, it is not clear that existing treaties could be adequately altered to encompass them, and they would need looking at afresh.

Additionally, particularly for technologies such as injecting aerosols into the stratosphere, the costs are relatively low, which means that a rich country might be able to engage in this kind of activity unilaterally. And the effects are not predictable, and cannot be contained with national boundaries. We should be keen, therefore, to avoid a situation where one nation, deliberately or otherwise, alters the climate of another nation without prior agreement.

We concluded that, and I quote: "The science of geoengineering is not sufficiently advanced to make the technology predictable, but this, in itself, is not grounds for refusing to develop a regulatory framework. There are good scientific reasons for allowing investigative research to proceed effectively to devise and implement some regulatory frameworks, particularly for those techniques that a single country or small group of countries could test or deploy and impact the whole climate."

We also concluded that there is a need to develop a regulatory framework for geoengineering. Whether our existing international regulatory regimes, which need to develop a focus on geoengineering, or some regulatory systems that need to be designed and implemented for those solar radiation management techniques that currently fall outside any international framework.

Having decided that there is a need for regulatory regimes for geoengineering, we considered what principles might govern them. So, a group of academics from universities at Oxford, University College London and Cardiff, came up with a set of five principles, of which we are very supportive.

And these principles are: First, that geoengineering should be regulated as a public good, and we need to define what a public good is. Second, that public participation in geoengineering and decision-making is absolutely essential. If we don't take people with us, we may well lose the argument. Third, that disclosure of geoengineering research and open publication of results is absolutely essential if we are going to take the scientific community with us, and particularly, if we are going to take the public with us. Fourth, independent assessment of impacts. Peer review in this area is crucially important. And finally, governance before deployment, that we make sure that we have a framework before, in fact, there is major deployment.

May I conclude with a few specifics that might be of interest to your inquiry?

Following careful consideration of a wide range of views on geoengineering, we concluded the following. First, regarding research that uses computers to model the impact of geoengineering technologies, we wholeheartedly support that work, so long as it adheres to principle three on the disclosure and open publication of results.

We thought that even a short-term ban on solar radiation management research would be a mistake, largely, because it would be unenforceable, and therefore, having bans would not work.

Third, it seems sensible that if small-scale testing of solar radiation management geoengineering is going to take place, it should adhere to the full set of principles that I just outlined, and there should be negligible or predictable environmental impact as far as is possible, and that there should be no trans-boundary effects.

Fourth, it would be prudent for researchers exploring the impact of geoengineering techniques to make a special effort to include international expertise, and particularly, scientists from the developing world, which is most vulnerable to climate change.

And finally, we concluded that, and I quote: "Any testing that has impacts on the climate," that is large scale enough to have a real impact on the wider climate, must be subject to an international regulatory framework.

May I finish my comments, Mr. Chairman, by making some broader observations? We found this to be a hugely complex area. International agreements are not always easy for noncontroversial issues, but climate change, which is a controversial issue, because of the impact that mitigation efforts might have on our economies, has proven very difficult to get international agreement on, as we saw recently at Copenhagen.

I cannot see how geoengineering could be any easier, but that should not be a reason to back off. If the climate warms dangerously, and we can't fix the problem by reducing carbon emissions or adapting to the changing climate, geoengineering might be our only chance.

It would be irresponsible of us not to get the ball rolling on regulation. And to that end, we considered the only appropriate forum for managing something like geoengineering would be the United Nations. Geoengineering covers such a wide range of technologies that more than one international body would be required to work on international agreements. And we suggested that the U.K. government—and it is something it might be able to do in partnership with the U.S. government—should one, press hard for a suitable international body to commission a review of how geoengineering regulation might work in practice, and two, we should press hard for the establishment of an international consortium to explore the safest and most effective geoengineering options.

Thank you very much indeed, Mr. Chairman.

[The prepared statement of Chairman Willis follows:]

PREPARED STATEMENT OF PHIL WILLIS

INTRODUCTION

This inquiry really began life in April 2009, when we visited Washington DC and met with your Chairman, Bart Gordon. We discussed then the possibility of a joint inquiry. My fellow committee members and I are delighted that we have managed—within the restraints of procedure—to undertake something that approached a 'joint' inquiry.

May I state for the record that our staff have found your staff to be terrific to work with, professional, helpful and knowledgeable.

And we as a committee have thoroughly enjoyed the process of dovetailing our inquiry on geoengineering specifically to fit neatly into your larger inquiry into geoengineering issues more broadly. I very much hope that this relationship between the two committees is something that outlast mine and Bart's tenures.

BACKGROUND

Today we published our Report, the Regulation of Geoengineering.[1] Geoengineering is a topic that as a committee we have been interested in for a while. We were, I believe, the very first legislature to examine geoengineering, which we did as part of a larger report on engineering. In that report we urged the U.K. Government to consider the full range of policy options for managing climate change, and that includes various geoengineering options as potential "plan B", in the event of "plan A"—mitigation and adaptation—not being sufficient.

We divided geoengineering into technologies that reduce solar insolation (that is, keep the earth cooler by reflecting more of the sun's energy) and carbon sequestration (that is, taking carbon out of the atmosphere to reduce the greenhouse effect).

We cautioned against mass rollout without extensive research and suggested that our U.K. research councils fund research on modelling the effects of geoengineering and start a public debate on the use of geoengineering techniques—both of which are now underway.

Following that inquiry, the Royal Society produced a report on geoengineering—a fine report that detailed the scientific and technological issues and options—and I believe that you took evidence from Professor John Shepherd, who was chairman of the Royal's geoengineering panel.

One of the key recommendations from the Royal's report was that the regulation of geoengineering required careful consideration. We decided—as part of a dove-

[1] The Science and Technology Committee, The Fifth Report of Session 2009–10, The Regulation of Geoengineering, HC 221

tailing exercise with your committee to take on that challenge and move the debate on the regulation of geoengineering a little further.

A NEED FOR REGULATION?

The first question in our terms of reference for this inquiry was: is there a need for international regulation of geoengineering research and deployment and if so, what international regulatory mechanisms need to be developed? We discovered two things.

First, some geoengineering techniques are already subject to regulation. For example, ocean fertilisation is being managed by the London Convention on ocean dumping under the London Protocol. And existing international regulatory arrangements such as the UN Framework Convention on Climate Change could relatively easily incorporate some geoengineering techniques such as carbon dioxide removal technologies.

Second, as regards the remaining techniques—such as stratospheric aerosols or space mirrors—it is not clear that any existing treaties could be adequately altered to encompass them. Additionally, particularly for technologies such as injecting aerosols into the stratosphere, the costs are relatively low—which means that a rich country might be able to engage in this kind of activity unilaterally-and the effects are not predictable and cannot be contained with national boundaries—we should be keen to avoid a situation where one nation deliberately or otherwise alters the climate of another nation without prior agreement.

We concluded that "the science of geoengineering is not sufficiently advanced to make the technology predictable, but this of itself is not grounds for refusing to develop regulatory frameworks. There are good scientific reasons for allowing investigative research and better reasons for seeking to devise and implement some regulatory frameworks, particularly for those techniques that a single country or small group of countries could test or deploy and impact the whole climate."

We also concluded that there is a need to develop regulatory frameworks for geoengineering. There are existing international regulatory regimes, which need to develop a focus on geoengineering. And some regulatory systems need to be designed and implemented for those solar radiation management techniques that currently fall outside any international regulatory framework.

PRINCIPLES FOR GEOENGINEERING REGULATIONS

Having decided that there is a need for regulatory regimes for geoengineering we considered what principles might govern them. A group of academics from Oxford, University College London and Cardiff came up with a set of five principles of which we are very supportive. These principles are:

- geoengineering to be regulated as public good
- public participation in geoengineering decision-making
- disclosure of geoengineering research and open publication of results independent assessment of impacts, and
- governance before deployment.

We made a series of recommendations on the basis of these excellent suggestions.

1. Geoengineering should be for the public good. That is a given. And therefore any regulations should support this position. However, we suggested that for the sake of clarity,"public good" should be defined; after all, there are many different "publics"—some would benefit from global warming and they might not be too pleased with geoengineering deployment. We also noted that striving to make geoengineering for the "public good" might risk intellectual property rights, and that would be a shame. No IP means no industrial and private sector input; and without industrial input, a lot of these technologies might never get off the ground.

2. We are in favour of public consultation, but a bit cautious about "public participation in . . . decision-making". For example, could people who were adversely affected by geoengineering—even if the majority of people benefited—veto or alter geoengineering tests?

3. Our support for the notion of full disclosure of geoengineering research and the open publication of results is unqualified. In fact, we went further and suggested that an international database of geoengineering research to encourage and facilitate disclosure might be useful.

4. The called for "independent assessment of impacts" is very important. Independent assessment is a key scientific concept—it takes the task of assessing the effectiveness of an intervention away from its inventors. That is a good thing. However, we do think that the term 'impacts' covers a range of issues. For example, de-

ployment of geoengineering might occur only when temperatures go past a dangerous point of warming, say 3.5 degrees centigrade, so our definition of impact would need honing. Another issue it raises is compensation for people that suffer because of geoengineering. This legal aspect of geoengineering is unavoidable and central to the reasons why good regulation is necessary.

5. The last of the principles, "governance before deployment", again, we support without qualification. We suggested that our government commission research and press for research to be carried out through international bodies on the legal, social and ethical implications of geoengineering.

SPECIFICS

May I conclude with a few specifics that may be of interest to your inquiry? Following careful consideration of a wide range of views on geoengineering, we concluded the following:

- regarding research that uses computers to model the impact of geoengineering technologies, we support that work-so long as it adheres to principle 3 on the disclosure and open publication of results;
- we thought that even a short-term ban on all solar radiation management research would be a mistake, at least in part because it would be unenforceable;
- it seems sensible that if small-scale testing of solar radiation management geoengineering is going to take place it should adhere to the full set of principles that I just outlined, that there should be negligible or predicable environmental impact as far as is possible, and that there should be no transboundary effects;
- it would be prudent for researchers exploring the impact of geoengineering techniques to make a special effort to include international expertise, and particularly scientists from the developing world which is most vulnerable to climate change; and
- finally, we concluded that "any testing that impacts on the climate"-that is, that is large-scale enough to have a real impact on the wider climate-"must be subject to an international regulatory framework".

CLOSING

May I finish my comments, Chairman, by making some broader observations. We found this to be a very complex area. International agreements are not always easy for non-controversial issues. Climate change, which is a controversial issue because of the impact that mitigation efforts might have on our economies, has proven very difficult to get international agreement on. I cannot see how geoengineering would be any easier.

But that should not be a reason to back off. If the climate warms dangerously, and we can't fix the problem by reducing carbon emissions or adapting to the changing climate, geoengineering might be our only chance. It would be irresponsible for us not to get the ball rolling on regulations.

To that end, we considered that the only appropriate forum for managing something like geoengineering would be the U.N. Geoengineering covers such a wide range of technologies that more than one international body would be required to work on international agreements. We suggested that the U.K. government—and this is something it might be able to do in partnership with the U.S. government—should (1) press hard for a suitable international body to commission a review of how geoengineering regulations might work in practice; and (2) press hard for the establishment of an international consortium to explore the safest and most effective geoengineering options.

BIOGRAPHY FOR PHIL WILLIS

Phil Willis was born in Burnley, Lancashire. At school he excelled in sport and at one time was a trialist for Burnley FC. He went to study History and Music at the City of Leeds and Carnegie College, qualifying as a teacher in 1963 from the University of Leeds Institute of Education. Later in his career he was seconded to Birmingham University where he gained a B.Phil. degree with distinction in 1978.

Phil's teaching career was mostly spent in Leeds where he rose rapidly from Assistant Master at Middleton Secondary Boys' School in 1963 to become Deputy Headteacher at West Leeds Boys' Grammar School in 1974, Perhaps his most rewarding period was spent at Primrose Hill High School in the Chapletown district of Leeds where for seven years he was involved in multi-cultural education and outreach youth work.

In 1978 he became head of Ormesby School in Middlesbrough where he helped pioneer the integration of children with physical disabilities into mainstream education. In 1983 he returned to Leeds as Head of one of the city's largest comprehensive schools, John Smeaton Community High School. Situated in one of the more deprived areas of Leeds, he continued his mission, for 'inclusive' education.

He became nationally recognised for the inclusion of children with severe learning difficulties and others with sensory impairments into mainstream education. Prior to his election to Westminster he was involved with another pioneering development—'The family of Schools' initiative—which brought together all agencies concerned with developing first class opportunities for children from disadvantaged backgrounds.

Phil joined the Liberal party in 1985 and was elected to Harrogate Borough Council in 1988. He became leader of the Council in 1990 and following his election to North Yorkshire County Council in 1993 became Deputy Group Leader.

His period as Leader of Harrogate Council coincided with an unprecedented rise in Liberal Democrat representation and he is credited with many of the economic generating initiatives which have made the area one of the top earners in the country. His most notable success was turning the famous Harrogate Conference Centre from a loss making 'white elephant' into a £1m a year success story.

At Westminster, he was appointed Shadow Secretary of State for Education and Skills in 1999 retaining the post until 2005, when he was appointed Chairman of the House of Commons Science and Technology Select Committee. In May 2007 he was also appointed Chair of the Joint Committee on the Draft Human Tissue and Embryos Bill. In November 2007 the Science and Technology Select Committee was disbanded and the House of Commons Innovation, Universities, Science and Skills Select Committee was formed; Phil Willis was elected chairman soon after.

In the summer 2009 departmental reshuffle the department for Innovation, Universities and Skills was disbanded, along with its corresponding Select Committee. Following a hard-fought campaign from Phil and leading members of the Science community, the Science and Technology Select Committee was re-created on October 1st, with Phil elected as Chairman.

Married with two children, Phil is a keen supporter of Leeds United and spends much of his spare time in Ireland where he retains an interest in his family's farm in Donegal

Also submitted for the record by Chairman Willis:

United Kingdom House of Commons Science and Technology Committee. *The Regulation of Geoengineering.* Fifth Report of Session 2009–10. London: The Stationery Office Limited. 10 March 2010.

This report, totaling 119 pages, is available in its entirety archived online as of June 21, 2010 at *http://democrats.science.house.gov/Media/file/Commdocs/hearings/2010/Fu11/18mar/UKR_Regulation_of_Geoengineering_report.pdf.* The full report should be considered Chairman Willis' full submission for the hearing record.

Attached here are:

I. Table of Contents

II. Executive Summary

III. Introduction

House of Commons

Science and Technology Committee

The Regulation of Geoengineering

Fifth Report of Session 2009–10

Report, together with formal minutes, oral and written evidence

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The Science and Technology Committee

The Science and Technology Committee is appointed by the House of Commons to examine the expenditure, administration and policy of the Government Office for Science. Under arrangements agreed by the House on 25 June 2009 the Science and Technology Committee was established on 1 October 2009 with the same membership and Chairman as the former Innovation, Universities, Science and Skills Committee and its proceedings were deemed to have been in respect of the Science and Technology Committee.

Current membership

Mr Phil Willis *(Liberal Democrat, Harrogate and Knaresborough)(Chair)*
Dr Roberta Blackman-Woods *(Labour, City of Durham)*
Mr Tim Boswell *(Conservative, Daventry)*
Mr Ian Cawsey *(Labour, Brigg & Goole)*
Mrs Nadine Dorries *(Conservative, Mid Bedfordshire)*
Dr Evan Harris *(Liberal Democrat, Oxford West & Abingdon)*
Dr Brian Iddon *(Labour, Bolton South East)*
Mr Gordon Marsden *(Labour, Blackpool South)*
Dr Doug Naysmith *(Labour, Bristol North West)*
Dr Bob Spink *(Independent, Castle Point)*
Ian Stewart *(Labour, Eccles)*
Graham Stringer *(Labour, Manchester, Blackley)*
Dr Desmond Turner *(Labour, Brighton Kemptown)*
Mr Rob Wilson *(Conservative, Reading East)*

Powers

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Publications

The Reports and evidence of the Committee are published by The Stationery Office by Order of the House. All publications of the Committee (including press notices) are on the Internet at http://www.parliament.uk/science
A list of reports from the Committee in this Parliament is included at the back of this volume.

Committee staff

The current staff of the Committee are: Glenn McKee (Clerk); Richard Ward (Second Clerk); Dr Christopher Tyler (Committee Specialist); Xameerah Malik (Committee Specialist); Andy Boyd (Senior Committee Assistant); Camilla Brace (Committee Assistant); Dilys Tonge (Committee Assistant); Melanie Lee (Committee Assistant); Jim Hudson (Committee Support Assistant); and Becky Jones (Media Officer).

Contacts

All correspondence should be addressed to the Clerk of the Science and Technology Committee, Committee Office, 7 Millbank, London SW1P 3JA. The telephone number for general inquiries is: 020 7219 2793; the Committee's e-mail address is: scitechcom@parliament.uk.

Contents

Summary

Geoengineering describes activities specifically and deliberately designed to effect a change in the global climate with the aim of minimising or reversing anthropogenic (that is human caused) climate change. Geoengineering covers many techniques and technologies but splits into two broad categories: those that remove carbon dioxide from the atmosphere such as sequestering and locking carbon dioxide in geological formations; and those that reflect solar radiation. Techniques in this category include the injection of sulphate aerosols into the stratosphere to mimic the cooling effect caused by large volcanic eruptions.

The technologies and techniques vary so much that any regulatory framework for geoengineering cannot be uniform. Instead, those techniques, particularly carbon removal, that are closely related to familiar existing technologies, could be regulated by developing the international regulation of the existing regimes to encompass geoengineering. For other technologies, especially solar refection, new regulatory arrangements will have to be developed.

There are three reasons why, we believe, regulation is needed. First, in the future some geoengineering techniques may allow a single country unilaterally to affect the climate. Second, some—albeit very small scale—geoengineering testing is already underway. Third, we may need geoengineering as a "Plan B" if, in the event of the failure of "Plan A"—the reduction of greenhouse gases—we are faced with highly disruptive climate change. If we start work now it will provide the opportunity to explore fully the technological, environmental, political and regulatory issues.

We are not calling for an international treaty but for the groundwork for regulatory arrangements to begin. Geoengineering techniques should be graded with consideration to factors such as trans-boundary effect, the dispersal of potentially hazardous materials in the environment and the direct effect on ecosystems. The regulatory regimes for geoengineering should then be tailored accordingly. The controls should be based on a set of principles that command widespread agreement—for example, the disclosure of geoengineering research and open publication of results and the development of governance arrangements before the deployment of geoengineering techniques.

The UN is the route by which, eventually, we envisage the regulatory framework operating but first the UK and other governments need to push geoengineering up the international agenda and get processes moving.

This inquiry was innovative in that we worked collaboratively with the US House of Representatives Science and Technology Committee, the first international joint working of this kind for a House of Commons select committee. We found the experience constructive and rewarding and, we hope, successful. We are enthusiastic supporters of collaborative working between national legislatures on topics such as geoengineering with international reach. Our Report covering the regulation of geoengineering will now dovetail into a wider inquiry that the House of Representatives Committee is carrying out on geoengineering. Science, technology and engineering are key to solving global challenges and we commend to our successor committee international collaboration as an innovative way to meet these challenges.

1 Introduction

1. There were two spurs to this Report. First, in what we believe was a first for scrutiny by a legislature we examined geoengineering as one of the case studies in our Report, *Engineering: turning ideas into reality*.[1] We wished to follow-up that earlier work. Second, during our visit to the USA in April 2009 we met the Chairman of the House of Representatives Science and Technology Committee, Representative Bart Gordon, who suggested that the committees might find it beneficial to coordinate their scrutiny on a subject. Later in the year we agreed that geoengineering was an area where we could pool our efforts and complement each other's work, particularly as it has a significant internal dimension—a large geoengineering test could have global repercussions, deployment certainly would.

Previous scrutiny of geoengineering

2. In our earlier Report, *Engineering: turning ideas into reality*, we carried out a wide examination of geoengineering. The Report provided us with an opportunity to consider the implications of a new engineering discipline for UK policy-making. The broad definition of geoengineering that we used in the earlier Report holds good: we use the term "geoengineering" to describe activities specifically and deliberately designed to effect a change in the global climate with the aim of minimising or reversing anthropogenic (that is, human made) climate change.[2] A more succinct definition was provided by one of the witnesses to the current inquiry, Professor Keith: the intentional large-scale manipulation of the environment.[3]

3. To set the scene for this inquiry it is worth recalling some of our earlier findings, conclusions and recommendations from the earlier inquiry which informed our approach to this inquiry.

- We noted that unlike mitigation and adaptation to climate change, the UK had not developed any policies relating to geoengineering research or its potential role in mitigating against climate change.[4]

- We did not consider a narrow definition of geoengineering technologies to be helpful and took the view that technologies to reduce solar insolation[5] and to sequester carbon should both be considered as geoengineering options.[6]

1 Innovation, Universities, Science and Skills Committee, Fourth Report of Session 2008–09, *Engineering: turning ideas into reality*, HC 50–I, chapter 4

2 HC (2008-09) 50–I, para 160

3 DW Keith, "Geoengineering the climate: history and prospect", *Annual Review of Energy and the Environment*, (2000) 25:245–284

4 HC (2008–09) 50–I, para 159

5 Insolation is the offsetting of greenhouse warming by reducing the incidence and absorption of incoming solar (short-wave) radiation.

6 HC (2008–09) 50–I, para 182

- We were of the view that the Government should give the full range of policy options for managing climate change due consideration and that geoengineering technologies should be evaluated as part of a portfolio of responses to climate change, alongside mitigation and adaptation efforts.[7]

- The decision not to consider any initiative other than "Plan A"—mitigation—could be considered negligent, particularly since uncertainties in success of "Plan A—for example, climate sensitivity—could be greater than expected. Geoengineering should be considered "Plan B".[8]

- In order to identify those geoengineering options it might be feasible to deploy safely in the future, it was essential that a detailed assessment of individual technologies was conducted. This assessment had to consider the costs and benefits of geoengineering options, including their full life-cycle environmental impact and whether they were reversible. We welcomed the efforts of the Royal Society to review the geoengineering sector.[9]

- We considered that support for detailed modelling studies would be essential for the development of future geoengineering options, and to the construction of a credible cost-benefit analysis of technological feasibility. We urged the UK Research Councils to support research in this area.[10]

- We recommended that the Government engage with organisations including the Tyndall Centre, Hadley Centre, Research Councils UK and the Carbon Trust to develop a publicly-funded programme of geoengineering research.[11]

- Before deploying any technology with the capacity to geo-engineer the climate, we considered that it was essential that a rational debate on the ethics of geoengineering was conducted. We urged the Department for Energy and Climate Change (DECC) to lead this debate, and to consult on the full range of geoengineering options.[12]

- We were of the view that it was essential that the Government support socio-economic research with regard to geoengineering technologies, in order that the UK could engage in informed, international discussions to develop a framework for any future legislation relating to technological deployment by nation states or industry.[13]

7 HC (2008–09) 50–I, para 185

8 HC (2008–09) 50–I, para 187

9 HC (2008–09) 50–I, para 197

10 HC (2008–09) 50–I, para 203

11 HC (2008–09) 50–I, para 217

12 HC (2008–09) 50–I, para 226

13 HC (2008–09) 50–I, para 229

4. The Committee's Report was published in March 2009 and the Government replied in June 2009.[14] The main points relevant to this inquiry that the Government made were as follows.

- Geoengineering options currently did not represent viable alternatives to reducing greenhouse-gas emission. However, it recognised that it was important to keep such options under review as some might ultimately have a role to play in helping to ameliorate climate change, if emissions reductions were not achieved quickly enough. The Government therefore saw a need for some research on the potential of geoengineering technologies, to determine whether any of them could be used as an additional (Plan B) policy option for managing climate change, to complement the conventional mitigation and adaptation approaches.[15]

- The Government agreed that a detailed (and independent) assessment of geoengineering options was needed and welcomed the study that the Royal Society had been undertaking into climate engineering. It said that it would consider carefully the findings of this study and use it to inform its policy development on geoengineering.[16]

- The Government agreed with the Committee's view that support for detailed modelling studies would be essential, to help evaluate the feasibility and suitability of different geoengineering options. As indicated in the Committee's report, the nature of geoengineering research meant that much of it would need to be done on a "virtual" basis and the use of climate models would also enable a risk assessment of individual options.[17]

- Geoengineering technologies raised a number of very significant and difficult socio-economic issues and the Government agreed that some publicly-funded research on this aspect would also be needed, to inform and underpin its policy position in any future international negotiations that might take place on the possible deployment of individual geoengineering options.[18]

5. In September 2009, the Royal Society published its report, *Geoengineering the climate: science, governance and uncertainty*.[19] The report aimed "to provide an authoritative and balanced assessment of the main geoengineering options" but made the point that "far more detailed study would be needed before any method could even be seriously considered for deployment on the requisite international scale".[20] The report emphasised that geoengineering was not an alternative to greenhouse gas emission reductions and that, although geoengineering might hold longer-term potential and merited more research, it

14 Innovation, Universities, Science and Skills Committee, Fifth Special Report of Session 2008–09, *Engineering: turning ideas into reality: Government Response to the Committee's Fourth Report*, HC 759

15 HC (2008–09) 759, pp 11–12

16 HC (2008–09) 759, p 13

17 HC (2008–09) 759, p 13; see also Ev 36 [British Geophysical Association], para 1.

18 HC (2008–09) 759, p 14

19 The Royal Society, *Geoengineering the climate Science, governance and uncertainty*, September 2009

20 The Royal Society, *Geoengineering the climate Science, governance and uncertainty*, September 2009, p v

offered "no quick and easy solutions that should distract policy-makers from working toward a reduction of at least 50 percent in global carbon dioxide [...] emissions by 2050".[21]

6. We welcomed both the Government's response to our Report—albeit we consider some parts to be too cautious—and the Royal Society's report. Both are constructive and show that further work needs to be done. We considered therefore what part we could play in moving geoengineering policy on in the limited time left in this Parliament. One of the recommendations in the Royal Society's report was that:

> The governance challenges posed by geoengineering should be explored in more detail, and policy processes established to resolve them.[22]

The report explained:

> A review of existing international and regional mechanisms relevant to the activities and impacts of [geoengineering] methods proposed to date would be helpful for identifying where mechanisms already exist that could be used to regulate geoengineering (either directly or with some modification), and where there are gaps.[23]

We considered that the national and international regulation of geoengineering was an issue we could examine in more detail by means of a short inquiry.

Coordinated working with US House of Representatives Science and Technology Committee

7. When the Innovation, Universities, Science and Skills Committee, as we were until October 2009, visited the USA in April 2009 we met Representative Bart Gordon, Chairman of the House Science and Technology Committee. Representative Gordon suggested that the two Committees might wish to identify a subject on which they could work together. The Commons Committee (now the Science and Technology Committee) discussed the proposal after its return from the USA and explored possible topics and arrangements for coordinating work. During the summer geoengineering emerged as an attractive subject, particularly as geoengineering has a large international dimension. In addition, the two Committees were at different stages in examination of the subject with the Commons Committee having, as we have noted, already produced a report and the House Committee about to embark on its first examination of the subject. This meant that each could cover different ground and complement each other's work.

8. In October 2009 the Committees agreed a timetable and working arrangements within the procedural rules of their respective legislatures. The text of a joint statement agreed between the Committees is the Annex to this Report.

9. The House Committee began its examination of geoengineering with a hearing in Washington DC on 5 November 2009, in which testimony was provided by a panel of

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21 Ev 51, para 2

22 The Royal Society, *Geoengineering the climate Science, governance and uncertainty*, September 2009, rec 6.1

23 The Royal Society, *Geoengineering the climate Science, governance and uncertainty*, September 2009, para 5.4

expert witnesses that included Professor John Shepherd, who chaired the working group that produced the Royal Society's report, and leading US climate scientist Professor Ken Caldeira, Carnegie Institution, from whom we took evidence in our earlier inquiry. That session assessed the implications of large-scale climate intervention. On 4 February 2010 the House Committee took evidence on the scientific basis and engineering challenges from Professor Klaus Lackner, Columbia University, from whom we took evidence for our earlier inquiry, and from Professor David Keith, who gave evidence to this inquiry. The third hearing is planned for 18 March 2010 and will cover issues of governance.[24] It is planned that our Chairman will give testimony to that session. Ultimately, the hearings may lead to the formation of legislation authorising US government agencies to undertake certain geoengineering research activities and establish intergovernmental research agreements with other nations.

10. It is our intention that this report will assist members of the House Committee in their deliberations on the regulation of geoengineering. We also see our work on geoengineering as a pilot for future collaborative scrutiny between select committees of the House of Commons and the committees of other national legislatures, which is an issue we examine further in this Report.

The inquiry

11. In our call for evidence on 5 November 2009 we stated that the inquiry would focus on the regulation of geoengineering, particularly international regulation and regulation within the UK. The following were the terms of reference of our inquiry.

- Is there a need for international regulation of geoengineering and geoengineering research and if so, what international regulatory mechanisms need to be developed?
- How should international regulations be developed collaboratively?
- What UK regulatory mechanisms apply to geoengineering and geoengineering research and what changes will need to be made for the purpose of regulating geoengineering?[25]

12. We received 13 written submissions (excluding supplementary memoranda) in response to our call for submissions, which we accepted as evidence to the inquiry and which are appended to this Report. We are grateful to all those who submitted written memoranda. We are especially pleased that with the international dimension to this Report we received submissions from across the world.

13. On 13 January 2010 we took oral evidence from three panels consisting of:

a) Dr Jason J Blackstock, Centre for International Governance Innovation, Canada, Professor David Keith, Director, ISEEE Energy and Environmental Systems Group,

24 "Subcommittee Examines Geoengineering Strategies and Hazards", US House of Representatives Science and Technology Committee, Press Release, 4 February 2010

25 "The regulation of geoengineering", Science and Technology Committee press release 2008–09 no. 10, 5 November 2009

University of Calgary, and John Virgoe, an expert in geoengineering governance based in Australia;

b) Sir David King, Director of the Smith School of Enterprise and the Environment and former Government Chief Scientific Adviser in the UK, and Dr Maarten van Aalst, Associate Director and Lead Climate Specialist at the Red Cross/Red Crescent Climate Centre, who gave evidence in a personal expert capacity;[26] and

c) Joan Ruddock MP, Minister of State, DECC, Professor David MacKay, Chief Scientific Adviser, DECC, and Professor Nick Pidgeon, on behalf of Research Councils UK.

14. We are grateful to those who provided oral evidence. All three members on the first panel gave their evidence by video link from, respectively, the USA, Canada and Australia. The arrangements worked well and, other than a couple of blips, each witness was able to hear the others and to comment on their responses. There was almost no time delay in the transmissions which greatly facilitated the flow of the session. It would assist the operation of the facility if the visual quality was improved and all the witnesses could see each other as well as the Committee. We wrote to the Speaker and the Liaison Committee to commend the facility and its development and we were encouraged by the Speaker's response. He replied in February 2010 and said that some technical aspects have been improved and that the audio-visual facilities in all committee rooms were being reviewed. **We welcome the review that the House is carrying out of the audio-visual facilities in committee rooms to enable the taking of oral evidence in committee by video link.**

Structure of this Report

15. This report is in four parts. The second chapter examines categories of geoengineering, the third examines the need for regulation of geoengineering, the fourth considers the outline of future regulatory arrangements and the final chapter looks at collaborative working between committees in national legislatures.

DISCUSSION

Chairman GORDON. Well, thank you, Chairman Willis, for that very good presentation.

We received your report, I think, 130 pages, today, which we are starting to go through.

INTERNATIONAL RESEARCH DATABASE

I certainly concur with you that geoengineering is controversial, both on the left and the right. It is, and I concur that it is something that we hope that will never take place, but it would be irresponsible for us not to start at least looking at the foundation for potential research.

I think any implementation is decades out, but you have to start somewhere. And so, we very much appreciate your participation, and that of your excellent staff.

Now, we will at this point move to the first round of questions, and the Chair will recognize himself for five minutes. As you mentioned in your testimony, you felt that an international database would be a very good way to have a tool for transparency and public understanding.

Do you have any suggestions on how that database might be developed or how it would work?

Chairman WILLIS. Well, first of all, Mr. Chairman, there are no extensive examples of international databases. I mean, here in the United Kingdom, we have a database which deals particularly with clinical trials, and the use of clinical trials. And in fact, the World Health Organization [WHO] also has a voluntary database on clinical trials. So, that is an example.

And the National Center for Biotechnology, or GenBank, which is, of course, held in the United States, has an excellent international global database for looking particularly at gene therapies and the like.

So, I think there are examples there. But really, it is hugely important that in terms of actually creating a database, that that is done in terms of international collaboration, that we include particularly Third World countries as well in that, because they are the most affected by climate changes, as we know.

So, I think it is important to, first of all, find somewhere where, in fact, we would have the repository, and there would have to be international agreement on that. I think secondly, we would want to know what would go in the database. And we felt that there were a number of things, first of all, in terms of simply listing current research.

I think it is quite possible, indeed, to pull together the research that is going on around the world. As you know, Mr. Chairman, there is some extensive research going on in the United States. There is research going on in Australia, in Canada, and elsewhere in the world.

I think secondly, we need to ensure that we state that research is out. If we are looking at particularly modeling from, for instance, aerosols in stratosphere, it is important that we get the results of that midterm. We don't wait for it to be completed.

I think thirdly, that we make sure that the database looks at the aims of research, that when research projects are being launched, that it is clear what the aims are, so that other scientists around the world can, in fact, collaborate and work with that, can actually replicate its experiments.

And I think fourthly, it is important that wherever research is taking place, that within the database comes the order of risk. That we know that a lot of these technologies are usually low risk and therefore, you know, can easily be lodged in a database without, in fact, having to have huge explorations or it causing controversy.

Where, in fact, you are, for instance, seeding the oceans, if in fact, you are going to put aerosols into the stratosphere, which might have an effect somewhere else, then clearly, those elements of risk have got to be assessed and put into the database. All that would be hugely influential in actually guiding future geoengineering regulation.

THE FUTURE OF GEOENGINEERING RESEARCH IN THE U.K.

Chairman GORDON. Thank you, and how do you foresee the future of geoengineering research in the United Kingdom? What direction will it go, if at all? Are national or European Commission geoengineering research programs likely to be a reality? Is the United Kingdom's Defense Department looking at geoengineering possibilities also?

Chairman WILLIS. Well, thank you, Mr. Chairman. I think what is interesting here is, if you would have asked me that question 18 months ago, I would have said no, no, no, and no to all those points, because I think 18 months to two years ago, geoengineering was not on the agenda.

I can recall having a Committee session in the U.K. Parliament with the Minister responsible for climate change, to ask if, in fact, there was any research being commissioned in this particular area, and the answer was no. We have Plan A, which is about mitigation, and we don't, in fact, plan to go down the road of geoengineering.

Eighteen months later, the government has commissioned research, to its credit. And in fact, the National Environment Research Council [NERC] is also conducting research. A number of leading universities in the U.K. are conducting research in terms of regulation, and as I have said to you, the Royal Society has conducted a major inquiry looking at the different types of geoengineering, and in fact, they have just announced that they are going to set up a major inquiry looking at the regulation of geoengineering.

In Europe as well, while there is nothing in the current framework program in terms of research projects for geoengineering, we understand that the European Research Council is, in fact, considering bids to actually look at, particularly, the modeling of geoengineering in terms of certain aspects.

So, this is on the rise, and I think it is good that that is happening, and it is good that we are not turning our minds away from the future need which might arise to use geoengineering technologies.

And I agree totally with you, Mr. Chairman, that this is an issue of last resort and must not, in fact, deflect us from our major task of making sure that we put less CO_2 into the air, and where it is there, that we look, in fact, to sequestrate it.

ADDITIONAL OPPORTUNITIES FOR INTERNATIONAL COLLABORATION

Chairman GORDON. And one last question. As we have discussed before, when you look at the major problems facing our world and globe, whether it is climate change, whether it is energy sustainability, or energy independence, or just sustainability of the planet, I think we are going to need cooperation with multinational efforts, both intellectually and financially.

And I wanted to get your thoughts, again, in the future, what additional topics might be taken up? I know you had talked about synthetic biology at one time. Any other suggestions on those type of global issues that we might work on in the future?

Chairman WILLIS. Well, Mr. Chairman, I think there is no doubt that the great challenges are not challenges simply for the United States or the United Kingdom, or indeed, for China or India, the emerging economies.

They are global challenges. The great challenges of water security, food security, energy, as well, of course, as issues like terrorism and other matters, all of which science has a major role to play, require global solutions.

And I think that there is a fairly exhaustive list. I mean, for instance, the whole of the oceans. I can remember being in the United States not long ago, at Woods Hole Laboratory, you know, looking at the effect of the oceans on the climate. I think that that is an area for international and global cooperation.

The issue of space, and the use of space, again, requires global activities. You and I talked, when you were last in London, about the whole issue of nanotechnologies, the way in which nanotechnologies are going to need very, very careful global cooperation if, in fact, we are going to make the most use of those technologies.

The issue of sustainable agriculture: there is no way, by 2050, we are going to be able to feed the world's population, given current agrarian policies. And therefore, the need for international cooperation there is enormous.

And if I may finally say, both your economy and our economy in the U.K. have suffered massively because of the economic downturn. And if there is one area where there is a need for far greater cooperation, certainly between our two nations, in terms of the social science of economics. My goodness, that is one area we ought to look at.

Chairman GORDON. Thank you, Chairman. My time has expired. In the United States, we have Americans and we have Texas Americans, and now I recognize my Ranking Member and good friend from Texas, Mr. Hall.

PUBLIC OPINION OF GEOENGINEERING

Mr. HALL. Now, being from Texas, we are happy to have international discussions from time to time, and about 10 or 15 years ago, we had a similar discussion on asteroids here, urging England, Germany, France, and others to come together to share the cost of tracing and tracking.

And it didn't work out, because I guess there was not enough there, but we learned during that time that an asteroid missed the Earth only about 15 minutes, I think in 1986 or '88, so there is a lot to learn together. And I admire the Chairman for making a trip over there. His trip there spawned this historical meeting, where you come before us, Chairman Willis, to testify. I have enjoyed hearing your testimony.

I will ask you just a question or so, as kind a question as I know how to ask. I don't really—I am not terribly enthusiastic about this, but I am excited about your appearance here and the Chairman's vision.

As you may have noticed from our newspapers, public opinion on the concept of geoengineering here in the United States covers the whole spectrum. It just goes everywhere here. Did you find yourself in a similar situation in England initially?

Chairman WILLIS. Well, Representative Hall, welcome to you and it is good to talk to you. Or is it Mr. Hall I should officially address you as? But there is no doubt that when we did, and we did, I said, a piece of investigation about geoengineering 18 months ago, as part of a bigger inquiry, that there were many people, and particularly some of the green NGOs, nongovernment organizations, who contacted us to say that this was really a distraction. It was distracting us from the main issue, which was about climate change, which was about removing CO_2, and which was about stopping the temperature of the Earth rising.

And it is interesting that that has slightly changed, and there is now an acceptance that this is a long-term technology, something which clearly needs to be put into the basket of tricks. But equally, it is important that it does not, in fact, actually take U.K. pounds, in your case, U.S. dollars, away from the main thrust, which is about creating sort of green technologies for transport, you know, for energy, and indeed, making sure that we don't continue to create the problem.

But I can tell you, Mr. Hall, that there are a significant number of people in the United Kingdom who actually regard this as a rather strange set of technologies, and ones that, quite frankly, we have better things to spend our time on.

THE U.K. INQUIRY PROCESS

Mr. HALL. Did you start with public hearings? How did you initiate it? Did you start with public hearings to discuss the issue?

Chairman WILLIS. Well, we—what we do with all our inquiries is, we announce a set of terms of reference for our inquiry, and of course, we engage the public immediately at that time.

We then try to seek out witnesses, as you did, including Professor Shepherd, from across the globe, in order to be able to feed into us, into our inquiry. And then to assemble a report, and make a number of key recommendations, including of course, interviewing the government, the government ministers, to see what government policy is.

And of course, we did not have any government policy in this particular area, because government did not have a policy towards geoengineering, and it is interesting that whilst they still don't have a major commitment to geoengineering as a mitigation technology, nevertheless, the governments have, I think to their credit, actually engaged with the science, and to at least examine whether the science is or could be could be effective and predictable.

Mr. HALL. I thank you for that, and I am near the end of my inquiry. Appreciate you being here. It is historic. I know his trip over there, visiting with you, spawned this meeting, and I think it is very helpful. Perhaps we can reciprocate with you somewhere down the line.

Thank you, sir, and I yield back my time.

Chairman GORDON. Ms. Fudge is recognized. Or Governor Garamendi is recognized for five minutes.

Mr. GARAMENDI. The inquiry—the information from the United Kingdom is excellent, and I don't have any questions right now. Thank you.

Chairman GORDON. And I see Ms. Dahlkemper, and Ms. Dahlkemper is recognized.

Ms. DAHLKEMPER. I thank you, Mr. Chairman. This is a very interesting hearing, and I certainly appreciate the Chairman being here with us today, but I also do not have any questions at this time.

I am sure, as we go forward with this cooperation, we will have many more questions. So, thank you, and I yield back.

Chairman GORDON. Well, Chairman Willis, as I said earlier, we are on the precipice of votes here. We received your report last night. We have been in constant contact with your staff, and been very pleased with that.

We are going to digest that now, and hopefully, we will have a chance to be back in touch with you, but we want to thank you for the excellent body of work that you have presented us with.

Chairman WILLIS. Thank you indeed, Mr. Gordon, and it has been a pleasure not only to present to your committee, but on the two opportunities we have been able to meet over the past year, you have treated us with huge courtesy, and we hope that this will be the sign of things to come, certainly after our general election here in May.

Chairman GORDON. Thank you. And we are going to move to a second panel, of which we are going to keep you tuned in, and so, if you would like to continue to hear that, you are welcome, until, again, we are required to leave for votes.

And so, I would ask the second panel to come forward. We are now told that it is going to be about 1:00 before the votes get started, so—okay.

So, we are ready now for our second panel. It is my pleasure to introduce our witnesses. First, Dr. Frank Rusco is the Director of Natural Resources and Environment at the Government Accountability Office, GAO.

Dr. Scott Barrett is the Lenfest Professor of Natural Resource Economics at the School of International and Public Affairs and the Earth Institute at Columbia University.

Dr. Jane Long is the Deputy Principal Associate Director at Large at Lawrence Livermore National Lab [LLNL].

And Dr. Granger Morgan is Professor and Head of the Department of Engineering and Public Policy, as well as the Lord Chair Professor in the Engineering at the Carnegie Mellon University.

As witnesses should know, you have five minutes for your spoken testimony. Your written testimony has been included in the record, and when you complete your spoken testimony, we will then have questions. Each member will have five minutes to ask those questions.

So, Dr. Rusco, we will begin with you.

STATEMENTS OF DR. FRANK RUSCO, DIRECTOR OF NATURAL RESOURCES AND ENVIRONMENT, GOVERNMENT ACCOUNTABILITY OFFICE

Dr. RUSCO. Chairman Gordon, Ranking Member Hall, and Members of the Committee, thank you for the opportunity to speak before you today on the important issue of domestic and international governance of geoengineering.

Geoengineering has recently become an area of intensified interest, in part, because of challenges in reaching international agreement to limit the growth of, and eventually reduce, global greenhouse gas emissions.

In this context, if severe or relatively sudden climate change occurs at some future date, attempts to reverse or slow such trends through deployment of geoengineering technologies, either by reflecting some of the sun's rays that help heat the Earth, or by removing and sequestering ambient carbon dioxide, may become relatively more attractive, especially in nations or regions that are particularly vulnerable to the effects of climate change.

Three facts point to the importance of getting in front of the issue of domestic and international governance of geoengineering research and deployment. First, the severity of the effects of large scale geoengineering, efforts are uncertain, and would likely be distributed unevenly, potentially creating relative winners and losers.

As a result of the unknown severity and potential unevenness of outcomes, geoengineering research or deployment at a scale large enough to actually influence the global climate would carry with it the potential to be economically and politically destabilizing.

Second, climate change modeling exercises or small scale physical experiments for certain geoengineering approaches, such as stratospheric aerosol injection, may be inadequate to evaluate the efficacy or extent and distribution of unintended effects of geoengineering deployed if at full scale. Put simply, to adequately assess the efficacy and distribution of effects of geoengineering, it may be necessary to actually deploy these technologies on a large scale and for a long period of time.

Research on this scale would, itself, have uncertain and likely uneven effects around the globe, would potentially create winners and losers, and could lead to conflict over how to mitigate or adapt to any adverse effects.

Third, some geoengineering technologies could be implemented at low enough cost that they could be undertaken by nations or other actors unilaterally, or in coalitions. Simply put, if a nation or group perceives it in their interest to deploy such a technology that will have global but uncertain and unevenly distributed effects, it may well be possible for them to do so without broad international consensus or assistance.

In our ongoing work in this area, we have found that some federal agencies have funded research and small demonstration projects of technology related to geoengineering. However, federal agencies have not been directed to, nor does there exist, a coordinated federal geoengineering research strategy.

Further, some existing federal laws could apply to geoengineering research and deployment. However, some federal agencies have not yet assessed their authority to regulate geoengineering, and those agencies that have done so have identified regulatory gaps.

For example, under the Marine Protection, Research, and Sanctuaries Act of 1972, certain persons would be prohibited from dumping material for ocean fertilization into the ocean without a permit from EPA. EPA officials told us that the ocean dumping permitting process is sufficient to regulate certain ocean fertilization activities. However, they noted a domestic company could conduct ocean fertilization outside of EPA's regulatory jurisdiction if, for example, the company's fertilization activities took place outside

U.S. territorial waters from a foreign registered ship that embarked from a foreign port.

With regard to international governance, legal experts we spoke with identified a number of existing international agreements that are potentially relevant to specific geoengineering technologies. However, these agreements were not drafted with geoengineering in mind, and the signatories and parties to these agreements have typically not determined whether and how they apply to geoengineering.

Further, these agreements have generally not been signed by all countries, nor have all signatories ratified or acceded to the agreements, thereby giving them the force of law.

While GAO cannot advise Congress at this time on specific needs for domestic or international governance of geoengineering research or deployment, we found broad consensus among both legal and scientific experts we spoke with that any geoengineering research of a large enough scale to have trans-boundary effects should be addressed in a transparent and international manner.

However, there was a variety of views on the precise structure of such regulation or governance. For example, scientific experts recommended that research governance be established in consultation with the scientific community, in order to not unduly restrict research.

Similarly, we found a broad consensus that additional geoengineering research is warranted, but no consensus on the desirable extent of such research. We look forward to continuing our work in this area for the Committee, and hope to be able to make specific recommendations for Federal actions in future reports.

Mr. Chairman, this concludes my statement. I would be happy to answer any questions you or the Committee may have.

[The prepared statement of Dr. Rusco follows:]

PREPARED STATEMENT OF FRANK RUSCO

United States Government Accountability Office

GAO

Testimony

Before the Committee on Science and Technology, House of Representatives

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CLIMATE CHANGE

Preliminary Observations on Geoengineering Science, Federal Efforts, and Governance Issues

Statement of Frank Rusco, Director
Natural Resources and Environment

GAO
Accountability * Integrity * Reliability

GAO-10-546T

March 18, 2010

GAO Accountability·Integrity·Reliability

Highlights

Highlights of GAO-10-546T, a testimony before the Committee on Science and Technology, House of Representatives

CLIMATE CHANGE

Preliminary Observations on Geoengineering Science, Federal Efforts, and Governance Issues

Why GAO Did This Study

Key scientific assessments have underscored the urgency of reducing emissions of carbon dioxide to help mitigate potentially negative effects of climate change; however, many countries with significant greenhouse gas emissions, including the United States, China, and India, have not committed to binding limits on emissions to date, and carbon dioxide levels continue to rise.

Recently, some policymakers have raised questions about geoengineering—large-scale deliberate interventions in the earth's climate system to diminish climate change or its potential impacts—and its role in a broader strategy of mitigating and adapting to climate change.

Most geoengineering proposals fall into two approaches: solar radiation management (SRM), which offset temperature increases by reflecting a small percentage of the sun's light back into space, and carbon dioxide removal (CDR), which address the root cause of climate change by removing carbon dioxide from the atmosphere.

Today's testimony focuses on GAO's preliminary observations on (1) the state of the science regarding geoengineering approaches and their effects, (2) federal involvement in geoengineering activities, and (3) the views of experts and federal officials about the extent to which federal laws and international agreements apply to geoengineering. To address these issues, GAO reviewed scientific literature and interviewed federal officials and scientific and legal experts.

View GAO-10-546T or key components. For more information, contact Frank Rusco, at (202) 512-3841 or ruscof@gao.gov.

What GAO Found

Substantial uncertainties remain on the efficacy and potential environmental impacts of proposed geoengineering approaches, because geoengineering research and field experiments to date have been limited. GAO's review of relevant studies and interviews with experts to date found that relatively few modeling studies for SRM approaches have been published, and only limited small-scale testing—primarily of carbon storage activities relevant to CDR approaches—have been performed. Consequently, the experts GAO spoke with stated that a sustained effort of coordinated and cooperative research would be needed to determine whether proposed geoengineering approaches would be effective at a scale necessary to reduce temperatures and to attempt to anticipate and respond to potential unintended consequences—including the political, ethical, and economic issues surrounding the use of certain approaches. Specifically, just as the effects of climate change in general are expected to vary by region, so would the effects of certain large-scale geoengineering efforts, therefore, potentially creating relative winners and losers and thus sowing the seeds of future conflict.

Federal agencies have funded some research and small demonstration projects of certain technologies related to proposed geoengineering approaches; but these efforts have been limited, fragmented, and not coordinated as part of a federal geoengineering strategy. Officials from interagency bodies coordinating the federal response to climate change stated that their offices (1) have not developed a coordinated research strategy, (2) do not have a position on geoengineering, and (3) do not believe is it necessary to coordinate efforts due to the limited federal investment to date. In the event that the federal government decides to expand geoengineering research, GAO's interviews with experts suggest that transparency and international cooperation are key factors for any geoengineering research that poses a risk of environmental impacts beyond our borders. Further, GAO's past work indicates that a comprehensive assessment of costs and benefits that includes all relevant risks and uncertainties is a key component in strategic planning for technology-based research.

According to legal experts and federal agency officials, some existing federal laws and international agreements could apply to geoengineering research and deployment. However, some federal agencies have not yet assessed their authority to regulate geoengineering, and those that have done so have identified regulatory gaps. Although legal experts have identified some relevant international agreements and parties to two agreements have taken actions to address geoengineering, it is not certain whether and how other agreements would apply. Most scientific and legal experts GAO spoke with distinguished the governance of research from governance of deployment and noted that governance of geoengineering research with transboundary impacts, such as SRM approaches, should be addressed at the international level in a transparent manner and in consultation with the scientific community. However, the experts' views on the details of governance varied.

Mr. Chairman and Members of the Committee:

I am pleased to be here today to participate in the committee's hearing on geoengineering. Changes in the earth's climate attributable to increased concentrations of greenhouse gases may have significant environmental and economic impacts in the United States and internationally. These impacts are expected to vary across regions, countries, and economic sectors. Among other potential impacts, climate change could threaten coastal areas with rising sea levels, alter agricultural productivity, and increase the intensity and frequency of floods and tropical storms. Furthermore, the National Academies of Science (NAS) has reported that human alterations of the climate system may increase the possibility of large and abrupt regional or global climatic events, and that because abrupt climate changes of the past have not yet been fully explained, future abrupt changes cannot be predicted with any confidence, and climate surprises are to be expected.

Key scientific assessments have underscored the urgency of reducing emissions of carbon dioxide to help mitigate the negative effects of climate change; however, many countries with significant greenhouse gas emissions including the United States, China, and India, have not committed to binding limits on emissions to date, and carbon dioxide levels continue to rise.[1] In addition to mitigation, we have reported that policies to adapt to climate change could help reduce the vulnerability of countries and regions to potentially adverse impacts and may be viewed as part of a risk-management strategy for responding to climate change.[2] In particular, we reported that federal entities such as the President's Council on Environmental Quality (CEQ), the Office of Science and Technology Policy (OTSP), and the U.S. Global Change Research Program (USGCRP) had begun to develop governmentwide strategies to address climate change adaptation and reduce the nation's vulnerability to adverse impacts

[1]There are six primary greenhouse gases that are monitored and reported by countries in accordance with the United Nations Framework Convention on Climate Change: carbon dioxide, methane, and nitrous oxide, as well as three synthetic gases including hydrofluorocarbons, perfluorocarbons, and sulfur hexafluoride. Because greenhouse gases differ in their potential to contribute to global warming, each gas is assigned a unique weight based on its heat-absorbing ability relative to carbon dioxide over a fixed period. This provides a way to convert emissions of various greenhouse gases into a common measure, called the carbon dioxide equivalent.

[2]GAO, *Climate Change Adaptation: Strategic Federal Planning Could Help Government Officials Make More Informed Decisions*, GAO-10-113 (Washington, D.C.: Oct. 7, 2009).

from climate change. Recently, some policymakers have begun to raise questions about geoengineering—deliberate large-scale interventions in the earth's climate system to diminish climate change or its impacts—and what role, if any, it could play in a broad risk-management strategy for addressing climate change.[3]

A September 2009 study from the Royal Society[4]—the United Kingdom's national academy of science—categorized most geoengineering proposals into two approaches: solar radiation management (SRM), which would offset temperature increases by reflecting a small percentage of the sun's light back into space, thus reducing the amount of heat absorbed by the earth's atmosphere and surface, and carbon dioxide removal (CDR), which would address what scientists currently view as the root cause of climate change by removing carbon dioxide—a greenhouse gas—from the atmosphere.[5]

Examples of SRM approaches in the study include the following:

- increasing the reflectivity of the earth's surface through activities such as painting building roofs white, planting more reflective crops or biomass, or covering desert surfaces with reflective material;
- increasing the reflectivity of the atmosphere by whitening clouds over the ocean or injecting reflective aerosol particles into the stratosphere to scatter sunlight; and
- space-based methods to use shielding materials to reflect or deflect incoming solar radiation.

Examples of CDR approaches in the study include the following:

- enhancing biological, physical, or chemical land-based carbon sinks to capture and store carbon in biomass or soil (carbon sequestration), or in chemically reactive minerals (land-based enhanced weathering);

[3]Geoengineering is also referred to as climate engineering or climate intervention.

[4]The Royal Society, *Geoengineering and the climate: science, governance and uncertainty* (London: September 2009).

[5]In addition to these two types of approaches, other large-scale interventions in the earth's climate system, such as removing other greenhouse gases from the atmosphere, have been considered as part of a potential response to reduce the impacts of climate change.

- enhancing biological, physical, or chemical ocean-based carbon sinks through the introduction of nutrients to promote phytoplankton growth (ocean fertilization), physically altering ocean circulation patterns to transfer atmospheric carbon to the deep sea, or adding chemically reactive minerals to increase ocean alkalinity (ocean-based enhanced weathering); and
- technology-based methods to remove carbon dioxide from the atmosphere (air capture) and then store the carbon dioxide—for example, in geological formations (geological sequestration).

According to the Royal Society study, while both approaches are ultimately designed to decrease temperatures, the discussed SRM approaches, once deployed, would only take a few years to reduce temperatures, but would create an artificial and approximate balance between increased atmospheric greenhouse gas concentrations and reduced sunlight that would introduce additional environmental risks and require long-term maintenance. In contrast, the discussed CDR approaches would take many decades to reduce global temperatures but, with some exceptions, involve fewer potential environmental risks because they would return the climate closer to its pre-industrial state. Additionally, certain SRM approaches, such as atmospheric aerosol injection, are considered to be relatively inexpensive to implement and generally hold greater potential for causing uneven environmental impacts beyond national or regional boundaries, thus risking undesirable social, ethical, legal, and political implications that would need to be addressed before any of these technologies are implemented. For example, the European Union has initiated a research program to study the scientific issues, as well as the policy implications of SRM geoengineering approaches. Domestically, NAS will be including geoengineering as part of its pending report on America's Climate Choices for Congress,[6] and some

[6]According to NAS, the final report for America's Climate Choices will examine issues associated with global climate change, including the science and technology challenges involved, and provide advice on actions and strategies the United States can take to respond. This report will be based on a series of workshop panels and other activities conducted in 2009.

nongovernmental organizations, such as the American Physical Society, have also undertaken studies to examine these issues in further detail.[7]

Within this context, our testimony today is based on our preliminary observations for the committee addressing (1) the general state of the science regarding geoengineering approaches and their potential effects, (2) the extent to which the federal government has sponsored or participated in geoengineering research or deployment, and (3) the views of legal experts and federal officials concerning the extent to which federal laws and international agreements apply to geoengineering activities. We expect to provide the committee with the final results of this review in a report issued later this year. Additionally, due to the interest of the committee and the strategic relevance of this topic, GAO has initiated a technology assessment on this topic which is also scheduled to be issued later this year.

To address these issues, we reviewed relevant studies from peer-reviewed literature, legal journals, and published policy studies related to geoengineering. We also identified a list of knowledgeable scientific, legal, and policy experts based on the following factors: participation on a geoengineering panel, the number of articles authored in peer-reviewed literature, and recommendations from other experts. From this list, we interviewed a sample of experts. Our interviews with other experts are ongoing. In addition, we met with officials and staff from interagency bodies coordinating the federal response to climate change, including OSTP, CEQ, and USGCRP, as well as the Department of Energy (DOE), which coordinates the Climate Change Technology Program (CCTP)—a multiagency research and development program for climate change technology. We also identified and reviewed federal laws and international agreements; interviewed international law experts; and interviewed officials from the Environmental Protection Agency's (EPA) Office of General Counsel, Marine Pollution Control Branch, and the Office of Water to discuss how federal laws are being or could be applied to activities related to geoengineering. Our work is ongoing, and we are continuing to collect and analyze information related to the objectives and findings presented in this testimony. We conducted our work on this testimony from December 2009 to March 2010 in accordance with

[7] According to its research proposal, the American Physical Society is currently conducting a study of the likely technological and economic potential of air capture technologies. Additionally, the National Commission for Energy Policy is also investigating the policy implications of geoengineering.

generally accepted government auditing standards. Those standards require that we plan and perform the audit to obtain sufficient, appropriate evidence to provide a reasonable basis for our findings and conclusions based on our audit objectives. We believe that the evidence obtained provides a reasonable basis for our findings and conclusions based on our audit objectives.

Substantial Uncertainties Remain Regarding Geoengineering Approaches and Their Potential Effects

Substantial questions remain on the efficacy and potential environmental impacts of proposed geoengineering approaches, in part, because geoengineering research and field experiments to date have been limited. According to the experts we spoke with, research related to proposed SRM geoengineering approaches is sparse. According to recent studies, much of the research into SRM approaches to date has been limited to modeling studies to assess the effects of either injecting sulfur aerosols into the stratosphere or brightening clouds to reduce incoming solar radiation at the earth's surface and produce a cooling effect. For example, one study found that combining a reduction of incoming radiation with high levels of atmospheric carbon dioxide could have substantial impacts on regional precipitation—potentially leading to reductions that could create drought in some areas.[8] Based on our literature review and interviews with experts to date, only one study has been published for a field experiment related to SRM technologies—a Russian experiment that injected aerosols into the middle troposphere.[9]

For CDR approaches, our discussions with experts, as well as our initial examination of relevant studies, found that a greater amount of research and number of field trials related to geological sequestration and ocean fertilization has occurred; but, these efforts were not necessarily designed for the purpose of applying the concepts to geoengineering. For example, according to the International Energy Agency (IEA),[10] several small-scale

[8]Gabriele C. Hegerl and Susan Solomon, "Risks of Climate Engineering," *Science* 325 (2009): 955-956.

[9]Yu. A. Izrael, V. M. Zakharov, N. N. Petrov, A. G. Ryaboshapko, V. N. Ivanov, A. V. Savchenko, Yu. V. Andreev, V. G. Eran'kov, Yu. A. Puzov, B. G. Danilyan, V. P. Kulyapin, and V. A. Gulevskii, "Field Studies of a Geo-engineering Method of Maintaining a Modern Climate with Aerosol Particles," *Russian Meteorology and Hydrology* 34, no. 10 (2009): 635-638.

[10]The IEA is an intergovernmental organization that acts as energy policy advisor to 28 member countries. Additional information on the IEA can be found at their website: http://www.iea.org. International Energy Agency, *Legal Aspects of Storing CO_2: Update and Recommendations* (Paris: 2007).

commercial applications of technology exist for injecting and monitoring the long-term storage of carbon dioxide in geologic formations. The IEA stated that the oldest of these started as a private-sector project in 1996 and now continues under funding from the European Commission. However, these projects are primarily associated with public and private initiatives to study, develop, and promote carbon capture and storage technologies as a greenhouse gas emissions reduction strategy, rather than the large scale that would be required to significantly alter the climate through geoengineering. Similarly, some ocean fertilization experiments using iron have been conducted as part of existing marine research studies or small-scale commercial operations. One expert familiar with these experiments noted that, while they improved scientific understanding of the role of iron in regulating ocean ecosystems and carbon dynamics, they were not specifically designed to determine the implications of ocean fertilization with iron as a geoengineering approach for large-scale removal of carbon dioxide from the atmosphere.[11]

Due to the limited amount of geoengineering research conducted to date, the experts we interviewed stated that a sustained program of additional research would be needed to address the significant uncertainties regarding the effectiveness and potential impacts of geoengineering approaches. Additionally, these experts noted that for certain approaches where transboundary impacts would be likely during field experiments, international cooperation for research would be necessary. Specifically, recent studies highlight the limitations of current models to accurately predict the environmental impact of SRM technologies at a regional scale—which would be necessary to accurately gauge potential impacts that might interfere with agricultural production for certain regions. Furthermore, studies indicate that, even for the most tested methods applicable to geoengineering, such as geological sequestration and ocean fertilization with iron, uncertainties remain surrounding the potential cost, effectiveness, and impacts of pursuing these approaches at a scale sufficient to reduce the amount of carbon in the atmosphere.

[11]According to the German Alfred Wegener Institute for Polar and Marine Research (AWI) and the Indian National Institute of Oceanography (NIO), the purpose of their joint ocean fertilization experiment last year was "to test a range of scientific hypotheses pertaining to the structure and functioning of Southern Ocean ecosystems and their potential impact on global cycles of biogenic elements." However, they noted that longer term experiments studying phytoplankton bloom development, and their effect on the deep ocean and underlying sediments, will have to be much larger than previous experiments.

Due to the potential for disparities in environmental outcomes from using these technologies—similar to the expected regional variation in climate change impacts—experts that we spoke with said that the political, ethical, legal, and economic issues surrounding the potential impacts of geoengineering technologies warranted close examination. These experts generally agreed that the policy implications for SRM and CDR approaches were very different. For example, certain SRM approaches, such as atmospheric aerosol injection, are generally perceived as being less costly to implement and would act more quickly to reduce temperatures than CDR approaches. However, these approaches are also associated with a greater risk of environmental impacts that cross national boundaries—which would have political, ethical, legal, and economic ramifications. Furthermore, according to several of these experts, the policy implications of SRM approaches are complicated by the fact that there are likely to be both positive and negative outcomes for nations or regions, and that one nation, group, or individual could conceivably take unilateral action to deploy one of these technologies. Experts emphasized that it is important to begin studying how the United States and the international community might address the ramifications of unilateral deployment of an SRM approach that would result in gains for some nations and losses for others. In contrast, with the exception of ocean fertilization, two of the experts we interviewed stated that most CDR approaches, such as air capture, would have limited impacts across national boundaries and could, therefore, mostly involve discussions with domestic stakeholders about societal, economic, and political impacts similar to those of existing climate change mitigation strategies. However, the Royal Society study noted that large-scale deployment of CDR approaches such as widespread afforestation—planting of forests on lands that historically have not been forested—or methods requiring substantial mineral extraction—including land or ocean-based enhanced weathering—may have unintended and significant impacts within and beyond national borders.[12]

[12]The Royal Society, *Geoengineering and the climate: science, governance and uncertainty.*

Federal Agencies Have Sponsored Some Research Activities, but These Activities Are Not Part of a Coordinated Federal Geoengineering Research Strategy

Our observations to date indicate that federal agencies such as DOE, National Science Foundation (NSF), U.S. Department of Agriculture (USDA), and others have funded some research and small-scale technology testing relevant to proposed geoengineering approaches on an ad-hoc basis. Some examples are as follows:

- For SRM approaches, DOE, through its Sandia National Laboratories, has sponsored a study investigating the potential unintended consequences and economic impacts of sulfur aerosol injection. Additionally, DOE has contributed a small amount of funding for modeling studies related to cloud-brightening and stratospheric aerosol SRM approaches at its Pacific Northwest National Laboratory—an effort that is primarily funded by the University of Calgary. For CDR approaches, DOE has sponsored research in both land-based and ocean-based carbon storage, including small-scale demonstration projects of geological sequestration as part of its Regional Carbon Sequestration Partnerships. In conjunction with other partners, DOE also provided funding for a study on carbon dioxide air capture technologies.

- NSF has funded projects relevant to both SRM and CDR approaches. For SRM approaches, NSF has sponsored some modeling studies for stratospheric aerosol injection and for a space-based SRM approach. NSF has also funded research investigating the ethical issues related to SRM approaches. For CDR approaches, NSF is supporting projects related to carbon storage in geological formations, saline aquifers, and biomass.

- Relevant to CDR approaches, USDA has supported research that examined land-based carbon storage approaches, such as biochar[13]—a way to draw carbon from the atmosphere and sequester it in charcoal created from biomass—through its Agricultural Research Service, and carbon sequestration in soil and biomass as part of its Economic Research Service.

- National Aeronautics and Space Administration (NASA) funded a research study investigating the practicality of using a solar shield in space to deflect sunlight and reduce global temperatures as part of its former

[13]Biochar is one by-product of heating biomass such as crop residue or wood wastes, in the absence of oxygen, in a process known as pyrolysis.

independent Institute for Advanced Concepts program.[14] Additionally, scientists at NASA's Ames Research Center, independent of headquarters, held a conference on SRM approaches in 2006, in conjunction with the Carnegie Institution of Washington.

- EPA has also sponsored research related to the economic implications of SRM geoengineering approaches through its National Center for Environmental Economics.

In addition to these efforts, federal officials noted that a large fraction of the existing federal research and observations on basic climate change and earth science could be relevant to improving understanding about proposed geoengineering approaches and their potential impacts. For instance, according to federal officials, ongoing research conducted by USGCRP agencies related to understanding atmospheric circulation and aerosol/cloud interactions could help improve understanding about the potential effectiveness and impacts of proposed SRM approaches. Similarly, these officials said that basic research conducted by USGCRP agencies into oceanic chemistry could help address uncertainty about the potential effectiveness and impacts of CDR approaches, such as ocean fertilization.

Staff from federal offices coordinating the U.S. response to climate change—CEQ, OSTP, and USGCRP—stated that they do not currently have a geoengineering strategy or position. Additionally, a USGCRP official stated that, while the USGCRP could establish an interagency working group to coordinate a federal effort in geoengineering research, such a group is not currently necessary because of the small amount of federal funding specifically directed toward these activities.

In the event that the federal government decides to fund a coordinated geoengineering research strategy, our review of relevant studies and interviews with experts to date identified some key factors for policymakers to consider when designing a federal strategy for geoengineering research. For example, the Royal Society study noted that

[14]According to its final report, the NASA Institute for Advanced Concepts (NIAC) was formed to provide an independent source of revolutionary aeronautical and space concepts that could dramatically impact how NASA develops and conducts its missions. As part of the NIAC selection process, the study related to SRM was selected through an open-solicitation and peer-reviewed competition, which was managed by the Universities Space Research Association, a private, nonprofit organization.

when there is a likelihood of transboundary impacts, such as the discussed SRM approaches, as well as one discussed CDR approach, ocean fertilization, transparency and international cooperation are key factors for pursuing geoengineering research. This point was reiterated by several experts at a recent panel discussion at the American Advancement for Science annual meeting. However, a couple of experts we interviewed noted that federal research for geoengineering approaches without likely transboundary impacts could be conducted independently of other countries, as is the case with the majority of currently proposed CDR approaches, such as air capture. Additionally, due to the variety of geoengineering approaches, several of the experts we interviewed recommended that federal geoengineering research should be an interdisciplinary effort across multiple agencies, and should be led by a multiagency coordinating body, such as OSTP or USGCRP.

Recent GAO work offers insights on key considerations for assessing risk and managing technology-based research programs. For example, we have reported on the advantages of using a formal risk-management approach and applying an anticipatory perspective when making decisions under substantial uncertainty.[15] Specifically, we reported that outlining the various alternative policy responses and the risks and uncertainties associated with pursuing each alternative is particularly important when prospective interventions require long lead times, high-stakes outcomes would likely result, and a delayed intervention would make impacts difficult to contain or reverse—conditions that could be considered relevant to the risks associated with climate change impacts. Furthermore, our review of DOE's FutureGen project—a program that partners with the electric power industry to design, build, and operate the world's first coal-fired, zero-emissions power plant—found that a comprehensive assessment of the costs, benefits, and risks of each technological option is an important factor when developing a strategic plan for technology-based research.[16]

[15]GAO, *Highway Safety: Foresight Issues Challenge DOT's Efforts to Assess and Respond to New Technology-Based Trends*, GAO-09-56 (Washington, D.C.: Oct. 3, 2008).

[16]GAO, *Clean Coal: DOE's Decision to Restructure FutureGen Should Be Based on a Comprehensive Analysis of Costs, Benefits, and Risks*, GAO-09-248 (Washington, D.C.: Feb. 13, 2009).

Existing Federal Laws and International Agreements Could Apply to Certain Geoengineering Activities, but Regulatory Gaps Remain

Existing federal laws and international agreements were not enacted or negotiated with the purpose or intent to cover geoengineering activities, but according to legal experts and federal officials, several existing federal laws and international agreements could apply to geoengineering research and deployment, depending upon the type, location, and sponsor of the activity. Domestically, however, interviews with agency officials to date and our past work indicate that federal agencies have not yet assessed their statutory authority to regulate geoengineering activities, and those that have done so have identified regulatory gaps. Examples include the following:

- EPA has authority under the Safe Drinking Water Act to regulate underground injections of various substances and is using this authority to develop a rule that would govern the underground injection of carbon dioxide for geological sequestration, which could be relevant to future CDR approaches. EPA issued a proposed rule on geological sequestration in July 2008. EPA officials told us that the final rule is currently scheduled to be issued in the fall of 2010. However, as EPA officials noted, the rulemaking was not intended to resolve many questions concerning how other environmental statutes may apply to injected carbon dioxide, including the Comprehensive Environmental Response, Compensation and Liability Act of 1980 (CERLCA) and the Resource Conservation and Recovery Act of 1976 (RCRA), which apply to hazardous substances and wastes, respectively.[17,18] The White House recently established an interagency task force on carbon capture and storage to propose a plan to overcome the barriers to widespread deployment of these technologies. The plan will address, among other issues, legal barriers to deployment and identify areas where additional statutory authority may be necessary.
- Under the Marine Protection, Research and Sanctuaries Act of 1972, as amended, certain persons are generally prohibited from dumping material, including material for ocean fertilization, into the ocean without a permit from EPA.[19] Although EPA officials told us that the law's ocean dumping permitting process is sufficient to regulate certain ocean fertilization activities, including research projects, they noted that the law was limited to disposition of materials for fertilization by vessels or aircraft registered in the United States, vessels or aircraft departing from the United States,

[17]Pub. L. No. 96-510 (1980), as amended, *codified at* 42 U.S.C. §§ 9601-9675.

[18]Pub. L. No. 94-580 (1976), as amended, *codified at* 42 U.S.C. §§ 6921-6939f.

[19]Pub. L. No. 92-532 (1972), as amended, *codified at* 33 U.S.C. §§ 1401-1445.

federal agencies, or disposition of materials for fertilization conducted in U.S. territorial waters, which extend 12 miles from the shoreline or coastal baseline. Consequently, a domestic company could conduct ocean fertilization outside of EPA's regulatory jurisdiction and control if, for example, the company's fertilization activities took place outside U.S. territorial waters from a foreign-registered ship that embarked from a foreign port.

Additionally, agency officials and legal experts noted that other laws such as the National Environmental Policy Act of 1969 (NEPA) could also apply to certain geoengineering activities.[29] For example, NEPA requires federal agencies to evaluate the likely environmental effects of certain major federal actions by using an environmental assessment or, if the projects likely would significantly affect the environment, a more detailed environmental impact statement. A geoengineering activity could well constitute a major federal action requiring a NEPA analysis.

Although some geoengineering approaches, such as geological sequestration of carbon dioxide in underground formations, would not involve international agreements because the activities and their effects would be confined to U.S. territory, other SRM and CDR approaches would. Legal experts we spoke with identified a number of existing international agreements that could apply to geoengineering activities but none directly address the issue of geoengineering. Our initial work indicates that parties to two international agreements have taken action to address geoengineering activities, but it is still uncertain whether and how other existing international agreements that legal experts have identified as potentially relevant could apply to geoengineering.

In our work to date, legal experts have identified a number of existing international agreements, such as the 1985 Vienna Convention for the Protection of the Ozone Layer and the 1967 Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, that could be relevant for injection of sulfate aerosols into the stratosphere and placement in outer space of material to reflect sunlight, respectively. However, these agreements were not drafted with the purpose or intent of applying to geoengineering activities and the parties to those treaties have not determined whether or how the agreement should apply to relevant geoengineering activities.

[29]Pub. L. No. 91-190 (1970), as amended, *codified at* 42 U.S.C. §§ 4321-4370f.

Moreover, once the parties make such determinations, they may have limited applicability because international agreements generally are only legally binding on countries that are parties to the agreement. For example, the 1996 Protocol to the Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter (also known as the London Protocol) generally prohibits the dumping of wastes or other matter into the ocean except for the wastes and matter listed in the London Protocol and for which a party to the agreement has issued a dumping permit that meets the Protocol's permitting requirements. In 2006, the parties to the London Protocol agreed to amend the Protocol to include, in certain circumstances, geological sequestration of carbon dioxide in sub-seabed geological formations on the list of wastes and other matter that could be dumped. However, only the 37 countries that are a party to the London Protocol and who have not objected to the amendment would be legally bound by it.

In two instances, the parties to international agreements have issued decisions but not amended the agreements regarding the agreement's application to ocean fertilization, including research projects. Generally these decisions by the parties are not considered to be legally binding, although they would aid in interpreting the international agreement. Specifically, the two instances are:

- Over the course of the last 2 years, parties to the Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matters and the London Protocol to the Convention have decided that the scope of these agreements include ocean fertilization activities for legitimate scientific research. Accordingly, they have asked the treaties' existing scientific bodies to develop an assessment framework for countries to use in evaluating whether research proposals are legitimate scientific research and, therefore, permissible under the agreements. In addition, the parties have agreed that ocean fertilization activities other than legitimate scientific research are contrary to the aims of the agreements and should not be allowed. Meanwhile, the parties are considering a potentially legally binding resolution or amendment to the London Protocol concerning ocean fertilization.
- In 2009, the parties to the Convention on Biological Diversity issued a decision requesting that parties to the Convention ensure that ocean fertilization activities, except for certain small-scale scientific research within coastal waters, do not take place until there is an adequate scientific basis on which to justify such activities and a global, transparent,

and effective control and regulatory mechanism is in place. The decision also urged the same from governments not party to the agreement.

In our interviews with legal experts to date, they suggested that governance of geoengineering research should be separated from the governance of deployment because scientists and policymakers lack critical information about geoengineering that would inform governance of deployment. The legal experts we spoke with all agreed that some type of regulation of geoengineering field experiments was necessary, but had different views as to the structure of such regulation. For example, some suggested a comprehensive international governance regime for all geoengineering research with transboundary impacts, under the auspices of the United Nations Framework Convention on Climate Change or another entity, while others suggested that existing international agreements, such as the London Convention and Protocol, could be adapted and used to address the geoengineering approaches that fall within their purview.

The scientific and policy experts we spoke with largely echoed the same themes and issues that the legal experts raised. Interviews with scientific experts to date suggest that governance issues related to geoengineering research with the potential for transboundary impacts should be addressed in a transparent, international manner in consultation with the scientific community. Some scientific and policy experts noted that the approach adopted by parties to the London Protocol engaged the scientific community about developing guidelines for assessing legitimate scientific research proposals that are not contrary to the treaties' aims, rather than prohibiting the scientific research necessary to determine the efficacy and impacts of ocean fertilization. Regarding geoengineering deployment, some scientific and policy experts noted that similar to the difficulties presented by achieving international consensus in carbon mitigation strategies—where there are definite "winners and losers" in terms of economic and environmental benefits—establishing a governance regime over geoengineering deployment for certain approaches may be equally challenging due to questions about whether deployment is warranted, how to determine an appropriate new environmental equilibrium, and compensation for adverse impacts, among other issues.

Mr. Chairman, this concludes my prepared statement. We look forward to helping this committee and Congress as a whole better understand this important issue. I would be pleased to respond to any questions that you or other members of the committee may have at this time.

GAO Contacts and Staff Acknowledgments

For further information about this testimony, please contact Frank Rusco, Director, Natural Resources and Environment at (202) 512-3841, or ruscof@gao.gov. Contact points for our Offices of Congressional Relations and Public Affairs may be found on the last page of this statement. Contributors to this testimony include: Tim Minelli, Assistant Director; Ana Ivelisse Aviles; Charles Bausell Jr.; Frederick Childers; Judith Droitcour; Lorraine Ettaro; Brian Friedman; Cindy Gilbert; Gloria Hernandezsaunders; Eric Larson; Eli Lewine; Madhav Panwar; Timothy Persons; Jeanette Soares; John Stephenson; Joe Thompson; and Lisa Van Arsdale.

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Public Affairs	Chuck Young, Managing Director, youngc1@gao.gov, (202) 512-4800 U.S. Government Accountability Office, 441 G Street NW, Room 7149 Washington, DC 20548

BIOGRAPHY FOR FRANK RUSCO

Frank Rusco is a Director in GAO's Natural Resources and Environment team, working on a broad spectrum of energy and related issues. He has worked at GAO for almost 11 years, at first, working as an economist in the Center for Economics. In addition to providing economics analysis, he also managed numerous teams working on energy topics, including electricity restructuring, and crude oil and petroleum products markets, as well as related natural resources work on oil and gas royalty collection and policy. Prior to coming to GAO, he was an assistant professor in the Department of Economics for the University of Hong Kong. He has published articles on energy, transportation, environmental economics and related topics. He received both his M.A. and Ph.D. in economics from the University of Washington in Seattle and his B.A. degree in music performance from the University of Nevada, Reno.

Chairman GORDON. Thank you, Dr. Rusco, and Dr. Morgan is recognized.

STATEMENTS OF DR. GRANGER MORGAN, PROFESSOR AND DEPARTMENT HEAD, DEPARTMENT OF ENGINEERING AND PUBLIC POLICY, AND LORD CHAIR PROFESSOR IN ENGINEERING, CARNEGIE MELLON UNIVERSITY

Dr. MORGAN. Mr. Chairman and distinguished Members, thank you for the opportunity to appear today to discuss issues related to research and governance in geoengineering.

I am Granger Morgan, head of the Department of Engineering and Public Policy at Carnegie Mellon University. Our department is the home of a large National Science Foundation-supported distributed center on climate decision research.

Some of our center's research has addressed the subject of solar radiation management, or SRM, that would involve adding fine reflective particles to the stratosphere. We have also supported research on technology for directly scrubbing carbon dioxide out of the atmosphere.

As part of our work on SRM, we have organized and run two workshops to engage leading climate scientists and foreign policy experts in discussions of the issues of global governance of SRM, and we have published a paper on this topic in the *Journal of Foreign Affairs* that I have appended to my written testimony.

I want to emphasize that I am not arguing that the U.S. or anybody else should engage in SRM. The U.S. and other large emitting countries need to get much more serious about reducing emissions and lowering the concentration of atmospheric carbon dioxide. I believe that can be done at an affordable cost.

However, we also need to understand, to undertake a serious program of research on SRM. In a piece attached to my written testimony, my colleagues and I argued, in *Nature* this January, that the risk of not understanding whether and how well SRM might work, what it would cost, and what its intended and unintended consequences might be, are today greater than the risks associated with undertaking such research.

Initial research on SRM should be supported via the National Science Foundation at a level of a few million dollars per year. NSF should be the initial funding agency for two reasons. One, NSF does a good job of supporting open, investigator-initiated research, and we need a lot of bright people thinking about this topic from different perspectives before developing any serious program or field studies.

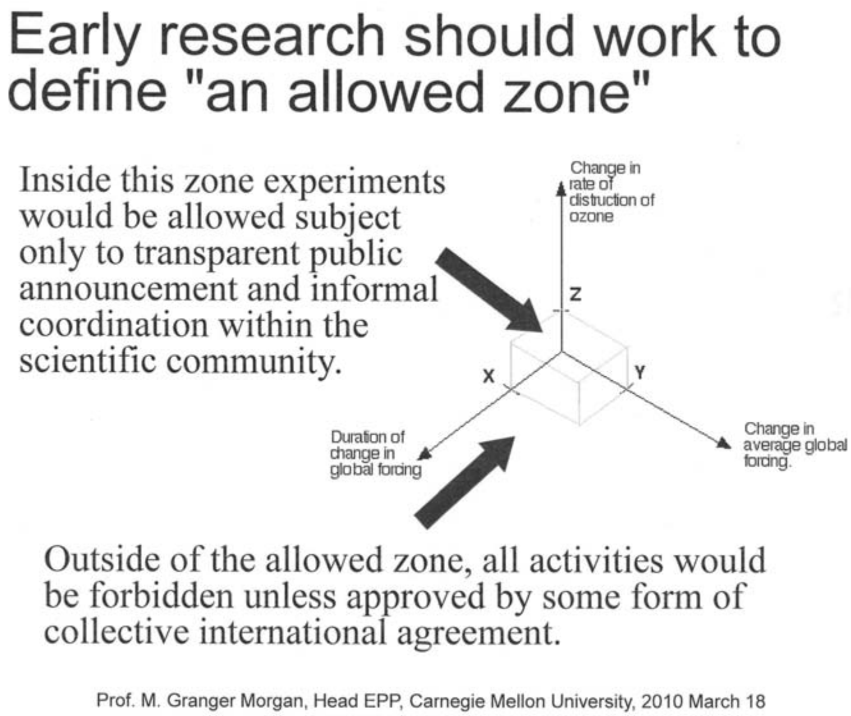
Two, in additional to natural science and engineering, NSF supports research in the social and behavioral sciences, and those perspectives on the subject are urgently needed. However, we will not be able to learn everything we need to learn with laboratory and computer studies, and once it is clear what sorts of field studies are needed, then NASA and/or NOAA should become involved. I believe that DOE should stay focused on the problems of de-carbonizing the energy system and reducing atmospheric concentrations of carbon dioxide.

All research on SRM should be open and transparent. Hence, SRM research should not be undertaken by DoD or the intelligence communities. Private, for-profit funding of SRM research should be actively discouraged, since it holds the potential to create a special interest that might push to move beyond research into deployment.

I turn now to the global governance of SRM research. I believe that there should be constraints on modest, low level field studies, done in an open and transparent manner, designed to better understand what is and what is not possible, what it might cost, and what possible unintended consequences might result.

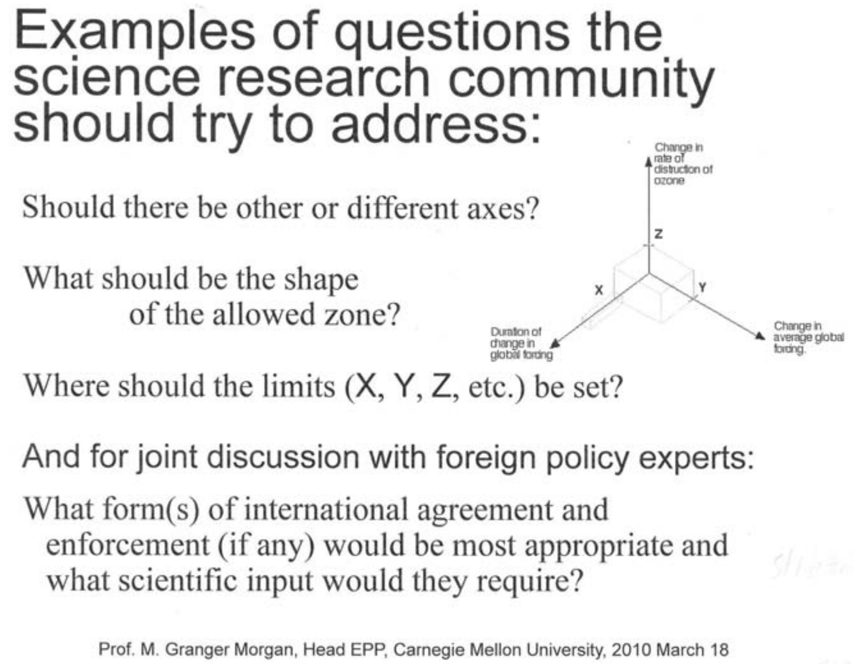
That said, I think it likely that pressure will grow for some more formal international oversight of SRM, and for that reason, I think one of the first objectives in a U.S. research program should be to give the phrase "modest low-level field testing" a more precise definition.

[The information follows:]



My first slide shows one way to frame this issue. In that diagram, X, Y, and Z define the limits of an allowed zone. They refer, respectively, to the upper bounds on the amount of radiative forcing that an experiment might impose, the duration of that forcing, and the possible impacts on ozone depletion.

[The information follows:]



As my second slide shows, early research should ask what should the allowed zone, how should the allowed zone be defined, and should it use different axes? What should be the shape of that zone? What should be the values of X, Y, Z, and so on, and then, in joint discussion with foreign policy experts, what forms of international agreement and enforcement, if any, would be most appropriate, and what scientific input would they require?

Now, all my remarks are focused on SRM. There are a number of technologies for directly scrubbing carbon dioxide from the Earth's atmosphere and sequestering it underground. These are very important. The Department of Energy should support research and development, and test such technologies, starting at a level of several tens of millions of dollars per year. Research and development by private, for-profit firms in this area should be very actively encouraged.

Mr. Chairman, thank you.

[The prepared statement of Dr. Morgan follows:]

PREPARED STATEMENT OF GRANGER MORGAN

Mr. Chairman, distinguished members, thank you for the opportunity to appear today to discuss research and governance related to the issue of geoengineering.

I am Granger Morgan, Professor and Head of the Department of Engineering and Public Policy at Carnegie Mellon University. I hold a Ph.D. in applied physics and have worked on a range of the technical and policy aspects of climate change for roughly 30 years.

When we were awarded a large NSF grant to create The Center for Integrated Study of the Human Dimensions of Global Change, in 1995, one of the early things we did was to conduct a review of the state of knowledge in geoengineering. My colleagues Hadi Dowlatabadi and David Keith published several papers as a result, including:

- David W. Keith, "Geoengineering the Climate: History and Prospect," *Annual Review of Energy and the Environment,* 25, pp. 245–284, 2000.
- David W. Keith and Hadi Dowlatabadi, "A Serious Look at Geoengineering, *Eos, Transactions American Geophysical Union,* 73, pp. 289–293, 1992.

After this initial work we moved on to other topics, and I did not think seriously about geoengineering again until about three years ago. At that time the foreign policy community was largely unaware of the possibility that humans might be able to rapidly increase earth's albedo (the fraction of sunlight reflected back into space) by roughly one percent and in so doing offset the warming caused by carbon dioxide and other greenhouse gases. The Royal Society had recently termed such activity SRM, or "solar radiation management."

In reflecting on the dismayingly slow pace of progress the world was making in cutting emissions of carbon dioxide, I began to be concerned that there is a growing risk that large effects from climate change might occur somewhere in the world that could induce a nation or group of nations to unilaterally modify the albedo of the planet in order to offset rising temperature. If someone were to do that, it could impose large effects on the entire planet.

In order to start a conversation with the foreign policy community I enlisted four colleagues (two like me with backgrounds in physics and planetary science backgrounds and two with backgrounds in political science and foreign policy). We organized a workshop at the Council on Foreign Relations (CFR) here in Washington, DC on May 5, 2008. We had excellent attendance from senior folks in both the science and foreign policy communities.

The five of us subsequently published a paper in the journal Foreign Affairs that summarized our thinking at that time:

- David G. Victor, M. Granger Morgan, Jay Apt, John Steinbruner, and Katharine Ricke, "The Geoengineering Option," *Foreign Affairs, 88*(2), 64–76, March/April 2009. (Attachment 2)

Because the CFR workshop involved only North Americans, and because this is a global issue, I subsequently organized a second more international workshop, again with the objective of stimulating discussion between the scientific and foreign policy communities. This second workshop was hosted by the Government of Portugal on April 20–21, 2009. Participants in this second workshop came from North America, from across the E.U., and from China, India and Russia.

SRM has five key attributes:

1. It is fast (i.e. cooling could be initiated in months not decades).
2. It is likely to be relatively inexpensive (i.e. as much as 100 to 1000 times cheaper than achieving the same temperature reduction through a systematic reduction of global emissions of carbon dioxide).
3. It will be imperfect (i.e. it will do nothing to offset the effects of rising carbon dioxide levels on ocean acidification and the associated destruction of coral reefs and ocean ecosystems; it will dry. out the hydrological cycle—and while recent studies indicate it will move temperature and precipitation back closer to what they were before climate change, it will not do so perfectly and there will be differences in how well it will work in different parts of the world); it will not offset impacts from elevated concentrations of carbon dioxide on terrestrial ecosystems.
4. Once started, if SRM is ever stopped, and carbon dioxide emissions have continued to rise, the resulting rapid increase in temperature would result in catastrophic ecological effects.
5. Unlike emission reduction which requires cooperation by all large emitters, a single nation (indeed, perhaps even a single very wealthy private party) could undertake SRM and effect the entire planet.

Up until now there has been very little serious research conducted on strategies to modify rapidly the albedo of the planet (i.e. on SRM): Historically, most folks in the climate science community have been reluctant to work in this area for two reasons:

- they did not want to deflect scarce funding and attention from the very important task of improving our understanding of the climate system;
- they were worried that if we better understand SRM and how to do it, that might deflect attention away from reducing emissions, and might also increase the probability that someone would actually engage in SRM.

I want to emphasize in the strongest possible terms that I am *not* arguing that the U.S. or anyone else should engage in SRM. We need to get much more serious about achieving a dramatic reduction in emissions of carbon dioxide.

However, because I believe that we are getting closer to the time when someone might be tempted to unilaterally engage in SRM in order to address local or regional problems caused by climate change, or a situation in which the world faces a sudden and unexpected climate emergency that places large number of people at risk, I think we have passed a tipping point. In my view, the risks of not understanding better whether and how SRM might work, what its intended and unintended consequences might be, and what it might cost, are today greater than the risks associated with doing such research. My colleagues and I have spelled out these arguments in two recent publications:

- David W. Keith, Edward Parson and M. Granger Morgan, "Research on Global Sun Block Needed Now," *Nature, 463*(28), 426–427, January 2010. (Attachment 3)
- M. Granger Morgan, "Why Geoengineering?," *Technology Review,* 14–15, January/February 2010.

With this background, I turn now to two questions which I understand this Committee is especially interested: who should fund research and what approach should be taken to issues of governance.

Up until now my remarks have been exclusively about SRM. There are a number of technologies for directly scrubbing carbon dioxide the earth's atmosphere and sequestering it deep underground. In my view, these are very important, and deserve considerably expanded research support, but do not pose significant issues of global governance. While slow, this approach is particularly attractive because it gets to the root of the problem by reducing the amount of carbon dioxide in the atmosphere. Thus, unlike SRM it also addresses ecosystem risks such as ocean acidification.

I believe that the Department of Energy should support research to develop and test technology to directly scrub carbon dioxide from the atmosphere at a level starting at several tens of millions of dollars per year. I do not believe that more than modest support is warranted for other strategies to remove carbon dioxide from the atmosphere.

As with power plants with carbon capture (CCS), once carbon dioxide has been captured it must be disposed of. At the moment, the best alternative is to do this via deep geologic sequestration. There are significant regulatory challenges for such sequestration. At Carnegie Mellon, we anchor the CCSReg project that is developing recommendations on the form that such regulation should take. Details are available on the web at www.CCSReg.org and are summarized in Attachment 4.

With respect to SRM, I believe that initial research support should be provided via NSF beginning at a level of a few million dollars per year. Indeed, both the policy and scientific work that I and my colleagues and Ph.D. student (Katharine Rieke) have been doing in this area have been conducted with support from NSF.

I argue that NSF should be the initial funding agency for two reasons:

1. NSF does a good job of supporting open investigator initiated research and we need a lot of bright people thinking about this topic from different perspectives in an open and transparent way before we get very far down the road of developing any serious programs of field research.
2. In addition to natural science and engineering, NSF supports research in the social and behavioral sciences. Perspectives and research strategies from those fields needs to be brought to bear on SRM as soon as possible.

We will not be able to learn everything we need to learn with laboratory and computer studies. Once it becomes clear that we need to be doing some larger scale field studies, then it would be appropriate to engage NASA and or NOAA. In addition to small scale field studies, it may also be possible to learn through more intensive studies of the "natural SRM experiments" that occur from time-to-time when volcanoes inject large amounts into the stratosphere. NSF, NASA or NOAA would all be able to prepare instrumentation and research plans to study such events, and should be encouraged to do so.

I would argue against involving DoE. They need to stay focused on the problems of decarbonizing the energy system.

While private funding should be encouraged for research and development of technologies to scrub carbon dioxide out of the atmosphere, steps should be taken to strongly discourage private funding for SRM since that holds the potential to create a special interest that might push to move past research to active deployment.

I believe that any research in SRM should be open and transparent. For this reason, and for reasons of international perceptions, 1 argue strongly that research on SRM should not be undertaken by DOD or by the intelligence communities.

Finally, I turn to the issue of global governance and SRM—the subject of the two workshops I described above. People do lots of things in the stratosphere today, most of which are pretty benign. So long as it is public, transparent, and modest in scale, and informally coordinated within the scientific community (e.g. by a group of leading national academies, the international council of scientific unions (ICSU), or some similar group) I believe there should be no constraints on modest low-level field testing, done in an open and transparent manner, designed to better understand what is and is not possible, what it might cost, and what possible unintended consequences might result.

That said, I think it likely that pressure will grow for some more formal international oversight. For that reason I think one of the first objectives in a U.S. research program should be to give the phrase "modest low-level field testing" a more precise definition. Figure 1 illustrates one way to think about this issue. In this diagram X, Y and Z define the limits to an "allowed zone." They refer respectively to upper bounds on the amount of radiative forcing that an experiment could impose, the duration of that forcing, and the possible impact on ozone depletion (the surface of particles can provide reaction sites at which ozone destruction could occur).

Initial research should explore whether these three axis are the right ones, or whether there should be other or additional dimensions.

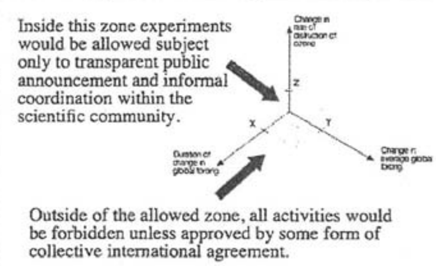


Figure 1: A possible strategy for defining a "space" in which experiments can be run only with transparency and informal coordination across the scientific community.

The "allowed space" might not be a simple cube. For example, as Figure 2 suggests, if the scientific community thought it was important to test a small number of particles that because of special properties would be very long lived, but would have de minimus effect on planetary forcing or ozone depletion, a more complex "allowed space" might be called for.

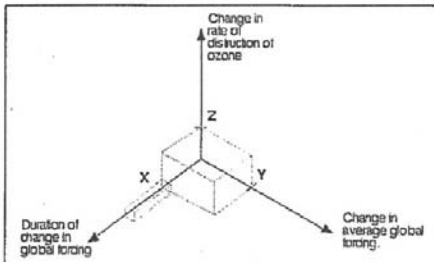


Figure 2: The shape of the "allowed zone" that makes the most sense scientifically may not be simple and should be the subject of careful early research.

I am not prepared to argue that there should be a formal treaty any time soon that addresses these issues. However, I think there is a good chance that pressure will grow for some form of international agreement (perhaps just an agreement among major states that others can choose to sign on to). For this reason we should start now to lay the scientific foundation for defining such an "allowed space." If work has not been done before hand it might be very hard to introduce a reasoned scientific argument if political momentum grows for serious limitations—perhaps even an outright ban or "taboo." For this reason I think we should continue to promote discussion between the scientific and foreign policy communities about what form(s) of international agreement and enforcement (if any) would be most appropriate and what sorts of scientific foundation they would require.

Attachments:

1. Short vita for M. Granger Morgan.
2. Copy of the paper "The Geoengineering Option" from *Foreign Affairs,* 2009.
3. Copy of the opinion piece "Research on Global Sun Block Needed Now" from *Nature,* 2010.
4. Summary of regulatory recommendations for deep geological sequestration of carbon dioxide from the **CCSReg** project.

nature Vol 463|28 January 2010

OPINION

ATTACHMENT 2

Research on global sun block needed now

Geoengineering studies of solar-radiation management should begin urgently, argue **David W. Keith, Edward Parson** and **M. Granger Morgan** — before a rogue state takes action.

The idea of deliberately manipulating Earth's energy balance to offset human-driven climate change strikes many as dangerous hubris. Solar-radiation management (SRM), a proposed form of geoengineering, aims to reduce Earth's absorption of solar energy by, for example, adding light-scattering aerosols to the upper atmosphere or increasing the lifetime and reflectivity of low-altitude clouds. Many scientists have argued against research on SRM, saying that developing the capability to perform such tasks will reduce the political will to lower greenhouse-gas emissions. We believe that the risks of not doing research outweigh the risks of doing it. Solar-radiation management may be the only human response that can fend off rapid and high-consequence climate impacts. Furthermore, the potential of unilateral deployment of SRM poses environmental and geopolitical risks which can best be managed by developing widely shared knowledge, risk assessment and norms of governance.

SRM has three essential characteristics: it is cheap, fast and imperfect. Long-established estimates show that SRM could offset this century's global-average temperature rise more than 100 times more cheaply than achieving the same cooling by emission cuts. A few grams of sulphate particles in the stratosphere could offset the radiative forcing of a tonne of atmospheric carbon dioxide. At about US$1,000 a tonne for aerosol delivery, that adds up to just billions of dollars per year. This low price tag is attractive, but it raises the risks of single groups acting alone, and of facile cheerleading that promotes exclusive reliance on SRM.

> "Solar-radiation management has three essential characteristics: it is cheap, fast and imperfect."

High leverage

SRM could alter the global climate within months — as suggested by the 1991 eruption of Mount Pinatubo, which cooled the globe about 0.5 °C in less than a year by injecting sulphur into the stratosphere. In contrast, because of the carbon cycle's inertia, even a massive programme of emission cuts or CO_2 removal will take many decades to slow global warming discernibly. SRM's speed provides strong grounds to pursue it as a hedge against the real but unlikely possibility that climate is much more sensitive than expected to rising greenhouse gases, or against extreme impacts such as major ice-sheet collapse. Because of the high level of uncertainty, even cutting emissions by an order of magnitude cannot ensure climate effects are held at acceptable levels.

These qualities make SRM a promising tool against climate change. But it is vital to remember that a world cooled by managing sunlight will not be the same as one cooled by lowering emissions. An SRM-cooled world would have less precipitation and less evaporation. Some areas would be more protected from temperature changes, creating local 'winners' and 'losers'. SRM could conceivably weaken monsoon rains and winds. It would not combat ocean acidification or other CO_2-driven ecosystem changes, and would introduce other environmental risks such as delaying the recovery of the ozone hole. Initial studies[1] suggest that known risks are small, but unanticipated risks remain a serious underlying concern. If the world relies solely on SRM to limit warming, these problems will eventually pose risks as large as those from uncontrolled emissions.

To posit a binary choice between SRM and cutting emissions creates a false and dangerous dichotomy — like previous suggestions of a binary choice between mitigation and adaptation. A prudent climate strategy requires adaptation and deep cuts in global emissions. We must develop the capability to do SRM in a manner that complements such cuts, while managing the associated environmental and political risks.

The path through this thicket involves two activities that must both begin immediately: a carefully designed, incremental, transparent and international programme of SRM research; and linked activities to create norms and understanding for international governance of SRM.

Research so far has largely consisted of a handful of climate-model studies, using very simple parameterization of aerosol microphysics. More complex models should be developed, and linked to global climate models. Field tests will be needed, such as generating and tracking stratospheric aerosols to block sunlight, and dispersing sea-salt aerosols to brighten marine clouds. Such tests can be small: releasing tonnes, not megatonnes, of material.

SUMMARY

- Field testing is required to understand the risks of solar radiation management (SRM)
- Linked activities must create norms and understanding for international governance of SRM
- If SRM is unworkable, the sooner we know, the less moral hazard it poses

Dearth of data

Decades of upper atmosphere research — such as that done to investigate the effect of supersonic passenger aircraft — has produced a mass of relevant science. But, except for a recent, small Russian test, there have been no field tests of SRM. Until now, there has been essentially no government research funding available for SRM anywhere in the world; although a few programmes for geoengineering have begun in the past few months. The environmental hazards of SRM cannot be assessed without knowing the specific techniques that might be used, and it is impossible to identify and develop techniques without field testing.

It is often assumed, for example, that a suitable distribution of stratospheric sulphate aerosols can be produced by releasing sulphur dioxide in the stratosphere. In fact, new simulations[2] of aerosol physics suggest that the resultant aerosol size distribution would be skewed to large particles that are relatively ineffective. Several aerosol compositions and delivery methods may offer a way around this problem, but choosing between them and quantifying their environmental effects will require in-situ testing. NASA's ER-2 high-altitude research plane might be used to release aerosols into the stratosphere, and fly through the plume to assess the effects. Such tests take years to plan and cost millions of dollars.

It would be reckless to conduct the first large-scale SRM tests in an emergency. Experiments should expand gradually to scales big enough to produce barely detectable climate effects and reveal unexpected problems, yet small enough (of the order of hundreds of kilotonnes) to limit risks. The ability to detect the climatic response to SRM grows with the test's duration, so starting sooner makes the scale of experiment needed to give detectable results by any future date — say by 2030 — smaller. A later start delays when results will be known, or requires a bigger intervention to detect the response.

SRM research should not be entrusted exclusively to either its proponents or its adversaries. Instead, there may be value in a 'blue team/red team' method, in which one team is charged to propose an approach that is as effective and low-risk as possible, and the other works to identify all the ways it can fail. Such an adversarial approach may increase the quality and utility of information available to future decision-makers, who might have to decide on SRM deployment in conditions of urgency or even panic. An international research budget growing from about $10 million to $1 billion annually over this decade would probably be sufficient to build the capability to deploy SRM and greatly improve understanding of its risks.

Global governance

Building responsibly towards future SRM capability will also require surmounting novel problems of international governance. These are quite unlike the problems of emissions governance, in which the main challenge is motivating contributions to a costly shared goal. For SRM, the main problem will be establishing legitimate collective control over an activity that some might seek to do unilaterally. Such a unilateral challenge could arise in many forms and from many quarters. At one extreme, a state might decide that avoiding the effects of climate change on its people takes precedence over the environmental concerns of SRM and begin injecting sulphur into the stratosphere, with no prior risk assessment or international consultation. If this were a small state, it could be quickly stopped by great-power intervention. If it were a major state, that might not be possible.

Alternatively a nation might grow frustrated at the pace of international cooperation and establish a national programme of gradually expanding research and field tests. This might be linked to a distinguished international advisory board, including leading scientists and retired politicians of global stature. It is plausible that, after exhausting other avenues to limit climate risks, such a nation might decide to begin a gradual, well-monitored programme of SRM deployment, even without any international agreement on its regulation. In this case, one nation — which need not be a large and rich industrialized country — would effectively seize the initiative on global climate, making it extremely difficult for other powers to restrain it.

"It is a healthy sign that a common first response to geoengineering is revulsion."

No existing treaty or institution is well suited to SRM governance. Given current uncertainties, immediate negotiation of a treaty is probably not advisable. Hasty pursuit of international regulation would risk locking in commitments that might soon be seen as wrong-headed, such as a total ban on research or testing, or burdensome vetting of even innocuous research projects.

A better approach would be to build international cooperation and norms from the bottom up, as knowledge and experience develop — as happened, for example, with the land-mine treaty, which emerged from action by non-governmental organizations. A first step might be a transparent, loosely coordinated international programme supporting research and risk assessments by multiple independent teams. Simultaneously, informal consultations on risk assessment, acceptability, regulation and governance could engage broad groups of experts and stakeholders such as former government officials and NGO leaders. Iterative links between emerging governance and ongoing scientific and technical research would be the core of this bottom-up approach.

Opinions about SRM are changing rapidly. Only a few years ago, many scientists opposed open discussion of the topic. Many now support model-based research, but field testing of the sort we advocate here is contentious and will probably grow more so. The main argument against SRM research is that it would undermine the already-inadequate resolve to cut emissions. We are keenly aware of this 'moral hazard', but sceptical that suppressing SRM research would in fact raise commitment to mitigation. Indeed, with the possibility of SRM now widely recognized, failing to subject it to serious research and risk assessment may well pose the greater threat to mitigation efforts, by allowing implicit reliance on SRM without scrutiny of its actual requirements, limitations and risks. If SRM proves to be unworkable or poses unacceptable risks, the sooner we know this, the less moral hazard it poses; if it is effective, we gain a useful additional tool to limit climate damages.

It is a healthy sign that a common first response to geoengineering is revulsion. It suggests we have learned something from past instances of over-eager technological optimism and subsequent failures. But we must also avoid over-interpreting this past experience. Responsible management of climate risks requires sharp emissions cuts and clear-eyed research and assessment of SRM capability. The two are not in opposition. We are currently doing neither; action is urgently needed on both. ■

David W. Keith is director of the energy and environmental systems group at the University of Calgary, Calgary, Alberta T2N 1N4, Canada. He has commercial interests in a carbon dioxide extraction technology and does academic research on SRM. **Edward Parson** is professor of natural resources and environment at the University of Michigan, Ann Arbor, Michigan 48109-215, USA. **M. Granger Morgan** is head of the Department of Engineering and Public Policy at Carnegie Mellon University, Pittsburgh, Pennsylvania 15213, USA.
e-mail: keith@ucalgary.ca

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Further reading accompanies this article online at go.nature.com/Jtdd8b.

IMAGE: F. M. I. FLORES; DATA SOURCE: REF. 3

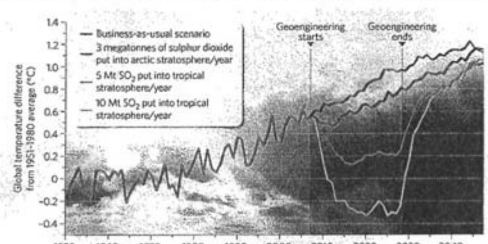


Figure 1 | Turning down the heat. A model[3] shows how quickly solar-radiation management (SRM) might alter global temperature, and how conditions might rebound after the geoengineering stops.

ATTACHMENT 3

FOREIGN AFFAIRS

MARCH / APRIL 2009

The Geoengineering Option

A Last Resort Against Global Warming?

David G. Victor, M. Granger Morgan, Jay Apt, John Steinbruner, and Katharine Ricke

Volume 88 • Number 2

The Geoengineering Option

A Last Resort Against Global Warming?

David G. Victor, M. Granger Morgan, Jay Apt, John Steinbruner, and Katharine Ricke

EACH YEAR, the effects of climate change are coming into sharper focus. Barely a month goes by without some fresh bad news: ice sheets and glaciers are melting faster than expected, sea levels are rising more rapidly than ever in recorded history, plants are blooming earlier in the spring, water supplies and habitats are in danger, birds are being forced to find new migratory patterns.

The odds that the global climate will reach a dangerous tipping point are increasing. Over the course of the twenty-first century, key ocean currents, such as the Gulf Stream, could shift radically, and thawing permafrost could release huge amounts of additional greenhouse gases into the atmosphere. Such scenarios, although still remote, would dramatically accelerate and compound the consequences of global warming. Scientists are taking these doomsday scenarios seriously because the steady accumulation of warming gases in the atmosphere

DAVID G. VICTOR is a Professor at Stanford Law School, Director of Stanford's Program on Energy and Sustainable Development, and an Adjunct Senior Fellow at the Council on Foreign Relations. M. GRANGER MORGAN is Head of Carnegie Mellon University's Department of Engineering and Public Policy and Director of the Climate Decision Making Center. JAY APT is Professor of Engineering and Public Policy at Carnegie Mellon University. JOHN STEINBRUNER is Professor of Public Policy and Director of the Center for International and Security Studies at the University of Maryland. KATHARINE RICKE is a doctoral student at Carnegie Mellon University. Additional materials are available online at www.cfr.org/geoengineering.

is forcing change in the climate system at rates so rapid that the outcomes are extremely difficult to predict.

Eliminating all the risks of climate change is impossible because carbon dioxide emissions, the chief human contribution to global warming, are unlike conventional air pollutants, which stay in the atmosphere for only hours or days. Once carbon dioxide enters the atmosphere, much of it remains for over a hundred years. Emissions from anywhere on the planet contribute to the global problem, and once headed in the wrong direction, the climate system is slow to respond to attempts at reversal. As with a bathtub that has a large faucet and a small drain, the only practical way to lower the level is by dramatically cutting the inflow. Holding global warming steady at its current rate would require a worldwide 60–80 percent cut in emissions, and it would still take decades for the atmospheric concentration of carbon dioxide to stabilize.

Most human emissions of carbon dioxide come from burning fossil fuels, and most governments have been reluctant to force the radical changes necessary to reduce those emissions. Economic growth tends to trump vague and elusive global aspirations. The United States has yet to impose even a cap on its emissions, let alone a reduction. The European Union has adopted an emissions-trading scheme that, although promising in theory, has not yet had much real effect because carbon prices are still too low to cause any significant change in behavior. Even Norway, which in 1991 became one of the first nations to impose a stiff tax on emissions, has seen a net increase in its carbon dioxide emissions. Japan, too, has professed its commitment to taming global warming. Nevertheless, Tokyo is struggling to square the need for economic growth with continued dependence on an energy system powered mainly by conventional fossil fuels. And China's emissions recently surpassed those of the United States, thanks to coal-fueled industrialization and a staggering pace of economic growth. The global economic crisis is stanching emissions a bit, but it will not come close to shutting off the faucet.

The world's slow progress in cutting carbon dioxide emissions and the looming danger that the climate could take a sudden turn for the worse require policymakers to take a closer look at emergency strategies for curbing the effects of global warming. These strategies, often called "geoengineering," envision deploying systems on a planetary scale, such

enough that in 1976 the United Nations adopted the Convention on the Prohibition of Military or Any Other Hostile Use of Environmental Modification Techniques to bar such projects. By the 1970s, after a string of failures, the idea of weather modification for war and farming had largely faded away.

Today's proposals for geoengineering are more likely to have an impact because the interventions needed for global-scale geoengineering are much less subtle than those that sought to influence local weather patterns. The earth's climate is largely driven by the fine balance between the light energy with which the sun bathes the earth and the heat that the earth radiates back to space. On average, about 70 percent of the earth's incoming sunlight is absorbed by the atmosphere and the planet's surface; the remainder is reflected back into space. Increasing the reflectivity of the planet (known as the albedo) by about one percentage point could have an effect on the climate system large enough to offset the gross increase in warming that is likely over the next century as a result of a doubling of the amount of carbon dioxide in the atmosphere. Making such tweaks is much more straightforward than causing rain or fog at a particular location in the ways that the weather makers of the late 1940s and 1950s dreamed of doing.

In fact, every few decades, volcanoes validate the theory that it is possible to engineer the climate. When Mount Pinatubo, in the Philippines, erupted in 1991, it ejected plumes of sulfate and other fine particles into the atmosphere, which reflected a bit more sunlight and cooled the planet by about 0.5 degrees Celsius over the course of a year. Larger eruptions, such as the 1883 eruption of Krakatau, in Indonesia, have caused even greater cooling that lasted longer. Unlike efforts to control emissions of greenhouse gases, which will take many years to yield a noticeable effect, volcano-like strategies for cooling the planet would work relatively promptly.

Another lesson from volcanoes is that a geoengineering system would require frequent maintenance, since most particles lofted into the stratosphere would disappear after a year or two. Once a geoengineering project were under way, there would be strong incentives to continue it, since failure to keep the shield in place could allow particularly harmful changes in the earth's climate, such as warming so speedy that ecosystems would collapse because they had no time to adjust. By carefully measuring the climatic effects of the next major volcanic eruption with satellites and aircraft, geoengineers could design a number of climate-cooling technologies.

ALBEDO ENHANCERS

TODAY, THE term "geoengineering" refers to a variety of strategies designed to cool the climate. Some, for example, would slowly remove carbon dioxide from the atmosphere, either by manipulating the biosphere (such as by fertilizing the ocean with nutrients that would allow plankton to grow faster and thus absorb more carbon) or by directly scrubbing the air with devices that resemble big cooling towers. However, from what is known today, increasing the earth's albedo offers the most promising method for rapidly cooling the planet.

Most schemes that would alter the earth's albedo envision putting reflective particles into the upper atmosphere, much as volcanoes do already. Such schemes offer quick impacts with relatively little effort. For example, just one kilogram of sulfur well placed in the stratosphere would roughly offset the warming effect of several hundred thousand kilograms of carbon dioxide. Other schemes include seeding bright reflective clouds by blowing seawater or other substances into the lower atmosphere. Substantial reductions of global warming are also possible to achieve by converting dark places that absorb lots of sunlight to lighter shades—for example, by replacing dark forests with more reflective grasslands. (Engineered plants might be designed for the task.)

More ambitious projects could include launching a huge cloud of thin refracting discs into a special space orbit that parks the discs between the sun and the earth in order to bend just a bit of sunlight away before it hits the planet.

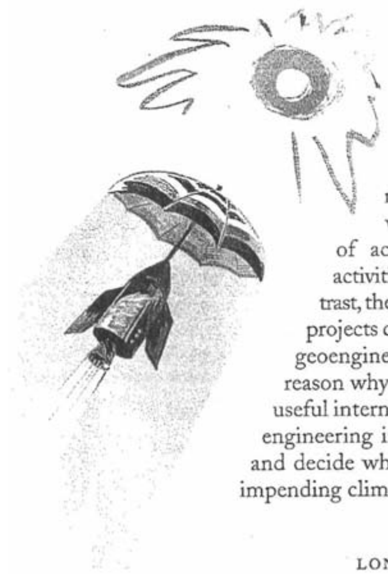
So far, launching reflective materials into the upper stratosphere seems to be the easiest and most cost-effective option. This could be accomplished by using high-flying aircraft, naval guns, or giant balloons. The appropriate materials could include sulfate aerosols (which would be created by releasing sulfur dioxide gas), aluminum oxide dust, or even self-levitating and self-orienting designer particles engineered to migrate to the Polar Regions and remain in place for long periods. If it can be done, concentrating sunshades over the poles would be a particularly interesting option, since those latitudes appear to be the most sensitive to global warming. Most cost estimates for such geoengineering strategies are preliminary and unreliable. However, there is general agreement that the strategies are cheap; the total expense of the most cost-effective options would amount to perhaps as little as a few billion dollars, just one percent (or less) of the cost of dramatically cutting emissions.

Every few decades, volcanoes validate the theory that it is possible to engineer the climate.

Cooling the planet through geoengineering will not, however, fix all of the problems related to climate change. Offsetting warming by reflecting more sunlight back into space will not stop the rising concentration of carbon dioxide in the atmosphere. Sooner or later, much of that carbon dioxide ends up in the oceans, where it forms carbonic acid. Ocean acidification is a catastrophe for marine ecosystems, for the 100 million people who depend on coral reefs for their livelihoods, and for the many more who depend on them for coastal protection from storms and for biological support of the greater ocean food web. Over the last century, the oceans have become markedly more acidic, and current projections suggest that without a serious effort to control emissions, the concentration of carbon dioxide will be so high by the end of the century that many organisms that make shells will disappear and most coral reef ecosystems will collapse, devastating the marine fishing industry. Recent studies have also suggested that ocean acidification will increase the size and depth of "dead zones," areas of the sea that are so oxygen depleted that larger marine life, such as squid, are unable to breathe properly.

Altering the albedo of the earth would also affect atmospheric circulation, rainfall, and other aspects of the hydrologic cycle. In the six to 18 months following the eruption of Mount Pinatubo, rainfall and river flows dropped, particularly in the tropics. Understanding these dangers better would help convince government leaders in rainfall-sensitive regions, such as parts of China and India (along with North Africa, the Middle East, and the desert regions of the southwestern United States), not to prematurely deploy poorly designed geoengineering schemes that could wreak havoc on agricultural productivity. Indeed, some climate models already suggest that negative outcomes—decreased precipitation over land (especially in the tropics) and increased precipitation over the oceans—would accompany a geoengineering scheme that sought to lower average temperatures by raising the planet's albedo. Such changes could increase the risk of major droughts in some regions and have a major impact on agriculture and the supply of fresh water. Complementary policies—such as investing in better water-management schemes—may be needed.

The highly uncertain but possibly disastrous side effects of geoengineering interventions are difficult to compare to the dangers of unchecked global climate change. Chances are that if countries begin deploying geoengineering systems, it will be because calamitous climate change is near at hand. Yet the assignment



of blame after a geoengineering disaster would be very different from the current debates over who is responsible for climate change, which is the result of centuries of accumulated emissions from activities across the world. By contrast, the side effects of geoengineering projects could be readily pinned on the geoengineers themselves. That is one reason why nations must begin building useful international norms to govern geoengineering in order to assess its dangers and decide when to act in the event of an impending climatic disaster.

LONE RANGERS

An effective foreign policy strategy for managing geoengineering is difficult to formulate because the technology involved turns the normal debate over climate change on its head. The best way to reduce the danger of global warming is, of course, to cut emissions of carbon dioxide and other greenhouse gases. But success in that venture will require all the major emitting countries, with their divergent interests, to cooperate for several decades in a sustained effort to develop and deploy completely new energy systems with much lower emissions. Incentives to defect and avoid the high cost of emissions controls will be strong.

By contrast, geoengineering is an option at the disposal of any reasonably advanced nation. A single country could deploy geoengineering systems from its own territory without consulting the rest of the planet. Geoengineers keen to alter their own country's climate might not assess or even care about the dangers their actions could create for climates, ecosystems, and economies elsewhere. A unilateral geoengineering project could impose costs on other countries, such as changes in precipitation patterns and river flows or adverse impacts on agriculture, marine fishing, and tourism. And merely knowing that geoengineering exists as an option may take the pressure off governments to implement the policies needed to cut emissions.

At some point in the near future, it is conceivable that a nation that has not done enough to confront climate change will conclude that global warming has become so harmful to its interests that it should unilaterally engage in geoengineering. Although it is hardly wise to mess with a poorly understood global climate system using instruments whose effects are also unknown, politicians must take geoengineering seriously because it is cheap, easy, and takes only one government with sufficient hubris or desperation to set it in motion. Except in the most dire climatic emergency, universal agreement on the best approach is highly unlikely. Unilateral action would create a crisis of legitimacy that could make it especially difficult to manage geoengineering schemes once they are under way.

Fiddling with the climate to fix the climate strikes most people as a shockingly bad idea.

Although governments are the most likely actors, some geoengineering options are cheap enough to be deployed by wealthy and capable individuals or corporations. Although it may sound like the stuff of a future James Bond movie, private-sector geoengineers might very well attempt to deploy affordable geoengineering schemes on their own. And even if governments manage to keep freelance geoengineers in check, the private sector could emerge as a potent force by becoming an interest group that pushes for deployment or drives the direction of geoengineering research and assessment. Already, private companies are running experiments on ocean fertilization in the hope of sequestering carbon dioxide and earning credits that they could trade in carbon markets. Private developers of technology for albedo modification could obstruct an open and transparent research environment as they jockey for position in the potentially lucrative market for testing and deploying geoengineering systems. To prevent such scenarios and to establish the rules that should govern the use of geoengineering technology for the good of the entire planet, a cooperative, international research agenda is vital.

FROM SCIENCE FICTION TO FACTS

DESPITE YEARS of speculation and vague talk, peer-reviewed research on geoengineering is remarkably scarce. Nearly the entire community of geoengineering scientists could fit comfortably in a single university seminar room, and the entire scientific literature on the subject could be read during the course of a transatlantic flight. Geoengineering continues to be considered a fringe topic.

Many scientists have been reluctant to raise the issue for fear that it might create a moral hazard: encouraging governments to deploy geoengineering rather than invest in cutting emissions. Indeed, geoengineering ventures will be viewed with particular suspicion if the nations funding geoengineering research are not also investing in dramatically reducing their emissions of carbon dioxide and other greenhouse gases. Many scientists also rightly fear that grants for geoengineering research would be subtracted from the existing funds for urgently needed climate-science research and carbon-abatement technologies. But there is a pressing need for a better understanding of geoengineering, rooted in theoretical studies and empirical field measurements. The subject also requires the talents of engineers, few of whom have joined the small group of scientists studying these techniques.

The scientific academies in the leading industrialized and emerging countries—which often control the purse strings for major research grants—must orchestrate a serious and transparent international research effort funded by their governments. Although some work is already under way, a more comprehensive understanding of geoengineering options and of risk-assessment procedures would make countries less trigger-happy and more inclined to consider deploying geoengineering systems in concert rather than on their own. (The International Council for Science, which has a long and successful history of coordinating scientific assessments of technical topics, could also lend a helping hand.) Eventually, a dedicated international entity overseen by the leading academies, provided with a large budget, and suffused with the norms of transparency and peer review will be necessary.

In time, international institutions such as the Intergovernmental Panel on Climate Change could be expected to synthesize the findings from the published research. The IPCC, which shared the Nobel Peace Prize in 2007 for its pivotal role in building a consensus around climate science, has not considered geoengineering so far because the topic is politically radioactive and there is a dearth of peer-reviewed research on it. The IPCC's fifth assessment report on climate change, which is being planned right now, should promise to take a closer look at geoengineering. Attention from the IPCC and the world's major scientific academies would help encourage new research.

A broad and solid foundation of research would help on three fronts. First, it would transform the discussion about geoengineering from an abstract debate into one focused on real risk assessment. Second, a research program that was backed by the world's top scientific academies could secure funding and political cover for essential but controversial experiments. (Field trials of engineered aerosols, for example, could spark protests comparable to those that accompanied trials of genetically modified crops.) Such experiments will be seen as more acceptable if they are designed and overseen by the world's leading scientists and evaluated in a fully transparent fashion. Third, and what is crucial, a better understanding of the dangers of geoengineering would help nations craft the norms that should govern the testing and possible deployment of newly developed technologies. Scientists could be influential in creating these norms, just as nuclear scientists framed the options on nuclear testing and influenced pivotal governments during the Cold War.

The option of geoengineering exists. It would be dangerous for scientists and policymakers to ignore it.

If countries were actually to contemplate the deployment of geoengineering technologies, there would inevitably be questions raised about what triggers would compel the use of these systems. Today, nobody knows which climatic triggers are most important for geoengineering because research on the harmful effects of climate change has not been coupled tightly enough with research on whether and how geoengineering might offset those effects.

Although the international scientific community should take the lead in developing a research agenda, social scientists, international lawyers, and foreign policy experts will also have to play a role. Eventually, there will have to be international laws to ensure that globally credible and legitimate rules govern the deployment of geoengineering systems. But effective legal norms cannot be imperiously declared. They must be carefully developed by informed consensus in order to avoid encouraging the rogue forms of geoengineering they are intended to prevent.

Those who worry that such research will cause governments to abandon their efforts to control emissions, including much of the environmental community, are prone to seek a categorical prohibition against geoengineering. But a taboo would interfere with much-needed scientific research on an option that might be better for humanity and the world's ecosystems than allowing unchecked climate change or reckless unilateral geoengineering. Formal prohibition is unlikely to stop determined rogues, but a smart and scientifically sanctioned research program could gather data essential to understanding the risks of geoengineering strategies and to establishing responsible criteria for their testing and deployment.

BRAVE NEW WORLD

FIDDLING WITH the climate to fix the climate strikes most people as a shockingly bad idea. Many worry that research on geoengineering will make governments less willing to regulate emissions. It is more likely, however, that serious study will reveal the many dangerous side effects of geoengineering, exposing it as a true option of last resort. But because the option exists, and might be used, it would be dangerous for scientists and policymakers to ignore it. Assessing and managing the risks of geoengineering may not require radically different approaches from those used for other seemingly risky endeavors, such as genetic engineering (research on which was paused in the 1970s as scientists worked out useful regulatory systems), the construction and use of high-energy particle accelerators (which a few physicists suggest could create black holes that might swallow the earth), and the development of nanotechnology (which some worry could unleash self-replicating nanomachines that could reduce the world to "gray goo"). The option of eliminating risk altogether does not exist. Countries have kept smallpox samples on hand, along with samples of many other diseases, such as the Ebola and Marburg viruses, despite the danger of their inadvertent release. All of these are potentially dangerous endeavors that governments, with scientific support, have been able to manage for the greater good.

Humans have already engaged in a dangerous geophysical experiment by pumping massive amounts of carbon dioxide and other greenhouse gases into the atmosphere. The best and safest strategy for reversing climate change is to halt this buildup of greenhouse gases, but this solution will take time, and it involves myriad practical and political difficulties. Meanwhile, the dangers are mounting. In a few decades, the option of geoengineering could look less ugly for some countries than unchecked changes in the climate. Nor is it impossible that later in the century the planet will experience a climatic disaster that puts ecosystems and human prosperity at risk. It is time to take geoengineering out of the closet—to better control the risk of unilateral action and also to know the costs and consequences of its use so that the nations of the world can collectively decide whether to raise the shield if they think the planet needs it.

ATTACHMENT 4

March 12, 2010

Developing a U.S. Regulatory Framework for CCS: A Summary of Recommendations from the CCSReg Project

Sean T. McCoy, Carnegie Mellon University

Carbon capture and sequestration (CCS) technology has the potential to contribute to a significant reduction in emissions of carbon dioxide (CO_2) from power generation and other industrial sectors if it can be deployed widely. While there are still significant technical challenges to be overcome, in the United States (U.S.) the absence of a consistent and predictable legal and regulatory framework to govern its use presents a serious obstacle to rapid and wide adoption.

In contrast to much of the world, where the deep pore space used in geologic sequestration is the property of the nation or the "crown," questions of ownership are based on myriad legal precedents that vary from one U.S. state to another. Operators in the U.S. inject large quantities of fluid waste underground under the U.S. Environmental Protection Agency's (EPA) Underground Injection Control (UIC) program without securing permission from surface landowners. Indeed, municipalities in Florida inject roughly 3 Gt/year of treated wastewater. However, absent law clarifying whether use of pore space for GS will require compensation, the moment an operator begins to inject CO_2, we anticipate that litigants will appear demanding compensation.

The other serious obstacle involves issues of long-term stewardship: who has responsibility for monitoring and remediation closed sites and who assumes the associated liability. The insurance industry is poised to insure all phases of a CCS project up until a closed project goes into long-term stewardship, but is not prepared to write policies that extend beyond that time.

Because it is operating under authority provided by the Safe Drinking Water Act, the EPA's current proposal to regulate CCS through the creation of a new well class under the UIC program, is not able to address either of these, or other key problems.

The CCSReg project was created to develop proposals that address these and other legal and regulatory barriers facing CCS in the U.S. Anchored in the Department of Engineering and Public Policy at Carnegie Mellon University, the project involves co-investigators at the Vermont Law School, and the Washington, DC law firm of Van Ness Feldman, and at the University of Minnesota. The project released an interim report that framed the issues in January of 2009.

The CCSReg project has now released six policy briefs that outline how the project believes the key regulatory issues should best be resolved in a U.S. context. These briefs address the overall structure that comprehensive regulation of CCS should take; the regulatory framework for pipelines transporting CO_2 for CCS; governing access to and use of pore space in geologic sequestration; managing liability and long-term stewardship for geological sequestration; and accounting for CO_2 sequestered through CCS.

Although some of the recommendations are included in the American Clean Energy and Security Act of 2009 and other pending state and federal legislation, the briefs take a more comprehensive look at an entire program for regulation of CCS.

Specific recommendations from these briefs include:

- Amend the U.S. Safe Drinking Water Act to direct Underground Injection Control (UIC) program regulators to create adaptive, performance-based rules for geologic sequestration, and to include mechanisms to resolve conflicts between multiple environmental objectives.
- Expand the federal UIC program to address conflicting uses of pore space during permitting; creating new federal legislation that would limit the trespass liability of a sequestration project developer operating pursuant to a valid UIC permit.

March 12, 2010

- Modify the U.S. Federal Land Policy Management Act to specifically authorize the use of federal lands for geologic sequestration.
- Create a Federal Geologic Sequestration Board ("FGSB") that would oversee long-term stewardship of properly closed sequestration projects.
- Create a revolving fund, based upon risk-based assessments on geologic sequestration projects during their operating life, which will finance the FGSB and any remediation or compensation necessary during long-term stewardship.
- Create a stop-gap federal indemnity program for the stewardship phase of "first-mover" geologic sequestration projects.
- Treat sequestered CO_2 as avoided emissions rather than offsets and require each component of a CCS project (i.e. capture, transport, and sequestration facilities) to report the amount of CO_2 handled.
- Require focused surface monitoring to locate and quantify atmospheric leakage only if subsurface monitoring indicates CO_2 has migrated through the confining formation and either surface monitoring of vegetation or soil gas detects leakage.
- Develop an "opt-in" federal regulatory regime providing the U.S. Federal Energy Regulatory Commission authority to grant or deny applications for federal siting permits for new CO_2 pipelines built for the purposes of geologic sequestration.

Forthcoming briefs in this series will address criteria for permitting and closure of geologic sequestration sites; removing commercial barriers to deployment of CCS technology; and managing the transition from Enhanced Oil Recovery to geologic sequestration.

The five briefs discussed here, the forthcoming briefs in the series, and other publications from the project are available at http://www.ccsreg.org.

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BIOGRAPHY FOR GRANGER MORGAN

M. Granger Morgan is Professor and Head of the Department of Engineering and Public Policy at Carnegie Mellon University where he is also University and Lord Chair Professor in Engineering. In addition, he holds academic appointments in the Department of Electrical and Computer Engineering and in the H. John Heinz III College. His research addresses problems in science, technology and public policy with a particular focus on energy, environmental systems, climate change and risk analysis. Much of his work has involved the development and demonstration of methods to characterize and treat uncertainty in quantitative policy analysis. At Carnegie Mellon, Morgan directs the NSF Climate Decision Making Center and co-directs, with Lester Lave, the Carnegie Mellon Electricity Industry Center. Morgan serves as Chair of the Scientific and Technical Council for the International Risk Governance Council. In the recent past, he served as Chair of the Science Advisory Board of the U.S. Environmental Protection Agency and as Chair of the Advisory Council of the Electric Power Research Institute. He is a Member of the National Academy of Sciences, and a Fellow of the AAAS, the IEEE, and the Society for Risk Analysis. He holds a BA from Harvard College (1963) where he concentrated in Physics, an MS in Astronomy and Space Science from Cornell (1965) and a Ph.D. from the Department of Applied Physics and Information Sciences at the University of California at San Diego (1969).

Chairman GORDON. Thank you. And Dr. Long is recognized. And we need to use your—there you go.

STATEMENTS OF DR. JANE LONG, DEPUTY PRINCIPAL ASSOCIATE DIRECTOR AT LARGE AND FELLOW, CENTER FOR GLOBAL STRATEGIC RESEARCH, LAWRENCE LIVERMORE NATIONAL LAB

Dr. LONG. Thank you. Okay, I hope the timer starts now. Mr. Chairman and Members of the Committee, thank you for this opportunity to talk to you.

My name is Jane Long. I am Principal Associate Director at Large at Lawrence Livermore, and I am currently acting as the Co-Chair of the National Commission on Energy Policies Task Force on Geoengineering. Today, my comments represent my own views, and not the views of either my laboratory or the NCEP Task Force, which has just begun its work.

I am going to talk about geoengineering, about three classes of geoengineering that were identified by the American Meteorological Society: climate remediation, or taking carbon dioxide out of the air; climate intervention, which is an actual act to change the nature of the climate; and the third category, which is a catch-all category. Most of my remarks will focus on the second category, because you are interested in governance, and this is where the governance issues largely occur.

My only remark about the category of climate remediation in my oral remarks today would be that there are fewer governance issues associated with it, that the research, as Dr. Morgan has pointed out, falls closely allied to CCS, carbon capture and storage research currently being pursued by the Department of Energy, and that this program should be expanded to include this. From a governance perspective, there is a question about whether the technology should be a public good, or we should tap into the forces of the market, and I think that that question depends on whether we end up having a price for carbon. If we have a price for carbon, this technology could easily be innovated in the private sector. If not, it is more like picking up the garbage, and should be a public good.

Let me turn my attention now to climate intervention. I really endorse the U.K. principles that were heard this morning. I think they are extremely important, and I would like to endorse those, and say that those are at the top of my list.

First of all, I think that the climate technology should be a public good, and we should say, up front, that we are not planning for deployment. If we start our research program by saying we are planning for deployment, we will feel a lot of pressure and a lot of pushback on whether people are against it. A lot of people who are against the idea of geoengineering are clearly for research, and we should not involve those at this point.

There are four questions that we need to get after in the national research governance format. One is what constitutes an appropriate level of governance for specific types of research? The second is, what are the guiding principles that should be used to sanction the research? And then, given these principles, what process should be used to sanction the research? And then, how will the governance process engage society?

Dr. Morgan has presented a concept for determining that level of research which should proceed with what I will call only "normal governance". I endorse that, and recommend that you convene a National Academy of Science panel now to help define what that bright line is, below which research can proceed with impunity. This is critically important, because we need to get started on research, and a lot of research is not problematic, and getting a definition of what we can go ahead with would be very important.

Then, we need to work on principles. I would like to add a few principles to those you heard this morning, and that is: beneficence should be a principle. We should have, we heard transparency, we heard public good, we heard public participation, we heard independent assessment of impacts, and we heard governance before deployment.

But I would like to add to that, we need to have some assessment that the benefits of the project, the potential benefits of the project, clearly outweigh any risks that are there. And some aspect of justice, ensuring a reasonable, non-exploitive, well considered procedures, and that the risks are fairly distributed.

In the research program, I think that the justice perspective is one that should be quite clear. We should not be taking advantage of people or peoples in doing research, but beginning to ask the question in the research program that will help us as we move towards possible deployment.

The review process then has to go forward, and let me just make one clear point about that. We don't know how to govern this research and do the review, but we have other models, and what I would recommend now is that we start a program with mock governance and mock review boards, that can try different principles and different procedures and see how they work, much as the institutional reviews for human subjects research try different ways to proceed, and then assess how well they have done.

Thank you for the opportunity to comment today, and I will, the rest of my remarks are my written testimony. Thank you.

[The prepared statement of Dr. Long follows:]

PREPARED STATEMENT OF JANE LONG

Mr. Chairman, members of the committee, thank you for this opportunity to add my comments about geoengineering to the record. This is a difficult and complex topic and your willingness to organize these sessions is both courageous and admirable. I hope I can add a little to the dialogue.

My academic background is geohydrology; I have worked in environmental and resource problems for over 35 years. My experience includes nuclear waste storage, geothermal energy, oil and gas reservoirs, environmental remediation, sustainable mining, climate science, energy efficiency, energy systems and policy, adaptation and recent attention to geoengineering. I have worked at two national laboratories, Lawrence Berkeley National Lab and Lawrence Livermore National Lab and have been a dean of engineering and science at University of Nevada, Reno. I am a Senior Fellow of the California Council on Science and Technology (CCST) and an Associate of the National Academy of Sciences. In my current position, I am a fellow in Lawrence Livermore National Laboratory's Center for Global Strategic Research and Associate Director at Large for the laboratory. I work in developing strategies for a new, climate friendly energy system and currently chair the CCST's California's Energy Future committee which is charged with examining how California could meet 80% reductions in greenhouse gas emissions by 2050. I am also a member of the State of California's Climate Change Adaptation Advisory Council. I currently serve as co-chair of the National Commission on Energy Policy's (NCEP) Task Force on Geoengineering. I work to understand and advance a full spectrum of management choices in the face of climate change: mitigation, adaption and now geoengineering.

My comments today reflect the perspective of my experience. They are my own opinions and do not reflect positions taken by my laboratory (Lawrence Livermore National Laboratory) or the NCEP task force on geoengineering I co-chair.

Introduction

Our climate is changing in response to massive emission of greenhouse gases. First, we have to stop causing this problem. We have to change our energy system, food system, transportation system, industries and land use patterns. Even with mandatory concerted effort, such massive change will take decades. During these same decades we will continue to burn fossil fuels and add to the greenhouse gases we have already emitted. This atmospheric perturbation will last for centuries and will continue to warm our planet. We have created, and will continue to create unavoidable risk of disruptions to our way of life which may force us to spend more on protection (*resistance*), change our way of life to accommodate the change (*resilience*), or perhaps even to abandon parts of the Earth that are no longer habitable by virtue of being under water or having too little fresh water (*retreat*).

Because the carbon dioxide we have already emitted will be with us for centuries, the problem of climate change cannot be "solved" in the same sense that other pollution problems—such as ozone depletion—have been solved by phasing out emissions over time. Climate change is like a chronic disease that must be managed with an arsenal of tools for many years while we struggle with a long term cure. In this future, if climate sensitivity (the magnitude of temperature change resulting from a doubling of CO_2 concentrations in the atmosphere) turns out to be larger than we hope or mitigation proceeds too slowly, we cannot rule out the possibility that climate change will come upon us faster and harder than we—or the ecosystems we depend on—can manage. No one knows what will happen, but we face an uncertain future where catastrophic changes are within the realm of the possible.

In the face of this existential threat, prudence dictates we try to create more options to help manage the problem and learn whether these are good options or bad options. I believe this is the most fundamental of ethical issues associated with our climate condition. We must continue to strive to correct the problem. This is why scientists today have become interested in a group of technologies commonly called geoengineering that are aimed at ameliorating the harmful effects of climate change directly and intentionally. Intentional modification of the climate carries risks and responsibilities that are entirely new to mankind. (We accept unintended but certain harm to climate from energy production much more easily that we accept unintended harm through intentional climate modification.) As we consider geoengineering, we have to recognize that society has not been able to quickly or easily respond to the climate change challenge. Consequently, the geoengineering option isn't just a matter of developing new science and technologies. It is also a matter of developing new social and political capacities and skills.

As much as I think we should research geoengineering possibilities, I think we should remain deeply concerned by the prospect of geoengineering. We will not be able to perfectly predict the consequences of geoengineering. Some effects may be irreversible and unequally distributed with harm to some even if there is benefit to many. Geoengineering could be a cause for conflict and a challenge for representative government. Geoengineering might be necessary in the future, but as we proceed to investigate this topic, we will need extremely good judgment and a very large dose of hubris.

Three different classes of geoengineering have been identified (American Meteorological Society, *http://www.ametsoc.org/POLICY/2009geoengineering climate_amsstatement.html*). The first is actively removing greenhouse gases from the atmosphere. This has been called "**Climate remediation**" or carbon dioxide removal (CDR) or "carbon management". Climate remediation is similar in concept to cleaning up contamination in our water or soil. The first problem is to stop polluting (mitigation) and the second is to remove the contaminants (remediation) and put them somewhere—for example filter CO_2 out of the air and pump it underground.

The second set of technologies has been called "**Climate intervention**" where we act to modify the energy balance of the atmosphere in order to restore the climate closer to a prior state. Climate intervention has also been called solar radiation management (SRM) or sun-block technology and some consider the technologies to be a radical form of adaptation. If we cannot find a way to live with the altered climate, we intervene to roll back the change.

The third is a **catch-all category** that includes technologies to manage heat flows in the ocean or actions to prevent massive release of methane in the melting Arctic. These technologies are less well understood and developed, but the classification recognizes that not all the ideas are in and, as well, we may wish to address some very specific global or sub-global scale emergencies caused by climate change.

I do not view any of these methods as stand-alone solutions, but some or all of these could be integrated in a comprehensive climate change strategy that starts with mitigation. A comprehensive climate change strategy might include:

- A steady, but aggressive transformation of the global energy system to eliminate emissions with concurrent elimination of air pollution in a few decades (mitigation)
- Carbon removal over perhaps 50 to 100 years to return to the "safe zone" of greenhouse gas concentrations (climate remediation)
- Time limited climate intervention to counteract prior emissions and reductions in air pollution, tapering off until greenhouse gases fall to a "safe" level (climate intervention).
- Specific focused actions to reverse regional climate impacts such as preventing methane burps or melting Arctic ice (technologies from the "catch-all" category)

My remarks below do not discuss the technologies themselves in any depth as that has been done by others nor are they comprehensive. I will discuss some of the implications for research and experimentation. Where possible I will comment on existing US research programs and their capacity or suitability to expand into geoengineering research. As well, I will try to point to specific research topics that I have not seen in the geoengineering discourse up to now which are critical for any future geoengineering capability. I will bring out specific issues related to governance and international relations and some possible approaches for dealing with these. Discussion of governance and international relationships will focus mainly on climate intervention methods which are in general a more difficult societal and research problem. I will also some important research needed in climate science which is also critical for geoengineering.

Climate remediation technologies

Climate remediation technologies are with some exceptions relatively safe and non controversial. They address the root cause of the problem, but these methods are slow to act. It would take years if not decades to reduce the concentration of CO_2 in the atmosphere through air capture and sequestration. These technologies are expensive when compared to the option of not emitting CO_2 in the first place. It costs less to capture concentrated streams of CO_2 in flue gas or to use non-emitting sources of energy in lieu of burning fossil fuel, so many carbon removal technologies are likely to remain uneconomical until we have exhausted the opportunities for mitigation. However, research into these ideas is important because at some point we may decide that the atmospheric concentrations must be brought down below stabilized levels. If we don't want to wait many hundreds of years for this to happen through natural processes, we may have to actively remove greenhouse gases. As we begin to understand more about the costs of adapting to unavoidable climate change, remediation technologies may become a cost effective option. Developing carbon removal technology that is reliable, safe, scalable and inexpensive should be the goal of a research program.

Some of the more promising technologies in carbon removal are closely related to carbon capture and storage (CCS) technologies. CCS offers the most, if not only promise for preventing greenhouse gas emissions from fossil fuel-fired electricity generation. For CCS, we contemplate separating out CO_2 after combustion of coal and then pumping it deep underground into abandoned oil or gas fields or saline aquifers. The technologies for removing CO_2 from air (air capture) and flue gas are similar.

In general, CCS is expected to be much less expensive than air capture, but air capture does have some possible advantages over CCS. It may be possible to site air capture facilities near a stranded source of energy (remote geothermal or wind power for example, or in the middle of the ocean) and also near geologic formations that are capable of holding the separated gases. This arrangement might obviate some of the infrastructure costs associated with capturing CO_2 at a power plant and having to choose between locating the power plant near the geologic storage reservoir and transmitting the power to the load, or conversely locating the power plant near load and conveying the CO_2 to the storage facility. Further the cost of capture is likely to decline. In the long-run these considerations may become dominant.

After capturing the CO_2, it has to be put somewhere isolated from the atmosphere. Currently, we are considering geologic disposal: pumping the CO_2 deep underground. There are important policy and legal issues associated with geologic storage. The implementer must obtain rights to the underground pore space and be able to assign liability for accidents and leakage etc. These same issues exist for storage of CO_2 in a CCS project and the US CCS project currently deals with them. However, Keeling (R. Keeling, Triage in the greenhouse, Nature Geoscience, 2, 820–822, 2009) has suggested that the amount of CO_2 we may need to remove from the atmosphere is such that we will have to consider disposal in the deep ocean as a form of environmental triage. Ocean dumping would clearly involve much more serious governance issues, similar to climate intervention which are discussed below.

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.

A second governance issue has to do with intellectual property (IP). If there is no significant price for carbon, and carbon removal becomes a function of the government (like picking up the garbage) we might consider making any air capture technology we develop freely available throughout the world as it is in our interest to have anyone who is able and willing help clean up the atmosphere. If however, there is a price for carbon, then IP could help to motivate innovation to gain a competitive edge which is also in the interest of society. Unfortunately, we don't have a price for carbon now, and we are not sure whether we will, so the choice is difficult.

Beyond air capture, the Royal Society report on Geoengineering (J. Shepherd et al., Geoengineering the Climate: Science, Governance and Uncertainty, The Royal Society, London, 2009 *http://royalsociety.org/geoengineeringclimate/*) lists a number of other carbon removal technologies. Among these, augmentation of natural geologic weathering processes and biological methods would fit well within either NSF's science programs or in DOE's Office of Science program. For the near term, research will involve the kind of modeling studies and field experiments that are already a mainstay of these programs. NSF is focused on university researchers and is extremely competitive which means that high risk ideas will likely not be funded. In the DOE program, there is more focus on mission, high risk research, and national laboratory researchers. There should be room for both. The US Geological Survey will certainly have highly applicable expertise.

A climate remediation program should also provide money to investigate issues such as the possibility of putting out coal mine and peat fires that continually burn underground and emit large amounts of CO_2 and other greenhouse gasses. With the demise of the US Bureau of Mines, there is no clear place for this research, but might be best done through the Mine Safety and Health Administration (MSHA). Biological methods of remediation might include genetically modified organisms (GMO) that would raise governance issues. Early stage research would likely be covered under existing review and governance mechanisms in place by NIH or NSF for other GMO research. Any large scale experimentation would also raise governance issues similar to those associated with climate interventions which are discussed below. Similarly, ocean iron fertilization methods have governance issues similar to climate intervention methods and may also be governed by existing treaties such as the London Convention or the Law of the Sea.

Climate intervention

Climate model simulations have shown that it is possible to change the global heat balance and reduce temperatures on a global basis very quickly with aerosol injection in the stratosphere for example. We also have experience with natural analogues in the form of volcanic eruptions which emit massive amounts of sulfates that cause colder temperatures for months afterwards. So we have a pretty good idea that some methods could be effective at reducing global temperatures.

Climate intervention techniques include a variety of controversial methods aimed at changing the heat balance of the atmosphere by either reducing the amount of radiation reaching the Earth or reflecting more into outer space. The common features of these technologies are that they are inexpensive (especially compared to mitigation), they are fast acting, and they are risky. Some could lower temperatures within months of implementation, but they do not "solve" the problem in that they do nothing to reduce the excess greenhouse gases in the atmosphere. So, if we reflect more sunlight and don't reduce CO_2 in the atmosphere, the oceans will continue to acidify, severely stressing the ocean ecosystems that support life on Earth. And if we keep adding CO_2 the atmosphere we will eventually overwhelm our capacity to do anything about it with geoengineering intervention. So, climate intervention cannot be a stand-alone solution. It is at best only a part of an overall strategy to reduce atmospheric concentrations of greenhouse gases and adapt to the unavoidable climate change coming down the pike. Climate interventions are unlikely to be deployed until or unless we become convinced that the risks of climate change plus climate intervention are less than the risks of climate change alone.

There are ideas for putting reflectors in space and increasing the reflectance of the oceans, land or atmosphere (see the Royal Society Report on Geoengineering). Some propose global interventions such as injection of aerosols (sulfate particles or engineered particles) in the stratosphere and the Novim report spells out the required technical research in some detail (J.J. Blackstock et al., Climate Engineering Responses to Climate Emergencies, Novim, Santa Barbara, CA 2009 *http://arxiv.org/pdf/0907.5140*). Others propose more regional or local interventions, such as injecting aerosols in the Arctic atmosphere only in the summer to prevent the ice from melting (On the possible use of geoengineering to moderate specific climate change impacts, M. MacCracken, Env. Res. Letters, 4/2009, 045107). Even more local and perhaps the most benign is the idea of painting rooftops and roadways white to reflect heat.

The more global and effective these methods, the more they harbor the possibility of unintended negative consequences which may be unequally distributed over the planet and extremely difficult to predict. We can expect few if any unintended consequences from painting roofs white, the benefit will be real and a cost-effective part of our arsenal. However, this action alone is not enough of an intervention to hold back runaway climate change. On the other hand, we could reverse several degrees of temperature rise by injecting relatively small amounts of aerosols in the stratosphere (because a few pounds of aerosols will offset the warming of a few tons of CO_2), but it may be difficult to predict exactly how the weather patterns will change as a result. Although the net outcome may be positive, certain regions may experience deleterious conditions. It will be very difficult to determine whether these deleterious conditions arise simply from climate variability or are due to the intentional intervention. In general, methods with high potential benefits also have higher risks of unintended negative consequences.

Climate intervention might be part of an overall climate strategy in ways and with difficulties that we have only begun to contemplate. Climate model simulations have shown that if we were to suddenly stop a global intervention, then the global mean temperature will quickly return to the trajectory it was following before the intervention. This means that temperatures could increase very rapidly upon cessation of the intervention which would likely to be devastating. Climate intervention may only provide temporary respite, and ironically would be difficult to stop. However, we already emit millions of tons of aerosols now in the form of air pollution which is masking an unknown amount of global warming, perhaps as much as 5 or 10 degrees C. So, as we clean up this air pollution to protect human health or stop emitting air pollution as we shut down coal-fired electricity generation in mitigation efforts, we will also cause a significant increase in short-term warming. (Long term warming remains largely a function of the concentration of CO_2.) We may want to offset this additional warming by injecting some aerosols in the stratosphere where they are even more effective at reflecting radiation. This plan might cause much less acid rain and improve human health impacts compared to the power plant and automobile emissions while continuing to mask undesirable warming. It is possible that the "drug" of aerosol injection could be a type of "methadone" as we withdraw from fossil fuels.

Beyond technical problems, international strife is possible. State or non-state actors may think it is in their interest to deploy geoengineering without international consensus. Could a country suffering from climate change see a benefit to the technology and not have sufficient concern with disrupting the rainfall in other countries? Any indication that a nation is doing research solely to protect their national interests will be met with appropriate suspicion and hostility. On the other hand, the possibility of reaching of global consensus to deploy these technologies seems utterly impossible. Who gets to determine what intervention we deploy or even what the goal of the intervention should be?

Climate intervention techniques offer tremendous potential benefits to life on Earth, at the same time they are hugely vulnerable to mismanagement and may have severe and unacceptable unintended consequences and risks. For all these reasons, practically no one thinks we should deploy these technologies now if ever and, we should remain skeptical and appropriately fearful of deploying these technologies at any point in time. But many, including me, think we should gain knowledge about them in a research program simply to inform better decisions later and to be sure we have explored all options in light of the enormity of the threat. It would be especially better to know more about what could go wrong and what not to do.

In light of these concerns, how should a research program proceed?

The nature of research into climate intervention may call for a focus on public management rather than private sector motivation. There is much at stake—literally the future of the planet. There are distinct problems with letting companies with vested financial interests in intervention technology have a say in the intervention choices we make. For example, when California decided it no longer had to dig up old leaking gas tanks because the bacteria in the soil were able to remediate the contamination if just left alone (intrinsic remediation), the industry that served to dig up leaking gas tanks fought the ruling. Not digging up the tanks was in the interest of society, but the industry was concerned with its financial future. We do not want to place the deliberations about how to modify the climate in a profit making discourse. The role of the private sector and public-private partnerships should be carefully constructed to avoid these problems.

The United States Government should make it absolutely clear we are not planning for deployment of climate intervention technology. Many serious people worry that geoengineering will form a distraction from mitigation. Many are worried because they do not see the societal capacity to make mitigation decisions commensurate with the scale of the climate problem. Others find the very thought of geoengineering abhorrent and unacceptable. However, many people who are against deployment are
in favor of research. By making it clear we are not planning to deploy we can take some of the political pressure off the research program and allow more room for honest evaluation.

A very good example of how this might work can be found in the Swedish nuclear waste program. In 1980, Sweden voted to end nuclear power generation in their country in the early part of the 21St century. Then, they began a program to build a repository to dispose of nuclear waste. Opposition to the nuclear waste program was not saddled by the question of the future of nuclear power. The program proceeded in an orderly manner and with extensive public interaction and consultation focused narrowly on solving the nuclear waste problem. They jointly developed a clear a priori statement of the requirements for an appropriate site before the site was chosen. Today, Sweden has chosen a repository site which is supported by the local population and is scientifically the best possible site in Sweden. (In contrast, the goal of the American policy was to show that we could store waste in order to have nuclear power, the repository site was chosen by Congress without public consultation. Astonishingly, the site criteria were established after the site was chosen. In the end we do not have a successful nuclear waste storage program. See J. C.S. Long and R. Ewing, Yucca Mountain: Earth-Science Issues at a Geologic Repository for High-Level Nuclear Waste, Annual Review of Earth and Planetary Sciences, Vol. 32: 363–401 May 2004) Likewise for geoengineering, a perception that the purpose of the research program is to plan deployment would saddle the research program with needless controversy. We should be careful to state we are not planning deployment.

Second, as in the Swedish nuclear waste program, we should embed public engagement in the research program from the very beginning. I will discuss science and public engagement from three perspectives: national governance, international interactions, and the requirement for adaptive management.

National research governance:

In constructing a national research program, we have to be concerned with these questions:

1. What constitutes appropriate levels of governance for specific types of research?
2. What are the guiding principles and values that will be used to sanction research?

3. Given these principles, what process will be used to sanction proposed research?
4. How will the governance process engage society?

Types of research

One of the truly difficult problems in climate intervention research has been pointed out by Robock et at (Science 29 Jan 2010, Vol 327, p 530). Namely, it is not possible to fully understand how a specific technology will work on a global scale, over extended periods of time without actual deployment. But we certainly would not want to deploy an intervention without understanding how it works first. We cannot plunge into deployment, so how should research proceed?

The first key point is that there are many types of research that require no new governance. For example computer modeling studies that simulate proposed interventions are clearly completely benign. On the other hand, a proposal for full- or even sub-scale deployment with non-trivial effects would clearly require a very high level of scrutiny. So, the first task is to determine the scale and intensity of experimentation below which research can proceed with impunity. What amount of perturbation, reversibility, duration, impact, etc falls squarely within the existing bounds of normal research? I will call this the "bright line," even though in practice the line is likely to be fuzzy and the characterization of this line is likely to be difficult to express quantitatively. Never-the-less, if research falls under the bright line, essentially no new governance is required.

There is no single bright line for all proposed climate intervention research; the nature of the "bright line" is technology dependent. Although the types of questions might be similar, the specific questions we would ask about aerosol injection in the stratosphere are completely different than the questions we would ask about putting small bubbles on the surface of the ocean. So, when a technology is sufficiently mature to be seriously considered for expanded research, it will become necessary to understand the bright line for that technology. The process and deliberation used by the National Academy of Sciences/ National Research Council (NAS/NRC) is ideal for determining this bright line. They assemble a panel of experts, take testimony, and opine on complex scientific and social issues. Two of the technologies currently under discussion, aerosol injection in the atmosphere and cloud brightening, have probably reached this level. An NAS/NRC panel should be convened now to determine what research projects in these two technologies can proceed with "normal" governance.

More difficult is the area of research above the bright line. The National Environmental Policy Act (NEPA) mandates federal agencies to prepare an Environmental Impact Statement (EIS) for any major federal action that significantly affects the quality of the human environment or to conduct an Environmental Assessment when the effects of the proposed action are uncertain. These and other environmental laws and regulations may directly affect above the line research. Beyond these environmental laws, governance principles and procedures are yet to be developed.

Nanotechnology has attributes in common with climate intervention research. There is great promise but risks that are hard to quantify. How will nano-particles behave in the environment? Will they disrupt natural processes in a way we cannot predict? One approach has been to fund research on the toxicology of nano-particles to find out what might wrong. At least part of a climate intervention research program should be dedicated solely to understanding the potential negative impacts and what might go wrong.

Principles

For research that rises above the bright line, there is a lot to be learned from examining other research governance principles and practices. Human subjects research is particularly apropos. The Nuremburg trials after WWII revealed horrendous medical experiments on human subjects by Nazi "doctors". America's shameful history of research on syphilis in the 1960s and 1970s which horribly mistreated the Tuskegee airman and subjected them to unimaginable suffering is another salient reminder of how dangerous experiments may be when detached from appropriate moral and ethical guidelines. These experiences led to a commission charged with providing guidance for future research governance. The Belmont report written by this commission lays out principles which must be met in order to sanction proposed research where humans are the subject of the research. (From Wikipedia *http://en.wikipedia.org/wiki/Belmont_Report*: The Belmont Report is a report created by the former United States Department of Health, Education, and Welfare (which was renamed to Health and Human Services) entitled "Ethical Principles and Guidelines for the Protection of Human Subjects of Research," authored by Dan Harms, and is an important historical document in the field of medical ethics.) The principles are quite basic and we can easily see how they might translate to principles that might apply to "Earth subject" research.

The three fundamental principles of the Belmont report are:

1. respect for persons: protecting the autonomy of all people and treating them with courtesy and respect and allowing for informed consent;
2. beneficence: maximizing benefits for the research project while minimizing risks to the research subjects; and
3. justice: ensuring reasonable, non-exploitative, and well-considered procedures are administered fairly (the fair distribution of costs and benefits to *potential* research participants.)

These principles stimulate a good discussion of possible governance principles for geoengineering. For the first principle, there are really two parts, respect and informed consent. The respect part probably translates to "Respect for all persons of the planet." Geoengineering research should not be frivolous, or dismissive of human life. As well, life other than human is also an issue, so perhaps this principle translates to "respect for life on Earth". Does the proposed research exhibit respect for life on Earth?

The informed consent principle is perhaps the most important and most vigorously evaluated principle in human subjects research review. Proposals are rejected based on obfuscation of the research methods. For example, a proposal for research on child molestation was recently rejected. The proposer told parents he would be playing a game of Simon Says with the children. What the proposer failed to tell the parents was that he would ask the children to do things like "suck my thumb". The proposal was denied based on lack of informed consent. The message here is that the researcher obscured the procedure in order to get consent from the parents. What is the moral equivalent of informed consent for geoengineering research? I think it is at least in part that the proposal methods, plans, analysis and even engineering should be open and transparent. We might ask researchers for specific actions to make their work transparent and collaborative. Say posting on a specific website, or advertisements in new media. Beyond this, it is not possible to get the informed consent of all life on Earth or even all countries. The question will be who is informed and who has to consent? How will the public and the democratic process be involved? These are matters for public deliberation.

The beneficence principle applies essentially without change. It is perhaps the most straightforwardly applicable of the three. The benefits of the research should outweigh the risk of unintentional harm to life on Earth. The research must be aimed at accomplishing a benefit and must not intentionally do harm. To demonstrate this, proposers should take actions such as modeling their results, evaluating natural analogues, assessing potential impacts, and other due-diligence measures that, in the end, must be evaluated by judgment in review. Again, the question is, who reviews? Who gets to sanction the research? We can examine the review process used for human subjects and other controversial research and learn more about what we should do for climate intervention research.

The third principle, justice, requires somewhat different articulation for geoengineering, but the basic ideas apply. The intent of this principle is to avoid experiments that take unfair advantage of a class of vulnerable people (prisoners or children for example) for the benefit of others. In the case of Earth subject research, the issue might be this: does the proposed activity sacrifice the interests of one group of people for the benefit of everyone else? I would think that at the research level, the answer to this question should be categorically "no", the research does not gain information about a proposed method at the expense of vulnerable populations. Proposers could be required to show how and why they expect their research to be fair. The problem will become more difficult as research reaches subscale or full scale deployment. If some parts of the Earth are harmed by the intervention, will there be compensation, how much and from whom? How will causation be established? Worse, is it fair to deprive some countries of the right to choose the temperature? These questions themselves must be topics for research and public deliberation.

There are of course major differences between the ethics governing medical research on human subjects and Earth subject research. One of the most interesting is that the need for research governance is diminished over time for medical research. Eventually, if the research is successful, protocols with statistical results to support them are obtained. The research results can be used to set standards of practice and the ethics become ethics of normal medical practice. The need for research review declines with time. In the case of geoengineering the research aspects are likely to continue indefinitely, and may become more acute with time. We cannot do double-blind studies. We cannot have a statistical sample of Earths. At some level, geoengineering, will always be research and always require research-ethics type governance. And the worst case from a risk perspective is actual implementation. Whereas in medical research, the need for governance subsides over time, for geoengineering, governance will get more and more pronounced over time, until or unless the idea is abandoned.

Review Process

In human subjects research, Institutional Review Boards (IRBs) are vested with the authority to review and sanction research. These boards review the research protocols and procedures to insure they meet ethical standards. If the IRB approves the research, then the institution is free to allow the research to be conducted. If the IRB disapproves, the institution may not conduct the research as proposed. The IRB cannot decide that the research will be done, only that it may be done. IF the IRB disapproves, the institution must comply with the ruling and cannot allow the research to continue.

There are perhaps three salient features of the IRBs that control the outcomes. First, they are part of the research institution. They are not an external body. However, once appointed, they are independent. Second, their rulings are not based on specific regulations. They are based on principles which are derived mainly from the Belmont report. Third, the board membership is defined by federal code: *http://www.accessdata.fda.Rov/scripts/cdrh/cfdocs/cfCFR/CFRSearch.cfm?fr=56.107*. This guidance specifies that each IRB must have at least five people, members must include those qualified to review the research and members from the community. So, it is the principles and the board appointments that insure the quality of the IRB decisions.

It is notable that IRB's from around the country meet regularly together and present prior cases without revealing their ultimate decisions until after the cases are discussed. Then the board that presented the case reveals the decision they actually made. In this way, the boards gain insight and skill at making difficult rulings. The point is, their rulings are not prescriptive, they are based on judgment and good judgment requires learning.

The IRB's have public members in order to protect public interests. Even so, dissatisfaction with this process arises from a sense that IRBs end up rubber-stamping research protocols, do not deliberate conflict of interest issues, and do not engage in any real public dialogue about values. Consequently, researchers and social scientists are experimenting with new models to engage the public in human subjects research.

Given the problems with governance of human subjects research, it would be wise to develop a program that seeks to propose and test research governance and engagement models. One of the best ways to learn about what works is to go through exercises in mock governance. For example, an institution or project could try out a governance process in a "moot court" type trial such as this:

- A draft set of guiding principles for research is given to blue and red teams. They might start with the principles outlined above for example. Both teams should include scientists, but also might include members of the public or social scientists.
- Blue teams would prepare mock (or real!) research proposals for geoengineering field tests and gives these to the red teams. For example, a team may propose an Arctic sulfate injection or mid ocean for cloud whitening trial.
- Red teams prepare critiques of the blue team proposals. The job of the red team is to try to find the weaknesses in the blue team proposal and bring these to light.
- Both teams present the research and critique respectively to a mock review board at the meeting following the draft guidelines/principles. We might choose the people for the mock board as a mix of scientific backgrounds and a strong mix of public interest members as well as ethicists or philosophers—ie far beyond the IRB membership as specified in the federal statute.
- The mock board uses the draft principles to evaluate the proposals. They could issue a mock ruling to sanction the research, turn the proposal down, or perhaps recommend additional measures for due diligence.

- Everyone discusses the process—did the principles cover the important issues? —was the process appropriate? How might the process go wrong? The goal should be to identify all salient lessons learned.
- Do this again changing the process as appropriate.

Another set of exercises are being tried in the field of nanotechnology research to incorporate the values of society. David Gustin, for example, describes experiments in "anticipatory governance" (Gustin, Innovation policy: not just a jumbo shrimp, Nature, Vol 454/21, August 2008). There are three parts to this process. The first part is designed to educate the public about the nature of the research and to bring public deliberation of values into the open. The second part is to have scientists and the public collaborate on imagining how the future might unfold given new technology and social trends. Gustin calls this "anticipatory knowledge". Discussions then give voice to public concerns about the future. Finally, the public engagement and anticipatory knowledge are integrated with the research. For example, social scientists and humanists have become "embedded" in nanotechnology research labs. They help the scientists reorient their work in more socially acceptable directions. This could also be a very good model for geoengineering. It would be possible to create a geoengineering forum where publics could be informed and express concerns. Exercises that highlight the possible futures with and without geoengineering would help all to understand how we should focus. Finally, keeping social scientists are part of any scientific research team may help with both guiding the research towards more socially acceptable directions and also help scientists with communication and outreach.

There is no absolute clear answer to the question how to govern geoengineering research. The fact is that we need research and experimentation to understand how to govern this research, ie research and experimentation on how to govern research with public engagement. It is likely that research governance models will be different for different types of technologies and there will not be a one-size-fits-all governance model. As technologies reach the stage of research that approaches the "bright line", specific governance models should be explored and evaluated.

International governance:

Geoengineering research has the potential to cause international conflict. Tensions could easily rise if countries perceive that the research is being conducted solely for national interests. If geoengineering research programs became part of defense research programs, it would certainly convey the message that the goal was to advance national interests. Consequently, research programs should explicitly only develop technology that will have international benefits. Research should not be managed by national defense programs (J. J. Blackstock and J. C. S. Long, The politics of Geoengineering, Science, Vol 327, p. 527, 29 Jane 2010.)

Secrecy also has the potential to create tension and conflict. It is important that geoengineering research be conducted in the open with results published in the open literature. Especially in the early stages, a pattern of trust and consultation will be critical to a future that might well require agreement and collaboration. Inclusion of international scientists in a national research program or the

establishment of international research programs would have tremendous benefits in both expanding the knowledge base and as an investment in future collaboration.

In starting down a research path, we must remember that critical decisions about deployment may be needed someday and that these decisions should not be made unilaterally. We should be extremely careful not to increase tensions or misperceptions that would make these decisions even harder. On the other hand, there is less and less confidence that all affected nations would ever be able to come to an agreement and sign a treaty to support a single set of actions. Such a treaty may still be our goal, but there are other strategies that can help us to make good choices together. I am fond of a quotation from the famous French sociologist, Emil Durkheim in which he noted: "Where mores are strong, laws are unnecessary. Where mores are weak, laws are unenforceable." In that spirit, we may hope that good cooperative relationships in geoengineering research and research governance may help to develop common norms of behavior and it may be these norms that provide the capacity to make good collaborative decisions in the future.

Adaptive management

Climate is a complex, non-linear system with many moving parts. When we set about to intentionally intervene in climate outcomes, there will always be uncertainty about whether our chosen actions will result in the desired outcomes. An essential feature of any climate intervention will be the need to provide for adaptive management, also known as "learning by doing". If we are to use adaptive management in a climate intervention it means that we

1. Choose to make an intervention,
2. Predict the results of the intervention,
3. Monitor the results of the intervention,
4. Compare the observations to the predictions,
5. Decide if we are going in the right direction and
6. Make a new set of decisions about what to do.

(See *http://en.wikipedia.org/wiki/Adaptive_management*.). In the real world it is very hard to actually do adaptive management.

First, it is difficult enough to make a decision to act. To then change this decision becomes confusing and politically negative. Consequently, successful adaptive management establishes a structure for the adaptive modification *a priori*. So, regular intervals and formats are established for comparing observations with predictions and a formal requirement is put in place for deciding whether or not and when to change directions. When this process is specified up front, it can avoid the political fallout of changing direction. Part of a geoengineering research program should examine the potential policy and institutional frameworks for conducting adaptive management. In particular it is important to determine a priori how the technical and political parts of the process will interact. Will the deciding entity be a board made up of scientists and policy makers and perhaps members of the public and social scientists?

Or should we structure a hierarchy of decision makers where higher level boards have decisions about overall direction, but less control of specifics?

Second, you must have a very good data base of observations. If you haven't made extensive observations all along, how will you be able to detect what is changing? This is not just a problem for geoengineering, but for all of our climate strategies. The observation network we have for climate related data is far too sparse and in some cases, inadequately calibrated. We need a major commitment for all our climate research to collecting and calibrating data relevant to climate change on a continuous, ubiquitous basis and perpetual basis. This is a sine qua non recommendation for any climate solution. We cannot rewind the tape and go back to collect data that we failed to collect over time. The observation network for climate is inadequate to our needs and this is an extremely high priority for research dollars.

Third, you must be able to discern whether a change is attributable to simple climate variability or to the specific intervention. The science of detection and attribution of human effects on climate has advanced tremendously in the past decades. But the challenge of detecting and attributing changes to intentional, fairly short term interventions has not been met. This must be a focus of research. As it is strongly related to the existing climate science program, the expanded work belongs there.

In the simplest terms, the scientific approach to attribution of human induced climate change—whether through unintentional emissions or intentional climate intervention—is to use climate models to simulate climate behavior with and without the human activity in question. If the results of the simulations including the activity clearly match observations better than the results without the activity, then scientists say they have "fingerprinted" the activity as causing a change in the climate. Perhaps the most famous illustration in the International Panel on Climate Change (IPCC) reports shows two sets of multiple model simulations of mean global temperature over the twentieth century, one with and the other without emitted greenhouse gases. On top of this plot, the actual temperature record lines up squarely in the middle of the model results that included greenhouse gas emissions. This plot is a "fingerprint" for human induced warming. Scientists have gone far beyond mean global temperature as a metric for climate change. Temperature profiles in the atmosphere and ocean, the patterns of temperature around the globe and even recently the time of peak stream flow have been used to fingerprint human induced warming.

Structured climate model intercomparison projects are fundamental to drawing fingerprinting inferences. No single model of the climate gets it all right. Each climate model incorporates slightly different approaches to approximating the complex physics and chemistry that control climate outcomes. So, we use multiple models all running the same problems. We can then examine a statistical sample of results and compare this to data. In a form of "wisdom of the crowd", the mean of all the model results has proven to be a better overall predictor of climate than any single model.

The science of fingerprinting is becoming more and more sophisticated. Increasingly, scientists are looking at patterns of observations rather than a single number like mean temperature. Patternmatching is a much more robust indicator of causality because it is much harder to explain alternative causality for a geographic or time-series pattern than for a single value of a single parameter. A famous example of this was discerning between global warming caused by emissions versus caused by a change in solar radiation. Solar radiation changes could not account for the observed pattern of cooling of the stratosphere occurring simultaneously with a warming of the troposphere, but this is exactly what models predicted for emission forced climate change. There exist "killer metrics" like this that tightly constrain the possible causes of climate observations.

We are making progress on the "holy grail" of using present observations to predict future climate states. Recently, Santer et al showed that it possible to rank individual models with respect to their particular skill at predicting different aspects of future climate. Interestingly, the models fall into groups. The top ten models that get the mean behavior right are different than the top ten models that get the variability right. (Santer et al., PNAS 2009, Incorporating model quality information in climate change detection and attribution studies, *http://www.pnas.org/content/106/35/14778.full?sid=e20c4c31-5ab1-4f69-b541-5158e62e4baf*).

Some think that the ability to detect and attribute intentional climate intervention will be nearly impossible. The fingerprinting of human induced climate change has been based on decades of data under extremely large human induced perturbations. For climate intervention, we contemplate much smaller perturbations and would like proof positive of their consequences in a matter of years. Even though this is clearly a big challenge, it is not hopeless. Neither should we expect a panacea. We will be able to identify specific observations that certain models are better at predicting and we will be able to find some "killer metrics" that constrain the possible causes of the observations. In some respects, conclusive results will not be possible and we will have to learn how to deal with this. Fingerprinting—detection and attribution of human intervention effects on climate—must be an important area for research if we are to be able to conduct adaptive and successful management of geoengineering. As this topic is closely interconnected to basic climate science, the program to extend research into intentional intervention should belong in the US Climate Science Program.

A geoengineering research program should include the development of technology and capacity for adaptive management.

The "Catch-All" Category

Recent studies have shown vast amounts of methane, a powerful greenhouse gas, are leaking from the Arctic Ocean floor. Billions of tons of methane are stored in permafrost and will be released as the frozen lands thaw. Methane is a green house gas that is approximately 25 times more powerful than CO_2. Abrupt increases in methane emissions have been implicated in mass extinctions observed in the geologic record and could trigger runaway climate change again. (It is the possibility of such runaway climate change that most clearly supports the need for geoengineering research.) James Cascio recently posed an idea for deploying genetically engineered methanotrophic bacteria (bacteria that eat methane) at the East Siberian Ice Shelf (*http://ieet.org/index.php/IEET/more/3793/*). Is this possible? Could bacteria survive in the Arctic? Could they eat the methane fast enough to make a difference?

What are the risks? Could release of genetically modified methanotropic organisms cause problems to the Arctic ecosystems? Is the idea worth pursuing? This may be an idea with merit -or it may be a very stupid idea.

Somewhere in the geoengineering research program there should be funding to freely explore theoretical ideas and perform the modeling and laboratory studies to determine which concepts are worthy of more work, and which are completely impractical or too dangerous. This should be a "gated" research program wherein small amounts of funding are provided to explore many out-of-the-box ideas with thought experiments, modeling and laboratory experiments as appropriate. At this stage, none of the research ideas should require more than traditional governance mechanisms provided by existing research programs. At the end of this initial funding, the concepts would have to be reviewed and if they are deemed to have promise, then they would become eligible for more funding. If the ideas are found to be lacking in merit, then they would be shelved. Several stages or gates should be set up with increasingly higher bars so that a large number of ideas can be generated at the first gate, but these are increasingly winnowed down as we learn more about their practicality, dangers and effectiveness.

Beyond this "bottom-up" approach, there should be a "top-down" research program that examines potential emergencies that could result from climate change and then attempts to design interventions for these specific situations. The primary climate interventions currently under discussion attempt to reduce temperature. Although higher temperatures that result from climate change will be a severe problem, I would argue that other impacts of climate change might be more critical. For example, one of the major impacts of climate change will be increased water stress—we will need more water because it is hotter and there will be less water because there will be more droughts. Water shortage will lead to problems with food security. A choice to control temperatures with aerosol injection for example might result in reduced precipitation. Volcanic eruptions such as Pinatubo provide a natural analogue for such aerosol interventions. Gillett et al. were able to show that a result of these eruptions caused a reduction in precipitation (Gillett, N.P., A.J. Weaver, F.W. Zwiers, and M.F. Wehner, 2004: *Detection of volcanic influence on global precipitation*, Geophysical Research Letters, 31, doi: 10.1029/2004GL020044.). So, we might reduce temperatures with aerosols, but make hydrological conditions worse. Reducing precipitation would clearly be a bad thing to do. By looking only at what we know how to do (reduce temperatures) vs what problem we want to solve (increase water supply), we could be making conditions worse. Geoengineering research should not only be structured around "hammers" we know about. We should also collect the most important "nails" and see if we can design the right hammer.

Thus, we might try to develop methods that directly attack specific climate impacts. Can we conceive of a way to control the onset, intensity or duration of monsoons to ensure successful crops in India? Can we conceive of a way to stop methane burps, or hold back melting glaciers? Some part of a geoengineering research program should take stock of the possible climate emergencies and then look for ideas that would ameliorate these problems.

Conclusions

The above comments describe a number of measures we might take in establishing a geoengineering research program. If we are to have a successful research program we must be careful about public engagement, principled actions, transparency, international interaction and adaptive management. We will have to build the capacity to develop rational options coupled to the capacity to make rational decisions about deploying them. If we succeed, it may be that these capacities spill over into other difficult climate problems. We may ask in the end: Are we building the capacity to do geoengineering or using geoengineering research to build capacity for any climate solution? If we are lucky, the answer will be the latter.

BIOGRAPHY FOR JANE LONG

Dr. Long is currently the Principal Associate Director at Large for Lawrence Livermore National Laboratory working on energy and climate. She is also a Fellow in the LLNL Center for Global Strategic Research. Her current interests are in managing climate change including reinvention of the energy system, adaptation and geoengineering. From 2004 to 2007, as Associate Director, she led the Energy and Environment Directorate for the Lawrence Livermore National Laboratory. The Energy and Environment Directorate included programs in Earth System Science and Engineering, Nuclear System Science and Engineering, National Atmospheric Release Advisory Center, and the Center for Accelerator Mass Spectrometry. In addition, the directorate included 12 disciplinary groups ranging from Earth sciences, to energy efficiency to risk science. From 1997 to 2003 Dr. Long was the Dean of the Mackay School of Mines. The Mackay School of Mines had departments of Geological Sciences, Mining Engineering and Chemical Engineering and Materials Science and Engineering as well as the Nevada Seismological Laboratory, the Nevada Bureau of Mines and Geology and the Keck Museum. Dr. Long led the University of Nevada, Reno's initiative for renewable energy projects and served as the Director of the Great Basin Center for Geothermal Energy and initiated the Mining Life-Cycle Center. Prior to this appointment, Dr. Long worked at Lawrence Berkeley National Laboratory for 20 years. She served as Department Chair for the Energy Resources Technology Department including geothermal and fossil fuel research, and the Environmental Research Department. She holds a bachelor's degree in engineering from Brown University and Masters and Ph.D. from U. C. Berkeley.

Dr. Long has conducted research in nuclear waste storage, geothermal reservoirs, petroleum reservoirs and contaminant transport. For the National Academy of Sciences, Dr. Long was chairman of the US National Committee for Rock Mechanics, the Committee for Fracture Characterization and Fluid Flow and a committee to recommend a research program for the Environmental Management Science Program for DOE. She served on the NAS/NRC Board on Radioactive Waste Management, as well as several study committees under the aegis of this board, and had been a member of the Board on Energy and Environmental Systems. In 2001, she was appointed as a member, subsequently chair of the State of Nevada Renewable Energy Task Force. She is an Associate of the National Academies of Science, member of the Stanford University College of Earth Sciences Advisory Board, the Energy and Environment and National Security Visiting Committee for Brookhaven National Laboratory, the Intercampus Advisory Board for the UC Energy Institute, the chairman for the mitigation advisory committee of the NAS Koshland Science Museum's Climate Change exhibition, and member of the Governor's Task Force on California's Adaptation to Climate Change sponsored by the Pacific Council. Dr. Long currently co-chairs the "California's Energy Future" study being conducted by the California Council on Science and Technology (CCST) and was recently elected as a Senior Fellow of CCST. She is a member of the National Commission on Energy Policy's Task force on Geoengineering. She has been a member of the UC Berkeley Department of Nuclear Engineering Advisory Board, the Colorado School of Mines Department of Geophysics Advisory Board, and the American Geological Institute Foundation Board.

Chairman GORDON. Thank you, Dr. Long, and Dr. Barrett is recognized.

STATEMENTS OF DR. SCOTT BARRETT, LENFEST PROFESSOR OF NATURAL RESOURCE ECONOMICS, SCHOOL OF INTERNATIONAL AND PUBLIC AFFAIRS AND THE EARTH INSTITUTE AT COLUMBIA UNIVERSITY

Dr. BARRETT. Thank you very much, Chairman Gordon, and thank you other Members for this opportunity.

Climate change is a real risk, and we have to do five things to limit that risk. First, we need to reduce global emissions of greenhouse gases. Second, we need to invest in research and development to develop new technologies to allow us to reduce emissions at lower cost in the future. Third, we need to prepare to adapt, and to assist more vulnerable countries to adapt. Fourth, we need to develop technologies that can remove carbon dioxide directly from the atmosphere.

And finally, we need to contemplate the possibility of using geoengineering, which I will define as being a technology that can address global warming without affecting the concentration of greenhouse gases in the atmosphere. Solar radiation management [SRM] might be a shorthand for what I just said.

I think it is helpful to look at this problem from two different perspectives. One is from that of the perspective of the world as a whole, and the other is the perspective of individual countries.

Let us start with the perspective of the world as a whole. I think there are four different options for thinking about deployment of geoengineering. The first one would be we just ban it, and there are a lot of people, I think, their first instincts would be that we should ban it. But then, you have to imagine going forward.

Suppose we are in the situation where we start to see the worst fears of abrupt, catastrophic climate change appearing. At that point, the only thing we could do that would have any impact, would have an immediate impact, would be to use geoengineering. So, I believe that a ban on geoengineering, although I understand the instinct, I believe it would not be a credible policy, or even a responsible policy.

The second thing we could do would be to rely entirely on geoengineering, a quick fix and an easy way of dealing with this problem. That would also be irresponsible, because this is a risk problem, and that would be putting all our eggs in one basket. Also, of course, the geoengineering that we are discussing won't address other problems, such as ocean acidification.

The third thing we might do is start using geoengineering, actually fairly soon, in conjunction with, say, emission reductions or other policies. And the fourth thing that we might do would be to develop the technology, and to keep it in reserve, should the moment arise in the future where we do face this scenario of abrupt and catastrophic climate change.

I have looked at all four options, and I think a case can be made for the last two. I think a case may not be made for the first two.

So, let us look at this issue now from the perspective of individual countries, and I think two scenarios are relevant. One is the scenario of gradual climate change. This is kind of the slow unfolding of climate change over time. And what we know about this scenario is that it produces winners and losers.

Now, the losers—and I have done some back of the envelope calculations—the losers may find it in their interests to want to use geoengineering to offset the effects of what I will call global warming. The problem is that if that kind of climate change creates winners and losers, the use of geoengineering will also create winners and losers. So, this is a situation in which there will be, I would say international tensions and possibly conflict.

I actually think, though, that when you have a situation like this, there are incentives there for the conflict to be resolved, and I am going to come back to that a little bit later. I don't worry about geoengineering wars.

The second scenario that I think is relevant would be abrupt and catastrophic climate change. In that scenario, opinion around the world is going to be very uniform, and a lot of countries are going to want to contemplate the use of this technology. So, I think in that scenario, clearly, you don't have a problem of international conflict.

In both cases, though, I think we need to contemplate the development now of rules, because rules will reduce uncertainty, and uncertainty is something we want to manage these risks. And in particular, I think we need rules for the possible use of geoengineering, as well as for research and development into geoengineering.

And the essential thing to understand about this is that we also need rules, we need international arrangements to reduce emissions, but the incentives for countries to reduce emissions individually are relatively modest, even though collectively, we would be much better off if all countries took action. So, we have a colossal free-riding problem.

But geoengineering is exactly the opposite. It would be something a country could do its own, and the costs, as we understand them today, are sufficiently low that it may be in one country's interest, or a small coalition of countries' interests, to actually use it.

So, for the one issue, reducing emissions, you want to encourage countries to act. On geoengineering, you want to do the opposite. You want to restrain countries from acting, when that action would be opposed and may possibly harm other countries.

Now, what kind of rules would we need to address geoengineering? I can think of seven that would be relevant right now. The first is that we need to understand that geoengineering is only one of, as I said, five things we need to do to reduce the risks associated with climate change, and I think that geoengineering should be embodied within an agreement like the Framework Convention on Climate Change, so we can balance all those risks.

Second, we should make that agreement open for all countries to participate, since all countries would be affected. Third, the focus of the agreement should be on what countries can agree on, and not what they cannot agree on. Fourth, there should be a requirement that states must declare, announce that they will use geoengineering. There should be prior information about that. Fifth, there should be an obligation for countries to cooperate, to resolve any conflicts. And finally, we should be seeking a seeking a consensus. And then, finally, on research and development, we should have transparency, and I would also encourage international cooperation.

I think the final point to make is that we need not only to understand the technology, but also, to build trust. Thank you.

[The prepared statement of Dr. Barrett follows:]

PREPARED STATEMENT OF SCOTT BARRETT

There are two ways to look at the policy challenges posed by the threat of global climate change. The first is "top down," from the perspective of the world as a whole. Looked at in this way, the fundamental challenge is to reduce risk. The second is "bottom up," from the perspective of each of nearly 200 countries. Looked at in this way, the fundamental challenge is to realign incentives. Ultimately, the aim of policy should be to realign incentives so that states will make choices, either on their own or in concert with others, that serve the same purpose as the first perspective—choices that reduce global risks.

Reducing global risks requires that we do five things. First, we need to reduce global emissions of greenhouse gases. Second, we need to invest in research and development and demonstration of new technologies so that we can reduce global emissions substantially, and at lower cost, in the future. Third, we need to adapt, and help vulnerable countries to adapt. Fourth, we need to invest in technologies that can directly remove greenhouse gases from the atmosphere. Finally, we need to consider the possible role that geoengineering can play in reducing global risks.

The important point is that geoengineering's role should be looked at in the context of all the other things we need to do, just as these other things should now be looked at in the context of us possibly choosing to use geoengineering.

Defining geoengineering

The term "geoengineering" lacks a common definition. I take it to mean *actions taken deliberately to alter the temperature without changing the atmospheric concentration of greenhouse gases*. More formally, the temperature is determined by the amount of incoming shortwave radiation and outgoing longwave radiation. Actions to limit concentrations of greenhouse gases seek to increase the amount of longwave radiation emitted by the Earth. Geoengineering options, as defined here, limit the amount of shortwave radiation absorbed by the Earth.

Some people define the term more broadly, to include interventions that remove greenhouse gases directly from the atmosphere. This approach to reducing risks is very important. It was the fourth of the five things I said we need to do to reduce risks. But it is very different from technologies that reduce incoming shortwave radiation, which is why I think it is better to distinguish between these approaches. Industrial air capture, assuming that it can be scaled to nearly any level, would be a true backstop technology. It is a nearly perfect substitute for reducing emissions. Changes in shortwave radiation—as defined here, "geoengineering" techniques—are an imperfect substitute for efforts to reduce emissions.

There are four basic ways to change incoming shortwave radiation—by increasing the amount of solar radiation reflected from space, from the stratosphere, from low-level clouds that blanket the skies over parts of the ocean, and from the Earth's surface. There are significant differences as between these approaches. There are interesting questions as to whether one approach may be better than the others, whether combinations of approaches may be better still, and whether new approaches, as yet unimagined, may be even better. In my testimony, I shall ignore all these distinctions and consider "geoengineering" as a generic intervention.

Geoengineering and related risks

From the perspective of risk, reducing emissions is a conservative policy. It means not putting something into the atmosphere that is not currently in the atmosphere. Energy conservation is an especially conservative policy for reducing climate change risks.

Adaptation lowers the damages from climate change. It would therefore reduce the benefit of cutting emissions. In other words, adaptation is a substitute for reducing emissions. It is often asserted that these approaches are complementary. What people mean by this, however, is that we will need to do both of these things. This is true; we should reduce emissions now and we will need to adapt in the future and make investments today that will help us to adapt in the future. But it is also true that the more we reduce emissions now, the less we will need to adapt in the future; and the more able we are to adapt to climate change in the future, the less we need to reduce emissions now.

R&D and demonstration is a complement to emission reductions. As we invest more in these activities, the costs of reducing emissions will fall. As we do more R&D, we will therefore want to reduce emissions by more; and the more we want to reduce emissions, the more we will want to spend on R&D.

Air capture is a substitute for reducing emissions, but it could be a more flexible option. Emission reductions, by definition, cannot exceed the "business as usual" level. Air capture, by contrast, can potentially remove more greenhouse gases from the atmosphere than we add to it. Only air capture can produce "negative" emissions.

Geoengineering is also a substitute for reducing emissions. It would be used to reduce climate change damages. One reason often mentioned for not considering geoengineering is the fear that, if it were believed that geoengineering would work, less effort would be devoted to reducing emissions. But if we knew that geoengineering would work, and if the costs of geoengineering were low relative to the cost of reducing emissions, then it would make sense to reduce emissions by less.

As noted before, however, geoengineering is an imperfect substitute for reducing emissions. For example, geoengineering would not address the problem of ocean acidification. Also, we don't know if geoengineering will work, or how effective it will be, or what its full side effects will be. We may contemplate using geoengineering to reduce climate change risks, but using geoengineering would introduce new risks. It would mean trying to reduce the risks of one planetary experiment (adding greenhouse gases to the atmosphere) by carrying out another planetary experiment (reducing shortwave radiation). As compared with reducing emissions by promoting energy conservation, geoengineering is a radical approach to reducing climate change risks.

We need to be careful how we think about this. We can reduce emissions somewhat by means of energy conservation, even using existing technologies. To reduce emissions dramatically, however, will require other approaches. It is difficult to see how emissions could be reduced dramatically without expanding the use of nuclear power. This may mean spread of this technology to countries—many of them non-democratic—that currently lack any experience in using it, increasing the risk of proliferation. It would certainly mean the need to dispose of more nuclear waste. Abatement of emissions can thus also involve risks.

I mentioned before that "air capture" is a near perfect substitute for reducing emissions. But if the carbon dioxide removed from the atmosphere were stored in geologic deposits, it might leak out or affect water supplies. If it were put into the deep ocean, it may harm ecosystems the importance of which we barely understand. It would also, after a very long time, be returned to the atmosphere. This technology also involves risks.

The main point I am trying to make here is that we face risk-risk tradeoffs. Geoengineering would introduce new risks even as it reduced others. But the same is true, more or less, of other approaches to reducing climate change risk. Adaptation maybe an exception (we don't yet know this; there may be some kinds of adaptation that introduce new risks), but adaptation, like geoengineering, is an imperfect substitute for reducing emissions.

I can imagine some people thinking that we can address the challenge entirely through energy conservation and by substituting renewable energy for fossil fuels. Some people might think that we can do this while also closing down all our existing nuclear power plants. It might even be believed that we could do this without having to remove carbon dioxide from the atmosphere and storing it underground. All these choices are certainly feasible. But they will also be costly. The question is whether people are willing to bear this cost in order to reduce the associated risks.

Even if we make all these choices, risks will remain. The threat of climate change has now advanced to the stage where every choice we make requires risk-risk tradeoffs. Many people believe that it is imperative that we limit mean global temperature change to 2 degrees Celsius. Indeed, some people believe that we ought to limit temperature change to no more than 1.5 degrees Celsius. Due to "climate sensitivity" and long delays in thermal responses, however, there is a chance we may overshoot these targets, even if we reduced global emissions to zero immediately. People who believe we must stay within these temperature limits should be especially open to the idea of using geoengineering. Alternatively, if they perceive that geoengineering is the greater threat, then they should reconsider the imperative of staying within these temperature change bounds.

Policy options for deployment

There are four main options.

First, we could ban geoengineering. One reason for doing so would be that use of geoengineering poses unacceptable risks. Another reason would be that, if use of geoengineering were banned, efforts to reduce emissions would be shored up.

One problem with this proposal is that, as already mentioned, our other options also pose risks. We need to be rational and consistent in how these risks are balanced.

Another problem is that a ban lacks credibility. Suppose that our worst fears about the future start to come true, and we are confronting a situation of "runaway climate change." At that point, adaptation would help very little. Air capture would reduce concentrations only over a period of decades, and because of thermal lags it would take decades more before these reductions translated into significant temperature change. Meanwhile, the climate changes set in motion could, and probably would, be irreversible. The only intervention that could prevent "catastrophe" would be geoengineering. If we had banned its use before this time, we would want to change our minds. We *would* change our minds.

In a referendum thirty years ago, voters in Sweden supported a phase-out of nuclear power. Today, the government says that new reactors are needed to address the threat of climate change. Polls indicate that the public supports this change. Bans can be, and often are, reversed.

Second, we could make geoengineering the cornerstone of our climate policy, and not bother to reduce emissions or do the other things I said we needed to do. One reason would be that this would spare us from having to incur costs in the short term. Another is that we wouldn't need to take action until uncertainties about climate change were revealed. Geoengineering would be a "quick fix."

A problem with this proposal is that we may find that geoengineering does not work as expected. It may not reduce temperature by much, or it may change the spatial distribution of climate. It may, and probably would, have unexpected side effects. We know it would not address ocean acidification. But it might also fail to address the "catastrophe" we face at that particular time, even if worked precisely as expected. For example, this catastrophe may be due to ocean warming, which geoengineering could alter only over a long period of time. Putting all our eggs, as it were, in the geoengineering basket would be reckless.

Third, we could use geoengineering soon and in combination with emission reductions, as suggested by Wigley (2006). By using geoengineering soon, we could prevent global mean temperature from increasing, or from increasing by much. By reducing emissions we could avoid serious climate change in the future. We could limit ocean acidification. We could also avoid the need to use geoengineering in the future. As noted before, it is extremely unlikely that we could limit global mean temperature change to 1.5 degrees Celsius by reducing emissions only. The goal is likely to be achievable only if we used air capture or geoengineering or a combination of the two approaches in addition to reducing emissions. By extension, the same may also be true for meeting the more modest but still very ambitious goal of limiting mean global temperature change to 2 degrees Celsius.

Finally, we might hold geoengineering in reserve, and use it only if and when signs of "abrupt and catastrophic" climate change first emerged. The advantage in this proposal is that we would avoid the risks associated with geoengineering until the risks of climate change were revealed to be substantial. The disadvantage is that, when we finally used geoengineering, we might discover that it does not work as expected, or that it cannot prevent the changes taking place at that time.

Overall, the third and fourth options have merit. I cannot see the case for the first and second options.

Implications for R&D

Having now contemplated when we might one day use geoengineering, let me now turn to the question of near-term decisions to carry out R&D.

A ban on R&D would expose the world to serious risks. Suppose we face a situation of "abrupt and catastrophic" climate change, and decide that we must use geoengineering, but that, because of the ban put in place previously, we had not done any R&D before this time. Then we would deploy the technology without knowing whether it would work, or how it would work, or how we could make it work better and with fewer side effects.

R&D can involve computer simulations, examination of the data provided by "natural, large-scale experiments" like volcanic eruptions, and "small-scale" experiments. Ultimately, however, large-scale experiments, undertaken over a sustained period of time, would be required to learn more about this technology. If

such an experiment were done for the purpose of learning how geoengineering might be deployed to avoid a future risk of "abrupt and catastrophic" climate change, it would resemble using geoengineering along with emission reductions to prevent significant climate change. This makes the distinction between R&D and deployment somewhat blurred. It also blurs the distinction between the third and fourth options discussed above.

It might be argued that carrying out R&D would hasten the use of the technology. That depends on what we discover. We might discover that it doesn't work, or that it has worrying side effects of which we were previously unaware (in addition to the worrying side effects of which we were previously aware). This would make us less inclined ever to use geoengineering. Alternatively, we might discover that we can make it work better, and reduce its side effects. This would make us more inclined to use it—but this knowledge *should* make us more inclined to use it.

It is very hard to understand how knowing less about this option could possibly make us better off.

The geopolitics of geoengineering

Thus far I have considered geoengineering's role in a climate policy oriented towards reducing global risks. As mentioned in my introduction, this is one of two important perspectives. The second is the perspective of the nation state.

It is important that we consider the perspective of different states and not only our own. Many countries are capable of deploying geoengineering. Over time, more and more countries will be capable of deploying geoengineering.

Risks and incentives

Let us now reconsider all the things that can and should be done to reduce the risks associated with climate change, but do so from the perspective of individual countries.

Emission reductions are a global public good. Emissions mix in the atmosphere. The benefits of reducing emissions are thus diffused. A country that reduces its own emissions receives just a fraction of the global benefit, while paying the full cost. There is thus a temptation for countries to "free ride." In the case of climate change this tendency is particularly powerful because the costs of abating one more ton increase as the level of emission reductions increases. Put differently, starting from a situation in which every state is cutting its emissions, each state has a strong incentive to save costs by abating less.

Countries are also interconnected through trade. As one country or small group of countries cuts its emissions, "comparative advantage" in greenhouse-intensive goods will shift to other countries, causing the emissions of these countries to increase. In addition, as some countries reduce their emissions by reducing their use of fossil fuels, the price of these fuels traded internationally will fall, causing other countries to increase their consumption and, hence, their emissions.

Overall, the incentive for countries to cut back their emissions is weak (Barrett 2005). This explains why international agreements to limit emissions worldwide are needed. This also explains why our efforts to develop effective agreements have failed. It is really because of this failure that we need to consider geoengineering.

We also need to undertake R&D into new technologies that can help us to reduce emissions at lower costs. However, the returns to this investment in R&D depend on the prospects of the knowledge generated being embodied in new technologies that are used worldwide to reduce emissions. In other words, the incentives to undertake R&D are derived from the incentives to reduce emissions. Because the latter incentives are weak, the former incentives are weak, which explains why the world has done remarkably little to develop the new technologies needed to address the threat of climate change fundamentally.

Adaptation is very different. The benefits of adaptation are almost entirely local. The incentives for countries to adapt are very powerful.

The problem here is that some countries are incapable of adapting. Much adaptation will be done via the market mechanism. The rest of it will mainly involve local public goods (dikes being an obvious example). The countries that have failed to develop are the countries that will fail to adapt.

These countries need our assistance, and we and other rich countries have pledged to offer this assistance, most recently in the Copenhagen Accord. But the incentives for the assistance to be given are rather weak. Climate change could widen existing inequalities.

The incentives to undertake air capture are mixed. On the one hand, air capture can be undertaken unilaterally. In theory, a single country could use this technology to stabilize atmospheric concentrations, even if every other country failed to lift a finger to help. Air capture is thus very unlike the challenge of getting countries to reduce their emissions. However, inexpensive options for air capture are of limited scale, while options to remove carbon dioxide from the atmosphere on a large scale are expensive (Barrett 2009). The latter options would only be used if the threat posed by climate change were considered to be very grave.

Geoengineering is like air capture. It can be undertaken as a single project. It can be done by a single country acting unilaterally, or by a few countries acting "minilaterally." It does not require the same scale of cooperation as reducing emissions. But geoengineering is very unlike air capture in other ways. It does not address the root cause of climate change. It does not address the associated problem of ocean acidification. Most importantly for purposes of this discussion, geoengineering is cheap (Barrett 2008a). The economic threshold for deploying geoengineering is a lot lower than the threshold for deploying air capture at a massive scale.

Because the cost of geoengineering is low, the incentives to deploy geoengineering unilaterally or minilaterally are strong. In this sense, geoengineering is akin to adaptation. The difference is that geoengineering undertaken by one country or by a coalition of the willing would change the climate for everyone. Depending on the circumstances, this could be a good thing (recall that the incentives for rich countries to adapt are powerful, but that their incentives to help the poor to adapt are weak) or a bad thing. It is because the incentives for individual countries to use geoengineering may be strong, and yet other countries may be adversely affected, that geoengineering poses a challenge for governance.

A scenario of "gradual" climate change

Imagine first a situation in which climate change unfolds gradually. In this scenario, there will be winners and losers over the next few decades, perhaps even for longer. (Over a long enough period of time, if climate change were not limited, all countries will lose.)

To be concrete, let us consider estimates of the effects of climate change on agriculture as developed by William Cline (2007). According to this work, India's agricultural potential could fall 30 percent for a 3° C mean global temperature increase by around 2080. Upon doing some back-of-the-envelope calculations, I have found that India might suffer a loss valued at around $70 billion in 2080. Estimates of the costs of offsetting this amount of warming by geoengineering are generally lower than this. Hence, it is at least plausible that India might be tempted to use geoengineering in the future.

To reinforce this point, note that about 70 percent of India's more than one billion people currently live in rural areas. Over time, this percentage will fall, but perhaps not by that much. Is it realistic to expect that a democracy will not act to help a substantial fraction of its people when doing so is feasible and not very costly?

Note as well that India has already sent an unmanned spacecraft to the moon. It is currently planning a manned mission to the moon. It is certainly within India's technical capability to deploy a geoengineering project.

It is also within its political capability. In early 2009, a joint German-Indian research team undertook an experiment on "ocean fertilization" in the South Atlantic, despite protests by environmentalists. India, it should also be remembered, developed nuclear weapons outside of the Nuclear Nonproliferation Treaty, and tested those weapons over the objections of other countries. External pressure for restraint may not deter India from deploying geoengineering, should India believe that its national interests are at stake.

India would also have a moral and quasi-legal case for using geoengineering. The Framework Convention on Climate Change says that "developed countries [need] to take immediate action . . . as a first step towards comprehensive response . . .." India might argue that developed countries failed to fulfill this duty. It might also claim that it lacked any alternative means of protection. India might conceivably assert a need to use geoengineering for reasons of "self-defense."

I am not saying that it is inevitable that India would want to deploy geoengineering. I am only saying that, under plausible assumptions, the possibility needs to be considered.

Of course, India may not be the first country to contemplate using geoengineering. May other scenarios can be imagined.

If "gradual" climate change produces winners and losers, then the use of geoengineering to reduce the effects of gradual climate change will also produce winners and losers. The winners would join India. They might be willing to provide financial support for India's geoengineering effort. If a "coalition of the willing" were to form, the economics of "minilateral" action would likely strengthen the likelihood of geoengineering being deployed.

The losers of any such geoengineering effort would have very different incentives. Cline (2007) finds that, due to gradual climate change, agricultural capacity in China, Russia, and the United States would likely increase 6 to 8 percent by around 2080. Under this scenario, if India, on its own or in concert with others, were to deploy geoengineering to protect their economies, other countries may suffer as a consequence.

What might these other countries do? They would certainly voice their objections. They might threaten to impose sanctions. They might attempt a countervailing geoengineering effort to warm the Earth. They might seek to "disable" India's geoengineering effort by military means. This last possibility is especially worrying, given that many of the states mentioned as being affected, whether positively or negatively, possess nuclear weapons.

But it is also for this reason that a military strike is most unlikely. The situation I have described here points to a clash in rights-the right of one or more states to use geoengineering to avoid losses from climate change versus the right of other states not to be harmed by geoengineering. Clashes like this occur all the time. They rarely, if ever, lead to military conflict.

To give an example, there are no general rules for assigning rights to transboundary water resources. An upstream state will assert its right to divert the waters of a shared river for its own purposes, while the downstream state will claim its right to an uninterrupted flow of this water. Resolution of such disputes invariably demands mutual concessions. Typically, the parties will seek an "equitable" solution, meaning a sharing of rights. The nature of the bargain that is struck will depend on the context, including the characteristics of the parties. For example, if the upstream state is poor and the downstream state rich, the latter state may need to pay the upstream state not to divert its waters. By contrast, if the upstream state is rich and the downstream state poor, the former may need to compensate the latter.

Perhaps, then, India will refrain from using geoengineering, or scale back its plans, in exchange for other countries offering to help India improve the productivity of its agriculture (taking the climate as given). By contrast, if the United States were inclined to use geoengineering first, it seems more likely that there would be an expectation that the US should finance investments in other countries, to blunt the negative impacts on these countries of its use of geoengineering. In both cases, the need for a state to take into account the concerns of other states would have a moderating influence.

A scenario of "abrupt and catastrophic" climate change

The situation changes when we peer farther into the future. Over longer periods of time, even gradual climate change will be harmful all around—melting of the Greenland Ice Sheet, for example, would increase sea level by about seven meters. It is hard to see how any country could gain from this degree of sea level rise, even if it unfolded, as expected, over a period of many centuries.

Abrupt climate change is a greater worry. Warming is expected to be especially strong in the Arctic region. Should this warming trigger massive releases of carbon dioxide and methane, a positive feedback will be unleashed. No country will gain from such a climate shock. A collapse of the West Antarctic Ice Sheet, though unlikely, would also have very serious consequences. No country will gain from this kind of change either.

It thus seems likely that the interests of states as regards geoengineering will tend to converge over time. Tensions that loom large in a world of gradual climate change will evaporate in the longer run and will disappear very quickly should the prospect of abrupt, catastrophic climate change appear imminent.

Outlines of a geoengineering regime

Should there be a regime for using, or not using, geoengineering? Currently, no such regime exists. There are some agreements and some aspects of custom that would be relevant to such a decision (Bodansky 1996). But the situation we are contemplating here is unprecedented. Should a country believe that its national security interests were at stake, it would make decisions largely unrestrained by international law. The absence of a regime essentially allows states to act as they please.

This means that the United States could act as it pleased, more or less. But it also means that Russia and China, India and Brazil, Europe, and Japan, and Indonesia and South Africa could all act as they pleased as well. It is in the interests of each county to agree to restrain its own choices in exchange for other countries agreeing to restrain theirs. The governance arrangement needed for geoengineering is thus one of *mutual restraint* (Barrett 2007).

As I have stressed throughout this testimony, geoengineering needs to be considered in the context of all the other things we need to do to limit climate change risk. For this reason, international governance arrangements for geoengineering should be developed under the Framework Convention on Climate Change. Currently, the focus of the Framework Convention is on limiting atmospheric concentrations of greenhouse gases. It would be better, in my view, if the agreement were revised to focus on reducing climate change risk, and on balancing this risk against the risks associated with addressing climate change. Every good international agreement is revised and reworked as circumstances change.

Protocols developed under this convention should address specific collective action challenges that serve to reduce risks. There should be many such protocols, even as regards reducing emissions (Barrett 2008b). There should also be a protocol for geoengineering governance.

A geoengineering protocol should be open to be signed and ratified by every party to the Framework Convention. It is important to underscore that every country is entitled to participate in the Framework Convention, and that nearly every country in the world is a party to this treaty today (the only non-parties are the Holy See and Andorra). This principle of universality is important. Every country will be affected by whatever is decided about geoengineering. Every country should have an opportunity to shape this technology's governance.

The protocol can be more or less restrictive. As it becomes more restrictive, fewer states will consent to participate. An agreement that fails to attract the participation of the geoengineering-capable states would be of little benefit. It will be in every country's interests that as many geoengineering-capable states as possible participate in this agreement. It may not be essential that every geoengineering-capable state participate, but at the very least the agreement should establish normative limits that would restrain the behavior even of non-parties.

As a general approach, negotiations should focus on what countries can agree on rather than on what they cannot agree on. The treaty should enter into force only after being ratified by a substantial number of countries. An additional requirement may be needed to ensure that the geoengineering-capable states also participate in great numbers. Note, however, that as the latter condition for entry into force becomes more restrictive the agreement will essentially hand every such state the veto. A consequence may be that the agreement would never enter into force.

What is it that countries can countries agree on? It is likely that all states will agree that every state ought to be obligated to inform all other states of any intention to deploy geoengineering. One reason for this is that deployment would be observable by other states in any event. As well, deployment must be sustained if it is to affect the climate. The element of surprise would offer no advantages.

Negotiations will likely focus on a state's rights and responsibilities—its right to deploy geoengineering to safeguard its own citizens and its responsibility not to harm other states. It is in the nature of this technology that the latter outcome could not be assured. This is likely to have a restraining influence on the decision to deploy.

Countries may agree that they should cooperate to resolve conflicts. A country declaring an intention to deploy geoengineering may agree to hear opposition to its plans (these will be voiced in any event, but an agreement may help to establish the basis on which opposition can be expressed). It is unlikely that the geoengineering-capable states would be willing to have their hands tied completely. It is also unlikely that they would agree to have their freedom of action be determined by a vote. Even if they did agree to this in principle, it would be very hard to conceive of a voting rule that would be acceptable to all states. It is, however, likely that states would agree to aim to seek a consensus.

Consensus has powerful advantages. It makes each state take into account the collective interests of all states, and the individual interests of every state. It creates a presumption in favor of unanimity. At the same time, however, it does not give any state the veto. Every state may retain the right to act, should a consensus not be possible. But any state contemplating deployment would have to face the consequences of its actions. These consequences would include possible counter measures by other states.

Rules for R&D will be influenced by the rules for deployment. An agreement to cooperate over deployment would reduce any advantages to undertaking R&D secretively. In justifying its decision to deploy, for example, a country would need to present evidence that geoengineering would not harm other states. Undertaking R&D openly, and collaboratively would favor a shared understanding of this technology's capabilities and effects. It would promote trust.

The rules I have sketched here are minimal. The main purpose of the protocol would be to provide a restraining influence, a forum for resolving conflicts, and a setting in which various risks can be balanced. Returning to the two scenarios outlined previously, in the case where some countries might be in favor of geoengineering and some against, the consensus rule would create a space for negotiating conflict resolution. In the case where nearly all countries would favor geoengineering, this arrangement would provide the stamp of approval.

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BIOGRAPHY FOR SCOTT BARRETT

Scott Barrett is the Lenfest-Earth Institute Professor of Natural Resource Economics at Columbia University in New York City. He is also a research fellow with CESifo (Munich), the Beijer Institute (Stockholm), and the Institute of World Economics (Kiel). Until recently, he was a professor at the Johns Hopkins University School of Advanced International Studies in Washington, DC. He was previously on the faculty of the London Business School, and has also been a visiting scholar at Yale. He has advised a number of international organizations on climate change, including the United Nations, the World Bank, the OECD, the European Commission, and the International Task Force on Global Public Goods. He was previously a lead author of the Intergovernmental Panel on Climate Change and a member of the Academic Panel to the Department of Environment in the U.K. He is the author of *Environment and Statecraft: The Strategy of Environmental Treaty-Making*, published in paperback by Oxford University Press in 2005. His most recent book, *Why Cooperate? The Incentive to Supply Global Public Goods*, also published by Oxford University Press, will appear in paperback, with a new afterword, in May 2010. His research has been awarded the Resources for the Future Dissertation Prize and the Erik Kempe Award. He received his Ph.D. in economics from the London School of Economics.

DISCUSSION

Chairman GORDON. Thank you, Dr. Barrett.

I think the concept of trying to find what we can agree upon is, unfortunately, unusual around here. We spend too much time on what we can't agree upon.

I thank all of our witnesses for their testimony. I understand that Dr. Barrett and Dr. Long are Co-Members of the Bipartisan Policy Centers Initiative. Well, you and we are all part of a pioneering effort here. So, we look forward to your additional information, in this, in the body of evidence, in this early, pioneering effort.

And I am, now I am going to yield to Mr.—Governor Garamendi for any question he might have.

INITIAL REGULATIONS

Mr. GARAMENDI. Thank you very much. Dr. Barrett, your rules are a great place to start. What we need is some forum in which to begin the discussion, and setting out the rules of the game. And I really urge this committee and Congress, and anybody else to try to figure out what that forum would be, to set that down.

Do you have a suggestion on how that might be accomplished?

Dr. BARRETT. You need a process to initiate discussion. You know, it is a great question, and right now, you know, in the follow-up to Copenhagen, there has been a lot of discussion about that process, and whether that process is the problem. And I actually don't think the process, the U.N. process is the problem. I think it is our approach to climate change that has been the problem. So, I think the diagnosis is very important.

I think on this issue, because all countries have a stake in the issue, and I think this is an issue that people need some time to think about. You know, our first reactions to this issue were not the same as our reactions as we think about it more.

So, I think the natural place in which there should be the beginning of a discussion would be under the United Nations Framework Convention on Climate Change [UNFCCC]. I think that agreement needs to be revised to address this fundamental problem of reducing risk, and once we look at this as a problem of reducing risk, we will want to, you know, conclude under that agreement a lot of different issues, including geoengineering.

A POTENTIAL ROLE FOR DOE AND NATIONAL LABS

Mr. GARAMENDI. I don't have time with my questions to go to each one of you about that, but I think that is really a central piece of where we need to go as a committee is to, okay, what is the next step, what is the process for that.

I wanted to—I would like to go to Dr. Long for a couple of reasons. One, we have had wonderful discussions about this over the years, and you are from my district. So, the other three please excuse me. And this really speaks to Dr. Morgan's point that the Department of Energy should not have a role here. I disagree with that, and I would like Dr. Long to really talk to this issue.

It turns out that the national laboratories, the Department of Energy labs, have a very, I think, wrongly defined mission at the moment, which is nuclear security, and I think they should have to have a change in their mission statement to one of national security, where all of the resources at those labs can be used to deal with a broader range of national security issues, non-bombs.

For example, the biggest and perhaps the best computer to deal with climate modeling is at Lawrence Livermore National Laboratories. Sometimes, Los Alamos will dispute that, and others will dispute it, but the labs do have extraordinary computing capability, which is central to this issue. And also, a lot of knowledge about things that go boom. For example, if you want to seed the atmosphere with sulfates, you are probably going to use something that goes boom.

Anyway, these kinds of things are there, and I would just recommend that.

So, Dr. Long, if you could speak about the assets that are at the laboratories, in the context of dealing with this issue?

Dr. LONG. Well, I think one of the most important things that is in my written testimony, and I didn't get a chance to talk about, is the need for adaptive management in this problem.

And to do adaptive management, we are going to have to be able to predict, we are going to have to make a prediction about the result of our actions, and then, we are going to have to be able to discern whether that prediction is correct, by making observations. And then, we are going to have to decide whether we are going in the right direction, and change direction if we are not.

There are many things that are required to do that. One of them is computing, and one of them is simulation of the climate. The laboratory conducts, currently, a program called PCMDI, which is program and model comparison for climate. These kinds of studies that provide very careful, even-handed assessments of whether the climate is changing in response to the actions we are taking, or it is just climate variability that we are seeing, are going to be critical. and These kinds of calculations are very demanding, and can be done at national laboratories.

But also, this problem, though, also relates to something that Dr. Barrett said. Somewhere in here, we have to engage with the public and with the policymakers at the same time that this kind of analysis is coming in, because the hardest piece is, as hard as it is to make a decision to take an action, we are also going to have to make decisions to change the direction of our action, and that is going to have to be supported hand in hand with really good analysis and fingerprinting of what we are actually doing. And that exists at the National Laboratories.

Mr. GARAMENDI. Dr. Morgan, do you want to jump in in the remaining seconds, do so.

Dr. MORGAN. One activity that is going forward, the Royal Society, as we heard in the first session, has just undertaken something called the Solar Radiation Management Governance Initiative, which will be undertaken by the Royal Society, the science societies of the developing world, by Environmental Defense Fund, the NGO, and a number of other organizations, including, for example, the International Risk Governance Council, whose Scientific and Technical Council I chair, and which convened one of the two workshops that I mentioned.

So, that is a process, an international process that is ongoing. I would argue that one does not want to get too firm a restriction in place on small scale studies early on, because it will tie the science's hands.

Mr. GARAMENDI. Well, you were very quick on—when the red light came on, right in the middle of a sentence. I don't know if the Chairman is that strict. Could you finish your sentence?

Dr. MORGAN. No, I was simply—I mean, the reason I showed that slide with the funny box was to simply say, I think what the science community ought to be trying to do is say, you do small scale stuff inside this space, and it is a scientific question what that space ought to be. There shouldn't be a lot of oversight and restriction. If you put too much U.N. approval and other stuff in place, we are never going to get any answers.

And so, we have got to find a space that is safe and appropriate to do studies, and then say, outside that, that is forbidden until, you know, there is some larger governance structure in place.

Mr. GARAMENDI. Mr. Chairman, I am going to take another 30 seconds if I might, and just compliment you on this meeting, and really urge you and your committee staff and the rest of us, to really hone in on this issue.

I am very taken by the issue of setting the rules, whatever those might be, and the caution that was given, and also, the full utilization of all of our research capabilities here in the United States and around the world, in some sort of a coordinated effort. It is really, really important in my mind, and I thank you for the hearing.

Chairman GORDON. Thank you, Governor. The lights are automatic, but folks have made a lot of effort to get here and participate, so we try to be generous with our time.

Mr. Hall is recognized.

Mr. HALL. Mr. Chairman, I only want to ask unanimous consent to do something here, if I can find it. I want to, a paper that was published in the Journal of Petroleum Science and Engineering, by the Economides couple. I would like unanimous consent to place that journal article into the record.

Chairman GORDON. Without objection.

[The information follows:]

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Sequestering carbon dioxide in a closed underground volume

Christine Ehlig-Economides [a,1], Michael J. Economides [b,*]

[a] Department of Petroleum Engineering, Texas A&M University, College Station, Texas 77843, USA
[b] Department of Chemical Engineering, University of Houston, Houston, Texas 77204, USA

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ABSTRACT

The capture and subsequent geologic sequestration of CO_2 has been central to plans for managing CO_2 produced by the combustion of fossil fuels. The magnitude of the task is overwhelming in both physical needs and cost, and it entails several components including capture, gathering and injection. The rate of injection per well and the cumulative volume of injection in a particular geologic formation are critical elements of the process.

Published reports on the potential for sequestration fail to address the necessity of storing CO_2 in a closed system. Our calculations suggest that the volume of liquid or supercritical CO_2 to be disposed cannot exceed more than about 1% of pore space. This will require from 5 to 20 times more underground reservoir volume than has been envisioned by many, and it renders geologic sequestration of CO_2 a profoundly non-feasible option for the management of CO_2 emissions.

Material balance modeling shows that CO_2 injection in the liquid stage (larger mass) obeys an analog of the single phase, liquid material balance, long-established in the petroleum industry for forecasting undersaturated oil recovery. The total volume that can be stored is a function of the initial reservoir pressure, the fracturing pressure of the formation or an adjoining layer, and CO_2 and water compressibility and mobility values.

Further, published injection rates, based on displacement mechanisms assuming open aquifer conditions are totally erroneous because they fail to reconcile the fundamental difference between steady state, where the injection rate is constant, and pseudo-steady state where the injection rate will undergo exponential decline if the injection pressure exceeds an allowable value. A limited aquifer indicates a far larger number of required injection wells for a given mass of CO_2 to be sequestered and/or a far larger reservoir volume than the former.

1. Introduction

According to the United Nations Intergovernmental Panel for Climate Change (IPCC, 2007), "the increases in atmospheric carbon dioxide (CO_2) and other greenhouse gases during the industrial era are caused by human activities," and the IPCC insists that anthropogenic greenhouse gas emissions are harmful to the planet and are causing global climate change evident as global temperature rise and local weather extremes. Although greenhouse gases include water vapor, carbon dioxide, and methane, that are emitted through various means, the focus of this paper is strictly on carbon dioxide emissions.

In 2008 coal consumption for electric power generation in the United States was 1.04 billion short tons (tonnes) per year (EIA, 2009), and total carbon dioxide emissions in 2007 were 6.02 billion metric tons (tonnes) including 2.16 billion tonnes from coal fired electric power generation, 2.6 billion tonnes from petroleum consumption mainly for transportation, and 1.2 billion tonnes from natural gas consumption. By 2030 US carbon dioxide emissions are forecast to reach 6.41 billion tonnes according to the EIA. The Kyoto Protocol proposed for the US to reduce carbon dioxide emissions to 93% of the 1990 emission level, or to keep it at a level below 4.67 billion tonnes for every year from December 1997, the year of its enactment, and onward. To satisfy the Kyoto Protocol, carbon dioxide emissions should already be reduced and would have to be reduced by 1.75 billion tonnes per year by 2030. This task is enormous and will be exacerbated further by recent legislation that proposes even more stringent goals.

Potential ways to reduce carbon dioxide emissions include reducing the need for fossil fuel combustion through more efficient energy use (although history has not proven this to be successful), substituting biofuel, hydrogen, or electric power for hydrocarbons in the transportation and electric power generation sectors, substituting natural gas for coal in electric power generation, substituting alternative energy sources for coal and natural gas in electric power generation, and capturing and sequestering carbon dioxide produced

* Corresponding author. Tel.: +1 713 7253826; fax: +1 713 7812548.
E-mail addresses: cee@economidesconsultants.com (C. Ehlig-Economides), mje@uh.edu (M.J. Economides).
[1] Tel.: +1 281 9483621; fax: +1 713 7812548.

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by combustion. While it is probably not feasible to capture and sequester carbon dioxide emitted from the transportation sector, there is considerable interest in the possibility of sequestering carbon dioxide produced from electric power generation. In particular, because new technologies for electric power generation from coal such as integrated gasification combined cycle (IGCC) produce about 90% of the carbon dioxide in a concentrated stream presumably suitable for underground sequestration, there is interest in carbon capture and sequestration (CCS) for future electric power generation from coal. CCS for retrofitted coal combustion electric power plants and for natural gas combined cycle (NGCC) plants is potentially feasible as well but at much higher cost. The common assumption is that the cost of carbon sequestration is much less than the cost of carbon capture (NETL, 2007). Further, current energy legislation assumes that the cost of power generation with CCS will be competitive with alternative energy options. We are not convinced that the recovery of carbon dioxide from low pressure combustion gas streams will ever be as efficient or effective as some have suggested but this discussion is outside the scope of this paper.

There are several processes that have been postulated as means for carbon dioxide sequestration. These include ocean sequestration that involves either deep release of the gas, causing dissolution in water or by promoting phytoplankton growth causing consumption of carbon dioxide. Other possibilities include mineral and biological sequestration involving the reaction of carbon dioxide with e.g., magnesium silicate. Biological processes may lead to carbonates or methane. Reforestation may also contribute to sequestration as increased vegetation may consume more carbon dioxide. While all these techniques have received attention they all have time constraints and considerable logistical problems. Geological sequestration has been espoused by many and it is the subject of this paper.

If all of the 1.75 billion tonnes annual reduction forecast for 2030 were to be achieved by sequestering carbon dioxide underground, this would amount to injection of 39 million bpd of supercritical carbon dioxide, assuming a density of 47.6 lbm/ft^3. The US currently produces crude oil and lease condensate at a rate of about 5.4 million STB/d with actual reservoir volume perhaps slightly greater depending on the average formation volume factor. By comparison, adding current natural gas and natural gas liquid production at 11.8 million barrels of oil equivalent (BOE) per day gives a total US liquid and gaseous hydrocarbon voidage rate of about 16.2 million BOE/d with much of the crude oil production supported by pressure maintenance via waterflooding or an active water drive (www.eia.doe.gov).

As another comparison, the US currently injects about 38 million bpd of oilfield water. Although this may appear to offer a reassuring analogy to the CO_2 volume, in reality it is not, because oilfield water is typically injected in hydraulic communication with the oil or gas production to achieve pressure maintenance and thereby avoid surface subsidence that can occur from underground pore pressure depletion. Injected water usually replaces fluids that are produced and, still, water breakthrough is a common occurrence. Likewise, industrial, municipal, and agricultural groundwater use is strictly monitored, and optimal water management restricts groundwater use to what is recharged via annual precipitation. Both oilfield water injection and groundwater production are, thus, largely steady state processes.

In contrast, carbon dioxide sequestration is not generally envisioned to be associated with any production of underground fluids, and analogies between carbon dioxide sequestration in deep saline aquifers or in depleted hydrocarbon reservoirs and EOR displacement processes are highly inappropriate.

In volumetric terms, for coal density of 94 lbm/ft^3 (depends on the type of coal) and supercritical carbon dioxide density of 48 lbm/ft^3 (depends on pressure and temperature), more than twice the volume is required to sequester carbon dioxide underground than to remove carbon as coal. However, while a coal seam is approximately 100% coal, the carbon dioxide must be injected into rock with porosity on the order of 20%, representing 10 times more volume than originally occupied underground by the coal. Further, this paper will show that the volume multiplier is another 50 times more when compressibility and solubility are taken into account. The net result is that it takes more than 500 times more volume to sequester carbon dioxide than was originally occupied as coal. The pore volume required to sequester 1.75 billion tonnes is 182 billion barrels annually, and this represents about 8.5 times the total US crude oil reserves of about 21.5 billion barrels.

To demonstrate these claims, this paper will consider carbon dioxide sequestration via EOR, in deep saline aquifers, and in depleted hydrocarbon reservoirs, using as a basis the emissions from an average coal power plant with generating capacity of 500 MW. Our very sobering conclusion is that underground carbon dioxide sequestration via bulk CO_2 injection is not feasible at any cost.

2. Geologic sequestration methods

While other potential mechanisms for carbon dioxide sequestration may be under consideration, petroleum engineers offer the most expertise for sequestration in an underground porous medium. This section considers two approaches: 1) via EOR or 2) via bulk carbon dioxide injection into a depleted oil or gas reservoir or a deep saline aquifer.

2.1. EOR

Oil recovery can often be enhanced by carbon dioxide injection, and this approach has been used commercially for many decades. Traditionally EOR follows waterflooding, and the enhanced oil recovery factor is typically a small fraction of the oil in place. With total (not annual) US oil reserves currently estimated by EIA at 21.5 billion barrels, if even 10% of this could be enhanced via carbon dioxide injection, the amount would represent on the order of 2 billion barrels, which would represent just under 14% of the Kyoto Protocol target of 1.75 billion tonnes (14.4 trillion barrels) for annual (not total) carbon dioxide reduction. The current worldwide use of CO_2 for EOR is about 57 million tonnes per year, about 3% of just the US mandated Kyoto Protocol reduction (Evans and Melzer, 2009).

2.2. Bulk carbon dioxide injection

The most commonly recommended method for carbon dioxide sequestration is by bulk injection into a depleted oil or gas reservoir or a deep saline aquifer. For depleted oil reservoirs, it is important to consider by what mechanism depletion occurred before field abandonment. If the field was abandoned following primary oil recovery only without active water drive, the average reservoir pressure may be considerably below the original reservoir pressure. In contrast, if the field was produced under active water drive or under waterflood, the abandonment pressure may be at approximately the original reservoir pressure or approximately the original bubble point pressure. In all cases the pore space is likely to be saturated mainly by liquid. Likewise for deep saline aquifers the pore space is saturated by brine. For depleted gas reservoirs, the pore space may be saturated by gas at abandonment pressure well below the original reservoir pressure plus connate water or it may be mainly saturated by water at original reservoir pressure if the gas was produced under active water drive.

By far the best prospect among these choices for bulk carbon dioxide injection is an abandoned gas reservoir depleted without active water drive. However, typically such reservoirs are used for natural gas storage and would not be available for carbon dioxide sequestration. Of the liquid saturated prospects, oil reservoirs abandoned at lower than initial pressure will offer somewhat more storability than oil reservoirs abandoned after waterflood or deep saline aquifers. The following discussion provides a conceptual model for bulk CO_2 injection in a deep saline aquifer, and with minor adjustments this would apply to any liquid filled underground reservoir, including depleted oil and gas reservoirs.

There are two considerations: the wellbore pressure increase over average reservoir pressure, and the increase in average reservoir pressure over the initial reservoir pressure. For a deep saline aquifer, the initial formation pressure in psi is likely to be hydrostatic and therefore equal to $0.433H$, where H is the aquifer depth in ft. The formation temperature will be a function of the geothermal gradient, which on average may be on the order of 1 °F per 100 ft. With a critical pressure of 1071 psi and critical temperature of 87.8 °F, CO_2 will be in a supercritical state at bottomhole injection conditions for aquifer depths exceeding 2473 ft. This is preferred because supercritical CO_2 is denser than gaseous CO_2 and, therefore, enables storage of more mass per unit underground pore volume.

At first, the bottomhole pressure during CO_2 injection at a constant rate is governed by transient flow of single phase brine given by the following equation:

$$p_{wi} = p_i - \frac{70.6(-q_{CO_2})\mu_w}{kh} \ln\left(\frac{kt}{1688\phi\mu c_{ti} r_w^2}\right) \tag{1}$$

where the downhole injection rate is shown as $-q_{CO_2}$, in bpd; wellbore injection and initial reservoir pressures are p_{wi} and p_i, both in psi; t in hours, k and ϕ are the aquifer absolute permeability in md and porosity; r_w is the well radius in ft; μ_w is the brine viscosity, and c_{ti} is the initial total compressibility in psi^{-1} accounting for brine and rock compressibility at initial injection conditions. During this early injection period, the injection rate may be ramped up gradually to avoid injecting at a pressure above the formation fracture pressure, p_f, which depends on the formation fracture gradient, which for almost all reservoirs will range from 0.71 to 0.82 psi/ft (Economides and Nolte, 2000). After a relatively short period, typically lasting from a few days to a few months, the bulk carbon dioxide injection establishes a zone near the well in which CO_2 flows as a single phase zone surrounded by a two-phase region where the saturation varies from nearly 100% CO_2 to 100% brine according to Buckley and Leverett (1942) displacement theory. Burton et al. (2008) provide equations for the radii of the single phase and two-phase zones and the pressure drop across each of these zones as well as the pressure drop in the single phase brine.

For this study, the pressure increase over average reservoir pressure is given by

$$p_{wi} = \overline{p} - \frac{141.2(-q_{CO_2})}{kh}\left[\frac{\mu_{CO_2}}{k_{r,S_{CO_2}=1}}\ln\left(\frac{r_{dry}}{r_w}\right) + \left(\frac{k_{CO_2}}{\mu_{CO_2}} + \frac{k_{rw}}{\mu_w}\right)^{-1}\Bigg|_{S_{CO_2,avg}} \ln\left(\frac{r_{BL}}{r_{dry}}\right) + \mu_w \ln\left(\frac{0.472 r_e}{r_{BL}}\right)\right] \tag{2}$$

where CO_2 and water viscosities are μ_{CO_2} and μ_w in cp; relative permeabilities are k_{CO_2} and k_{rw}; and outer radii of the single phase CO_2, 2-phase Buckley–Leverett, and single phase brine are r_{dry}, r_{BL}, and r_e. The relative permeability of the CO_2 in the single phase region is $k_{r,S_{CO_2}=1}$, and relative permeability values in the 2-phase region are evaluated at the average CO_2 saturation according to Buckley–Leverett displacement theory. The factor 0.472 in the last natural logarithm term in Eq. (2) accounts for average reservoir pressure, $\overline{p}$, as the average pressure in the brine region and is a departure from the Burton et al. (2008) approach, which claimed, incorrectly, that treating the aquifer as open, with a constant pressure outer boundary, was equivalent to modeling an effectively infinite aquifer.

Eq. (2) assumes the aquifer volume is limited and that pseudo-steady state flow behavior is established. The open aquifer, or steady state, flow condition assumes that at some distance, pressure in the aquifer is held at a constant value. For this to be true in practice, the aquifer must either outcrop to the land surface or in a stream, lake, or ocean bed where it would be in equilibrium either with atmospheric pressure or with the pressure at the stream, lake or ocean bottom. An outcropping aquifer would provide a potential path for injected CO_2 to escape back to the atmosphere, thereby defeating the purpose of CO_2 sequestration.

The consequence of assuming the aquifer has a limited area is that the average aquifer pressure will increase over time. Thus, accounting for material balance,

$$(\overline{p} - p_i) V_r c_t = V_{CO_2} \tag{3}$$

where V_{CO_2} is the total volume of CO_2 to be injected over the life of the sequestration project, V_r is the minimum required aquifer pore volume to store this volume of CO_2, and c_t is the total compressibility accounting for CO_2, brine, and rock compressibility as

$$c_t = \frac{[(r_{dry}^2 - r_w^2)c_{CO_2} + (r_{dry}^2 - r_{BL}^2)[S_{CO_2,avg}c_{CO_2} + (1 - S_{CO_2,avg})] + (r_e^2 - r_{BL}^2)c_w]}{(r_e^2 - r_w^2)} + c_f \tag{4}$$

using a bulk volume weighted average.

Finally, the difference between the wellbore injection pressure and the initial reservoir pressure will be

$$p_{wi} - p_i = p_{wi} - \overline{p} + \overline{p} - p_i = -\frac{141.2(q_{CO_2})}{kh}\left[\frac{\mu_{CO_2}}{k_{r,S_{CO_2}=1}}\ln\left(\frac{r_{dry}}{r_w}\right) + \left(\frac{k_{CO_2}}{\mu_{CO_2}} + \frac{k_{rw}}{\mu_w}\right)^{-1}\Bigg|_{S_{CO_2,avg}} \ln\left(\frac{r_{BL}}{r_{dry}}\right) + \mu_w \ln\left(\frac{0.472 r_e}{r_{BL}}\right)\right] + \frac{V_{CO_2}}{V_r c_t} \tag{5}$$

Many of the published works seem to be consumed by simulating the physics and thermodynamics of CO_2 displacing brine or its dissolution in the brine (the latter is a woefully slow process), while they are missing by far the most fundamental issue: during injection sequestration is not displacement but permanent storage in a closed system. Several authors (Kumar et al., 2005; Baklid and Korbo, 1996; Pruess, 2004; Nghiem et al., 2004; Sengul, 2006; Izpec et al., 2006) employ a constant pressure outer boundary when modeling CO_2 injection, which is convenient, but misleading. Actually, flow behavior in a reservoir with a constant pressure boundary does not mimic that of an effectively infinite aquifer, and authors who employ this condition are significantly misrepresenting this case. Likewise, authors like Orr (2004) and Noh et al. (2004), who emphasize the analogies with EOR, are on the wrong track. The consequence of these misrepresentations is that the volume required for CO_2 storage has been severely underestimated.

Pruess et al. (2001) modeled CO_2 injection in an infinite aquifer, but their approach again significantly overestimated storability. To their credit, van Engelenburg and Blok (1993), Schembre-McCabe et al. (2007), van der Meer and van Wees (2006), Ennis-King and Paterson (2002), and House et al. (2003), have already tried to alert investigators to the issue of pressure buildup in a limited aquifer, and Zakrisson et al. (2008) specifically address modeling multiple injection wells.

There are already some data that seem to warn of problems in the very few existing injection projects. The much cited Sleipner reservoir in the North Sea, as a successful case of CO_2 injection (about 1 million tonnes per year compared to 3 million that would be required for a 500 MW coal power plant) shows that much less CO_2 is stored radially than what seismic reflection data show (Bickle et al., 2007). They have seen significant leakage to overlying layers. The far reduced radial volume was attributed by the authors to the "significantly reduced… relative permeability of CO_2". They did not attempt to model the reservoir pressure profile.

2.3. Application for a single power plant

A modern commercial 500 MW coal power plant generates about 3 million metric tons of CO_2 per year. Assuming it is captured as a pure CO_2 stream, what will be the aquifer pore volume required to store the CO_2, and how many wells will be needed if the plant life is assumed to be 30 years?

Suppose an aquifer exists in the vicinity of the plant with porosity 20%, permeability 100 md, and thickness 100 ft. Suppose further that core analysis provides relative permeability curves

$$k_{rw} = \left[1-\left(\frac{S_{CO_2}}{1-S_{wr}}\right)\right]^m \tag{6}$$

$$k_{CO_2} = k^0_{CO_2}\left[\frac{S_{CO_2}}{1-S_{wr}}\right]^n \tag{7}$$

with $S_{wr}=0.558$, $k^0_{CO_2}=0.32$, $m=3$, and $n=3$.

For an aquifer depth of 6000 ft at a temperature of 150 °F (assuming geothermal gradient of 1 °F/100 ft) and hydrostatic pressure of about 2598 psi, the supercritical fluid density at reservoir conditions will be about 41 lbm/ft^3 (Jarrell et al., 2002). At this density the total volume of CO_2 to inject in a 30 year period is 4.86 billion cu ft, or 865 million bbl. The volumetric injection rate is 79,000 bpd. To determine the aquifer area required to inject this volume of CO_2, it is necessary to decide how much the aquifer will be pressurized above the initial aquifer pressure. Certainly it should not be pressurized above the formation fracture pressure. Assuming the fracture gradient is 0.7 psi/ft, the average reservoir pressure should not exceed 4200 psi. However, in order to inject at a constant rate for 30 years at the end of this time period, the wellbore injection pressure must exceed the average reservoir pressure as in Eq. (2), and this pressure must not exceed 4200 psi.

Experience with natural gas storage indicates that it is not possible to recover all of the stored gas if the reservoir is pressurized well over the initial reservoir pressure. This has been interpreted as an indication that some of the stored gas has leaked out of the reservoir. Exactly the same result may occur for CO_2 storage in an aquifer. Therefore, as a first case, assume the aquifer average pressure will not be elevated by more than 100 psi over the initial aquifer pressure. With this assumption Eq. (3) implies the required aquifer pore volume is 7.7 trillion cu ft. For the given aquifer thickness and porosity, the resulting area is 13,800 sq mi. If the injection pressure is allowed to approach the formation fracture pressure, the difference between injection and average pressures is $4200-2598-100=1502$ psi, and Eq. (2) indicates that ½ the required rate can be produced in ½ of this area without exceeding this pressure constraint. Therefore, 2 wells can inject all of the CO_2 produced by the plant for 30 years.

However, as points of reference, the Prudhoe Bay reservoir area is 337 sq mi, and 9 US states and the District of Columbia all have areas less than 13,800 sq mi.

It is possible to reduce the required area by increasing the amount to pressurize the reservoir. Assuming instead the aquifer average pressure will be elevated by 1000 psi, the required aquifer area is 1371 sq mi, somewhat less than the area of the state of Rhode Island, which has an area of 1545 sq mi. In this case 4 wells will be sufficient.

The minimum aquifer area, assuming pressurization of 1600 psi is approximately 853 sq mi, and 1155 wells are required.

Of course, greater aquifer thickness reduces the required aquifer area by increasing both injectivity and storability per unit area. If an otherwise similar aquifer is 200 ft thick instead of 100 ft, the area required with 1000 psi pressurization is reduced to 686 sq mi, and 2 wells, each requiring a square area approximately 17.5 mi on a side, are sufficient.

3. General relationships

Eq. (5) is generalized as follows:

$$p_{wi}-p_i = \Delta p_{max} = \frac{0.0690V_{CO_2}}{N_w kht_{plant}}\left[\frac{\mu_{CO_2}}{k_{r,S_{CO_2}=1}}\ln\left(\frac{r_{dry}}{r_w}\right) + \left(\frac{k_{CO_2}}{\mu_{CO_2}}+\frac{k_{rw}}{\mu_w}\right)^{-1}\Big|_{S_{CO_2,avg}}\ln\left(\frac{r_{BL}}{r_{dry}}\right)+\mu_w\ln\left(\frac{0.472}{r_{BI}}\right)\right]+\frac{V_{CO_2}}{V_r c_t} \tag{8}$$

where Δp_{max} is limited to no more than the difference between fracture and hydrostatic pressures, p_f-p_{hyd}, for an aquifer. The pressure of a depleted oil or gas field may be less than hydrostatic. Denoting the term in brackets as $1/M_r$, this can be further generalized as the following equation:

$$\frac{\Delta p_{max}}{V_{CO_2}} = \frac{0.0690}{M_r N_w kht_{plant}} + \frac{1}{V_r c_t} \tag{8}$$

where N_w is the required number of wells. Figs. 1 and 2 show this simple relationship for the specific depths of 4000 and 6000 ft and for injection of 3 million tonnes of CO_2 per year. The shallower formation depth has a

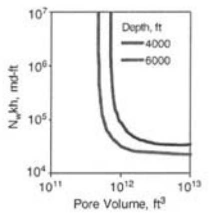

Fig. 1. Relationship between well count, permeability-thickness, and the required minimum pore volume for given relative permeability, Δp_{max}, and aquifer depth.

smaller window between formation and fracture pressures, leading to a larger volume requirement.

A critically important message from this generalization concerns storability. The following discussion explains how much pressure matters to the storability in a liquid saturated reservoir.

The volume of fluid that can be stored in a reservoir depends entirely on the fluid compressibility and associated pressure increase, which in turn depends on the reservoir volume. This can be evaluated by starting with the expression for isothermal compressibility.

The isothermal expansibility is defined as

$$c = \frac{1}{V}\left(\frac{\partial V}{\partial p}\right)_T \quad (9)$$

where V is the volume of the fluid. By separation of variables,

$$\int_{p_i}^{\bar{p}} c\,dp = \int_{V_i}^{V} \frac{dV}{V} \quad (10)$$

Assuming that c is constant over the pressure range,

$$c(\bar{p} - p_i) = \ln\frac{V}{V_i} \quad (11)$$

Rearrangement of Eq. (3) results in

$$\frac{V}{V_i} = e^{c(\bar{p}-p_i)} \quad (12)$$

The volume V is equal to $V_i + V_{CO_2}$, that is, the original plus that stored at the higher pressure. Finally, the storability factor, s_{CO_2}, is given by

$$S_{CO_2} = \frac{V_{CO_2}}{V_t} = e^{c(\bar{p}-p_i)} - 1 < e^{c(p_f - p_{hyd})} - 1 \quad (13)$$

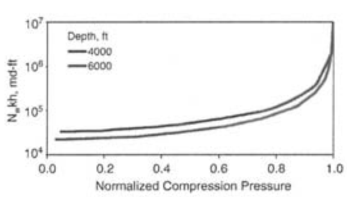

Fig. 2. Relationship between well count, permeability-thickness, and the compression pressure as a fraction of Δp_{max} for given relative permeability, Δp_{max}, and aquifer depth.

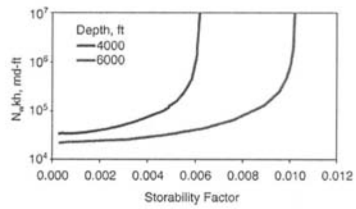

Fig. 3. Relationship between well count, permeability-thickness, and the storability factor for given relative permeability, Δp_{max}, and aquifer depth.

Fig. 3 shows the well count *kh* product as a function of the storability factor. Fig. 3 indicates that the best storability factor is about 1% of the pore volume. This is in stark contrast to claims in NETL (2007) that suggest that the CO_2 storage "efficiency factor between 1 and 4 percent of the bulk volume of saline formations for a 15–85 percent confidence range".

How do we explain this discrepancy, which represents a factor of from 5 to 20? First, NETL (2007) seems to have a typographical error in the above-quoted footnote. The efficiency factor, E, is explained in the following equation

$$G_{CO_2} = Ah\phi\rho_{CO_2}E \quad (14)$$

As such, E, which is further explained as a product of vertical and areal displacement efficiencies, represents a fraction of the pore volume, not the bulk volume. As such, Fig. 3 is closer to reported storage efficiency, but the upper limit in this estimate corresponds to the lower limit in the NETL estimate.

The remaining discrepancy comes from ignoring the likelihood that injection will be limited by the available volume in the aquifer, as indicated in Fig. 1. The smaller the available pore volume, the more wells will be required, and the more the aquifer pressure must be increased in order to sequester the target volume of CO_2.

Figs. 4 and 5 illustrate a fundamental difference between a model with limited aquifer volume and a model for an open aquifer using CMG numerical simulations. With a constant pressure boundary, it is possible to continue injecting CO_2 until CO_2 breakthrough as long as the injection pressure does not exceed the fracture pressure. For the closed reservoir injection must stop at 30 years to avoid exceeding the fracture pressure constraint. For the open reservoir injection can continue much longer, eventually filling more of the pore space with CO_2. Fig. 4 shows the comparison between the bounded and open aquifer cases both in a square drainage area with side 20 mi. The character of the pressure profile is similar for the bounded aquifer, but pressure increases with time throughout the aquifer as indicated by the material balance. Fig. 5 shows the same comparison but with distance in the logarithmic scale. This comparison shows that the single phase and two-phase zone radii expand in a similar way for both cases.

4. Aquifer appraisal

Results in this work provide insight on what will be required to sequester CO_2 from a typical coal power plant. Given aquifer depth, porosity, thickness, permeability, rock compressibility, and relative permeability data along with the brine salinity, the analytical model offers a quick estimate for the required aquifer size for a target total mass of CO_2 to be sequestered. Before starting the sequestration, it will be necessary to confirm the aquifer size through an aquifer appraisal process much like the appraisal work done for oil and gas

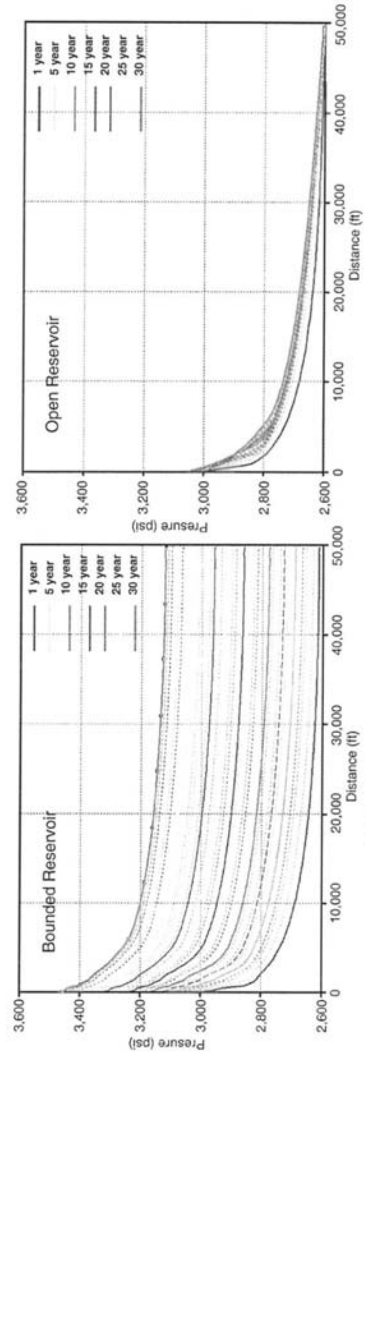

Fig. 4. CMG simulations comparing annual pressure profiles for the bounded and open aquifer cases. Pressure increases with time.

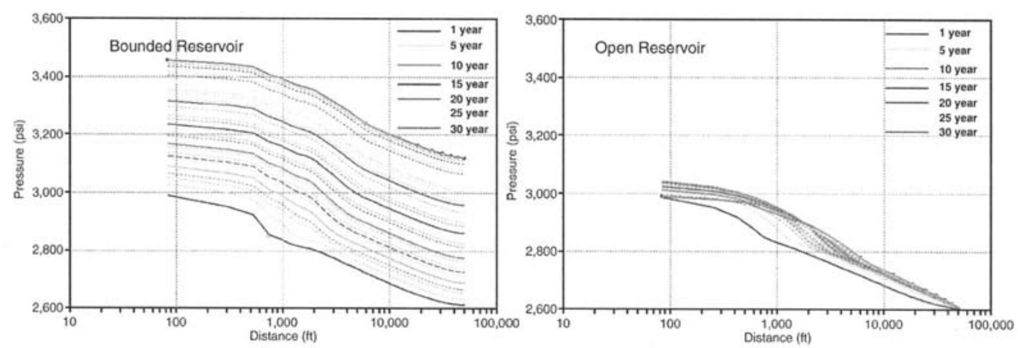

Fig. 5. CMG simulations comparing annual pressure profiles for the bounded and open aquifer cases using logarithmic distance scale that facilitates observation of the expanding single and two-phase zone radii. Pressure increases with time.

reservoirs. However, a conventional pressure buildup or injection falloff test cannot confirm aquifer areal extent of the size required for a sequestration project because the investigation radius, r_i, of a buildup or falloff test is given by

$$r_i = \sqrt{\frac{kt}{948\phi\mu c_t}} \quad (15)$$

for t in hours. For porosity and permeability of 20% and 100 md, and compressibility $6 \cdot 10^{-6}\,psi^{-1}$, it would take a buildup or falloff duration of 3.6 years to detect aquifer limits at a distance of only ten miles. Alternatively, a pressure buildup or falloff test with 1 month duration will only investigate a radius of about 1.5 mi, and not that in reality, because gauge resolution will not be sufficient for such a long time. Additional appraisal wells can be drilled, but it will be difficult to confirm they are in hydraulic communication. Without demonstration of sufficient aquifer areal extent, the project begins with the likely prospect of having to find other aquifers for continued storage of the relentless 79,000 bpd CO_2.

5. Conclusions

The implications of this work are profound. A simple analytical model shows immediate results very similar to those that take hours to produce with numerical simulation. Much more important, the work shows that models that assume a constant pressure outer boundary for reservoirs intended for CO_2 sequestration are missing the critical point that the reservoir pressure will build up under injection at constant rate. Instead of the 1–4% of bulk volume storability factor indicated prominently in the literature, which is based on erroneous steady state modeling, our finding is that CO_2 can occupy no more than 1% of the pore volume and likely as much as 100 times less.

This work has related the volume of the reservoir that would be adequate to store CO_2 with the need to sustain injectivity. The two are intimately connected. In applying this to a commercial power plant the findings suggest that for a small number of wells the areal extent of the reservoir would be enormous, the size of a small US state. Conversely, for more moderate size reservoirs, still the size of Alaska's Prudhoe Bay reservoir, and with moderate permeability there would be a need for hundreds of wells. Neither of these bodes well for geological CO_2 sequestration and the findings of this work clearly suggest that it is not a practical means to provide any substantive reduction in CO_2 emissions, although it has been repeatedly presented as such by others.

Nomenclature

A	areal extent, sq ft
c_t	total compressibility at the end of injection, psi^{-1}
c_{ti}	initial total compressibility, psi^{-1}
E	displacement efficiency factor, dimensionless
G_{CO_2}	CO_2 pore volume, cu ft
h	reservoir thickness, ft
H	depth, ft
k	permeability, md
k_r	relative permeability, dimensionless
p_i	initial reservoir pressure, psi
p_{wi}	bottomhole injection pressure, psi
q	injection rate, STB/d
r_i	pressure transient test radius of investigation, ft
r_w	wellbore radius, ft
s_{CO_2}	storability factor, dimensionless
S_{CO_2}	gas saturation, dimensionless
S_w	water saturation, dimensionless
t	time, h
t_{plant}	duration of CO_2 injection, yr
V_{CO_2}	CO_2 volume to inject, cu ft
V_r	reservoir volume, cu ft

Symbols

ϕ	porosity, dimensionless
μ	viscosity, cp

Acknowledgement

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Mr. HALL. I yield back my time, sir.

Chairman GORDON. Dr. Baird is recognized.

THE PROSPECT OF UNILATERAL GEOENGINEERING

Mr. BAIRD. I thank the Chair. I thank our witnesses. I find this one of the most fascinating things we are dealing with, because you have got as consequential a situation as you can imagine, and a system more complex than anything else on Earth, because it is Earth, and lots of unintended consequence risks.

In just the last week, or this week, I read an article about fertilization of the oceans leading to excessive algal blooms, presumably, and domoic acid. And the question here is, we are doing geoengineering. It is called the CO_2 we are putting into the atmosphere, and the methane, et cetera. And now, we are trying to sort of put that genie back in the bottle.

Let us suppose I am on the Maldive Islands, and I quite fairly and realistically assume that the likelihood of the industrialized world actually cutting CO_2 emissions in a reasonable time is grim, and it is existential for us, and I am going to just do some SRM on our own. You can't hardly fault them. We have done geoengineering in the other direction on our own. What is to prevent that, or even in a James Bond scenario, some rogue rich guy puts some airplanes in the air and seeds the clouds? What is to prevent that? Dr. Morgan, or Dr. Rusco, you please talk about that.

Dr. MORGAN. Nothing to prevent somebody initiating it, but the U.S. Navy can stop the Maldives. The U.S. Navy can't stop, you know, Russia, if it decides that the whole interior of the country has become an impermeable bog, because of the thawing of permafrost, China, because precipitation patterns have changed and they can't feed their people anymore.

So, one of the reasons that we initiated this workshop at the Council on Foreign Relations a couple of years ago was precisely to begin to address the issue of unilateral action of the sort you have described, and I think it remains a serious concern. There is disagreement within the foreign policy community about just how big a concern unilateral activity might be, but the notion that one or a couple of major states might decide to do it, I think, is quite troubling, and given the right circumstances, might be very hard to do much about.

Mr. BAIRD. And a new variation on mutually assured destruction. Yeah, Dr. Barrett.

Dr. BARRETT. It is a great question. I think an important, and actually, there is a scenario I developed in my written testimony about India. That would be much more likely, to be the country to use it. It is only a hypothetical, but still, it is very plausible, given the impact on their population.

Mr. BAIRD. Yes, indeed.

Dr. BARRETT. And the migration that would be forced by it, sure. Yes, indeed. And, but other countries, again, that scenario of graduated climate change. If India had the incentive to want to use geoengineering, other countries would be adversely affected. They, of course, would oppose that move, and you can imagine, first, opposition would be voiced, then other measures might be taken. There might be a development of counter-geoengineering measures, and also, there could be a military strike. It is precisely because of that, actually, I think what you are looking for, and I think what we want in the form of, what I call "rules." Or in terms of a kind of regime on geoengineering, a space in which countries can actually negotiate through their differences.

And I think there will be strong incentives to do that. The countries that are the most capable to act on geoengineering are all nuclear-capable states, and I think the most important thing is that we don't let this whole system rift, but we create the space for negotiation.

Mr. BAIRD. Dr. Long.

Dr. LONG. I would like to add to that that I think that the research program can help to mitigate the situation. The thing that we need to focus on is the creation of international norms and mores that support the same ethical constructs when it comes to deploying geoengineering, and by building that in to an international research program, and beginning to practice those kinds of relationships and norm-building exercises through the research program, I think we can help to mitigate that situation.

THE NATIONAL SECURITY AND GEOPOLITICAL IMPACTS OF CLIMATE CHANGE

Mr. BAIRD. I would really encourage this panel and my colleagues on the other side of the aisle to, I think there is an urgent need for a constructive dialogue with my friends on the other side of the aisle on this, because we spend an inordinate amount of time here, on this committee, unfortunately, debating whether or not this is real, as if the outcome of our debate will somehow impact what happens in the real world.

By that, I mean, as if climate change is going to be stopped if we declare it is not happening. But I think the adverse consequences that you are describing, the profound geopolitical, national security, economic disruption if you get your bet wrong, really has to be discussed. Because if we are at this level of discussion, and when you talk about India, the migratory disruption of coastal sea rises, it is astonishing, and how that affects everything else.

You really have to engage my friends on the other side, who have a good and healthy decent respect for national security and economic issues, to consider this aspect, and we haven't done it enough, and I would invite them to discuss with you folks these implications. Because if we just say well, we are not going to do anything, because climate change is a hoax, as is sometimes said by colleagues, that hoax can have some darn serious consequences if it is not a hoax.

And we just need to speak in the language of my friends on the Republican side, I think, will appreciate, in terms of national security, et cetera, and so, I hope—I am sorry they are not here, but I think it is an avenue that we ought to explore more.

Thank you, Mr. Chairman, for calling this hearing.

Chairman GORDON. Thank you, Dr. Baird. We will be sure to have metal detectors when we get ready to do that discussion.

THE ROLE FOR FEDERAL AGENCIES

Let me conclude here, unless Mr. Hall has some additional suggestions, there have been discussions about federal research. Could, I would ask the panel in general, what different agencies would be the, what agency or agencies would be the appropriate vehicles for this type of research, and we will just start and go down.

Dr. RUSCO. Thank you. We are in the process of engaging all the agencies that might have a role to play in this, and we will be reporting on that soon to the Committee.

Chairman GORDON. Will you speak something like the National Nanotechnology Initiative, where there would be a coordinated effort across a variety of different agencies?

Dr. RUSCO. I think that our past work points to a need for a coordinated effort on anything of this magnitude. There, you want to avoid unnecessary duplicative activities, but you also want to utilize all the many resources and assets that the Federal agencies bring to this sort of an effort. And so, a coordinated effort that looks at the costs and benefits of a national strategy for looking at this sort of research is what is needed.

Chairman GORDON. We are being called for votes, so let me just ask, I would assume everyone concurs with that, unless you have a suggestion of something specific. Otherwise, is there anyone that has anything else? Yes, Dr. Long.

Dr. LONG. In carbon remediation, on the carbon remediation side, we already, as I mentioned, we already run a CCS program that could be easily expanded. EPA should probably be involved in that. On the climate intervention technologies, many of them are related strongly to Climate Science Program, and much of it, particularly the observation network and the ability to predict what is going to happen when you make an intervention, that is, as an expansion of climate science, DOE, NASA, NSF, are all involved, and should be probably involved in that.

Dr. MORGAN. And my testimony speaks specifically to your question, so I won't.

Dr. BARRETT. Briefly. First, I would not have the Department of Defense, and second, I would encourage international collaboration.

Chairman GORDON. And you want to elaborate on why you would not have the Department of Defense participate?

Dr. MORGAN. I think this issue of trust that I ended my testimony on, is extremely important, and I think the moment that, and if our Defense Department can be involved, then so can other countries, and I think there is already enough distrust on a number of issues, including, for example, space, involving different countries.

And I think it could be much better to keep this as an issue that is addressing just the one threat.

Dr. BARRETT. Both of the international workshops reached much that same conclusion.

Dr. LONG. Thank you. And I would take it one step further, which is to say that our national programs should explicitly look at research that would enhance the global welfare, rather than the national welfare.

Mr. BAIRD. Mr. Chairman.

Chairman GORDON. Dr. Baird is recognized.

Mr. BAIRD. Would you not, however, think it is beneficial for the Department of Defense to at least inform the debate by this body about the consequences if we fail to address this? They may not be involved in structuring the global regulatory environment, but they certainly ought to be involved in gaming out the consequences for their responsibilities. Would that make sense?

Dr. BARRETT. I think they already are, in terms of what would happen, in terms of migration of peoples and that sort of thing.

Mr. BAIRD. They certainly are. Just—that point I made earlier. I want——

Dr. BARRETT. You give some credibility.

Chairman GORDON. As I said, we, our votes are on their way right now, so let me thank all of our witnesses for being here today. The record will remain open for two weeks for additional statements from Members, and for answers to any follow-up questions this committee may ask the witnesses.

Once again, I appreciate you giving you information to this pioneering body of information, that I think will be beneficial for generations to come.

And this hearing is concluded, and the witnesses are excused.

[Whereupon, at 1:23 p.m., the Committee was adjourned.]

Appendix 1:

Answers to Post-Hearing Questions

ANSWERS TO POST-HEARING QUESTIONS

Responses by Frank Rusco, Director of Natural Resources and Environment, Government Accountability Office (GAO)

Questions submitted by Chairman Bart Gordon

Q1. Geoengineering is an emerging field, and as such, it does not have a standard, widely agreed upon definition.

Q1,1a. How is geoengineering being defined today?

A1,1a. Our work to date indicates that scientists, policy experts, and major research bodies have not yet agreed on the definition of geoengineering. Our testimony uses the relatively broad definition of geoengineering—deliberate large-scale interventions to diminish climate change and its impacts—used by the United Kingdom's Royal Society in its September 2009 geoengineering report, which classified geoengineering approaches into two major categories: solar radiation management (SRM) and carbon dioxide removal (CDR).[1] The National Academy of Sciences used a similarly broad definition of geoengineering in its 1992 report on the policy implications of greenhouse warming.[2] However, some policy experts have published articles that apply a relatively narrow definition of geoengineering that only includes SRM approaches. Most recently, the scientific organizing committee of the March 2010 Asilomar International Conference on Climate Intervention Technologies released a statement reclassifying geoengineering approaches into two groups—climate intervention methods (SRM) and climate remediation methods (CDR).

Q1,1b. Discuss the pros and eons of the existing definitions.

A1,1b. We have not formally evaluated the advantages and disadvantages of the existing definitions for geoengineering as part of our work to date and, as a result, do not have an opinion on this issue. However, as we have testified, the experts we spoke with stated that there are different policy implications associated with pursuing SRM compared to most CDR approaches. Consequently, the definition policymakers chose when deciding whether to pursue geoengineering as part of a broader response to climate change would affect which policy issues and research needs a federal geoengineering strategy would have to address. For instance, we testified that some experts consider certain SRM approaches to be relatively inexpensive to implement and generally hold greater potential for causing uneven environmental impacts-such as changes in precipitation beyond national or regional boundaries. Thus, these approaches risk undesirable economic, ethical, legal, and political implications that would need to be addressed prior to deploying any of these technologies. In contrast, some experts noted that most CDR approaches-with the exception of ocean-based strategies such as fertilization-would have limited impacts across national boundaries and could, therefore, mostly involve discussions with domestic stakeholders.[3]

Q1,1c. Lastly, how should geoengineering be defined going forward?

A1,1c. Because we have not formally evaluated the pros and cons of different definitions, we do not have a position on the appropriate definition for geoengineering. However, other scientific and policy organizations will be providing their perspectives on geoengineering later this year, which may provide additional insight on this issue. For example, the National Academy of Sciences will be including geoengineering as part of its America's Climate Choices review for the Congress, which is scheduled for release this year. Additionally, the National Commission on Energy Policy has indicated that it has plans to explore the definition of geoengineering as part of its project due later this year. Finally, the scientific organizing committee of the Asilomar International Conference on Climate Intervention Technologies expects to issue a report this year on the conference's proceedings, which may include potential geoengineering research principles based on the discussions among participating scientific and policy experts.

[1] The Royal Society, *Geoengineering and the climate: science, governance and uncertainty* (London: September 2009).

[2] National Academy of Sciences, *Policy Implications of Greenhouse Warming: Mitgadon, Adaptation, and the Science Base* (Washington, D.C.: 1992).

[3] As we testified, the Royal Society noted that large-scale deployment of some CDR approaches such as widespread afforestation—planting of forests on lands that historically have not been forested—or methods requiring substantial mineral extraction—including land or ocean-based enhanced weathering-may have unintended and significant impacts within and beyond national borders.

Q2. Which federal research agencies or programs, as well as which nonfederal institutions, such as universities, have the capacity to contribute to potential geoengineering research programs?

A2. We have not specifically examined the capacity of federal agencies, programs, and universities to contribute to geoengineering research. However, we testified that some federal agencies, such as the Department of Energy, the National Science Foundation, and the National Aeronautics and Space Administration, among others, have already sponsored or conducted some research related to geoengineering. Furthermore, as we testified, federal officials stated that ongoing federal research and observations on basic climate change and earth science conducted by, for example, agencies participating in the U.S. Global Change Research Program (USGCRP), could be relevant to improving understanding about proposed geoengineering approaches and their potential impacts. Additionally, our interviews with experts to date indicate that a federal geoengineering research program should be an interdisciplinary effort across multiple agencies, although experts differed as to which agencies should be involved in such a program. We plan to provide further information on existing federal geoengineering efforts in our report to be issued later this year.

Q3. Which agencies or programs should not be involved? Why?

A3. We do not have a position on which agencies should or should not be involved in a federal geoengineering research program. As indicated in our response to question 1b; how narrowly or broadly geoengineering is defined could have implications for the design of a federal research program and for the decision on which agencies would participate.

Questions submitted by Representative Ralph M. Hall

Q1. There are several basic questions, about the governance of geoengineering that need to be explored before delving into this research. On the international side:

Q1,1a. If we were to enter into an international agreement to explore cooperative research efforts into geoengineering, which countries would necessarily need to be included?

A1,1a. This is an important question and is worthy of study. However, an analysis of which countries would need to be included in an international agreement to explore geoengineering research is beyond the scope of our ongoing work.

Q1,1b. Do you envision such an agreement facing resistance similar to previous attempts at global agreements addressing climate change?

A1,1b. We have not examined whether an international agreement to explore cooperative research would face resistance similar to previous climate change agreements. However, in our testimony we noted that legal experts we interviewed agreed that the governance of geoengineering research should be separated from the governance of deployment. These legal experts agreed that some type of regulation for geoengineering field experiments was necessary, but they differed on whether there should be a comprehensive international governance regime under the auspices of a treaty such as the United Nations Framework Convention on Climate Change, or whether other existing international agreements could be adapted and used to address specific geoengineering approaches that fall within their purview. Regarding deployment, we testified that some scientific and policy experts we interviewed noted that establishing a governance regime over geoengineering deployment for certain approaches may be as challenging as achieving international consensus on carbon mitigation strategies. This issue is challenging because of questions about whether deployment is warranted, how to determine an appropriate new environmental equilibrium, and what compensation should be offered for adverse impacts, among other issues.

Q1,1c. Should we be looking at this issue as a national security problem, not unlike a rogue state or terrorist group that releases a biological, chemical or nuclear weapon on some unsuspecting populace?

A1,1c. We do not have a position on whether the Congress should be looking at geoengineering as a national security problem. However, we testified that, according to the experts we spoke with, the potential uneven distribution of environmental and economic impacts associated with some geoengineering approaches, particularly SRM, may create relative winners and losers which would sow conflict among nations. As we also testified, several experts we spoke with stated that since some

SRM approaches are considered to be relatively inexpensive to implement, one nation, group, or individual could decide to unilaterally deploy one of these technologies. These experts stated that it is important to begin studying how the United States or the international community might respond to the unilateral deployment of a SRM technology that resulted in gains for some nations and losses for others.

Q1,1d. Could the actions of a lone "climate savior" have global effects that would rise to this level of concern? Or is the technology really not in place where this is an issue now? Should we be discussing it for the future?

A1,1d. As we noted in our response to your question 1c, we testified that some SRM approaches would be relatively inexpensive to implement and that a nation, group, or individual could decide to unilaterally deploy one of these technologies. Additionally, some experts we spoke with said that it would be possible to deploy some form of SRM, such as stratospheric aerosol injection, using current technology. Furthermore, as we testified, several experts stated that it is important to begin studying how the United States or the international community might respond to the unilateral deployment of a SRM technology that resulted in gains for some nations and losses for others.

On the domestic side:

Q1,1e. There are several existing federal laws that could cover some, but not all, aspects of geoengineering. What are the specific gaps in the domestic federal framework that would be needed for us to move forward with this? How much would such a regulatory structure cost to implement?

A1,1e. In our statement, we identified several domestic regulatory gaps. For instance, while EPA plans to issue a final rule governing underground injection of carbon dioxide for geological sequestration under the Safe Drinking Water Act, EPA officials noted that this rulemaking was not intended to resolve questions concerning how other environmental statutes might apply to injected carbon dioxide. Additionally, EPA officials noted that while the agency has the authority to regulate some ocean fertilization activities under the Marine Protection, Research and Sanctuaries Act of 1972, the law only applied under certain conditions. Consequently, a domestic company could conduct ocean fertilization—introducing nutrients to promote phytoplankton growth and enhance biological storage of carbon—outside of EPA's regulatory jurisdiction and control if, for example, the company's fertilization activities took place outside U.S. territorial waters, which extend 12 miles from the shoreline or coastal baseline, from a foreign-registered ship that embarked from a foreign port.

We will continue our work related to the views federal officials and experts have on how existing domestic laws and international agreements may apply to geoengineering. We expect to include additional detail on these issues in our final report to be completed later this year. While the costs for implementing a regulatory structure for geoengineering is certainly an important consideration for any future policy development and is worthy of study, such an analysis is beyond the scope of our current effort.

Q1,1f. Would the decision to deploy such a technology be appropriate for government only? Or, if there is private sector investment and work in this area, should they have a say in the decision? Are there any safeguards for the private sector to prevent the government from deploying such a technology?

A1,1f. We do not have a position on the level of involvement that the private sector should have in the decision to deploy any geoengineering approach, and this issue is beyond the scope of our work to date. Similarly, we have not examined the private sector's ability to prevent the government's deployment of a given geoengineering technology, and we will not be addressing this issue in our final report.

Q1,1g. Would the domestic decision to deploy a geoengineering technology be similar to the Presidential decision-making power to use nuclear weapons? Or, would this type of deployment benefit from the input of the Congressional and Judicial branches of government?

A1,1g. We have not studied the dynamics of federal decision-making concerning the deployment of any geoengineering technology and doing so is beyond the scope of our ongoing work.

Q1,1h. If we were to deploy such a technology, and it did not work as expected, where would the liability for the unintended consequences lie? With those who developed the technology, or with those who decided to use it?

A1,1h. Liability for unintended consequences from geoengineering is an important and complex governance issue that would require a detailed analysis. Specifically, the Royal Society report on geoengineering identified liability as a key governance issue that should be evaluated prior to any large-scale experimentation or implementation of a particular geoengineering approach.[4] Additionally, our prior work on carbon capture and storage discussed stakeholder concerns regarding liability for stored carbon dioxide in underground formations, which could be relevant to some CDR approaches.[5] Although conducting a detailed analysis of liability issues is beyond the scope of our ongoing work, we expect to provide some context for this issue in our final report based on our review of relevant literature.

Q2. Several months ago, a paper was published in the Journal of Petroleum Science and Engineering titled, "Sequestering carbon dioxide in a close underground volume." The authors of this study, Christine Ehlig-Economides and Michael J. Economides, suggest that "underground carbon dioxide sequestration via bulk CO_2 injection is not feasible at any cost," since the CO_2 would require up to 500 times more space underground than the carbon did when it was bound as coal, oil or natural gas.

Q2,2a. If this hypothesis is correct, how would this affect your estimation on the feasibility of geoengineering as a viable option from a technological and a cost effectiveness point of view?

A2,2a. We have not evaluated the feasibility of geoengineering approaches from a technological or cost-effectiveness perspective as part of our work to date. As we testified, substantial uncertainties remain regarding the efficacy and potential environmental effects of proposed geoengineering approaches, and additional research would be needed before a proper assessment of feasibility or cost effectiveness could be conducted However, should the government choose to move forward with geoengineering research, we have reported that a comprehensive assessment of costs and benefits that includes all relevant risks and uncertainties is a key component in strategic planning for technology-based research programs. We do not expect to report on the feasibility or cost-effectiveness of the various technological options for geoengineering as part of our final report. However, we are conducting a geoengineering technology assessment for the Committee, which will address technological feasibility in greater detail.

Q2b. How would such a hypothesis alter the debate that is currently ongoing about the need to mitigate climate change through reducing emissions?

A2b. We have not evaluated how such a hypothesis might alter the debate that is ongoing about the need to mitigate climate change through reducing emissions as part of our work to date, and this is beyond the scope of our ongoing work.

Q3. During your research into this topic, were there any discussions surrounding liability? For example, if one nation were to act using a stratospheric aerosol method, and several nations gained from the resultant "cooling", what if there were unintended negative impacts. Could each nation be liable in some way, or just the one nation taking the action? How would the liability or remediation be shared?

A3. See our response to your question 1h, above.

Q4. In your testimony, you list several Executive Branch agencies that currently enforce laws that would partially cover geoengineering research and deployment. The Environmental Protection Agency is the primary agency. Would you advocate that EPA take the primary role in developing a federal regulatory structure for the research and deployment of geoengineering technologies? Are they the most qualified? Are there any other areas of research like this in which EPA, which is first and foremost a regulatory and not a research agency, takes the lead Federal role?

A4. We do not have a position on whether EPA should take the primary role, or whether EPA is the most qualified agency to develop a federal regulatory structure for geoengineering research and deployment. Additionally, we have not examined whether there are other research areas where EPA has taken the lead federal role as part of our work to date. However, as we testified, while staff from federal offices coordinating the U.S. response to climate change—the President's Council on Envi-

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[4] The Royal Society, *Geoengineering arid the climate: science, governance and uncertainty.*

[5] GAO, Climate Change: Federal Actions Will GreatlyAffect the Viability of Carbon Capture and Storage as a Key Mitigation Option, GAO–08–1080 (Washington, D. C.: Sept. 30, 2008).

ronmental Quality (CEQ), the Office of Science and Technology Policy (OTSP), and the USGCRP—stated that they do not currently have a geoengineering strategy or position, several experts we interviewed stated that geoengineering research should be led by a multiagency coordinating body, such as OSTP or USGCRP. Furthermore, we testified that the White House recently established an interagency task force on carbon capture and storage (CCS)—which will report to CEQ—to propose a plan to overcome the barriers to widespread CCS deployment, and that the plan will address, among other issues, legal barriers to deployment and identify areas where additional statutory authority may be necessary. This task force was not specifically established to address regulatory barriers for geoengineering approaches; however, the legal and regulatory issues surrounding underground storage of carbon dioxide could apply to some CDR approaches. Additionally, we will continue to collect federal officials' and experts' views related to how existing domestic laws and international agreements are being applied to geoengineering and expect to include further detail on these issues in our final report.

ANSWERS TO POST-HEARING QUESTIONS

Responses by Scott Barrett, Lenfest Professor of Natural Resource Economics, School of International and Public Affairs and the Earth Institute at Columbia University

Questions submitted by Chairman Bart Gordon

Q1. How is geoengineering being defined today? Discuss pros and cons of existing definitions. How should geoengineering be defined going forward?

A1. There is no standard definition today. I think this is not important. It is, however, important that people define the term before using it.

In my opinion, the best definition is the one given in my written testimony; actions taken deliberately to alter the temperature without changing the atmospheric concentration of greenhouse gases. Importantly, by this definition, "solar radiation management" is geoengineering. "Carbon Dioxide Removal" is not. These two approaches really need to be distinguished because they are very different The former can act quickly, but does not address the problem fundamentally. The latter addresses the problem fundamentally, but is slow and expensive.

As our understanding of the technological possibilities improves, we'll start to focus on particular ideas. My guess is that, by the time we deploy geoengineering, should that time ever come, we will use a different approach from the ones being discussed today. It is because of this that I focused my written testimony on "geoengineering" as a generic intervention.

Q2. Which Federal agencies, as well as non-Federal institutions, have capacity to contribute to geoengineering research? Which should not be involved?

A2. I think the most important thing is that any research be done in the context of an international framework. The reason is that, if we are thinking of possibly doing geoengineering research, other countries will be thinking the same thing. Given the implications of deploying geoengineering, and the problem in distinguishing research from deployment, it is best that this be done under a governance arrangement.

For similar reasons, I think it would be best for research to be done in a collaborative way with other countries. It is essential that this process build trust.

We should not only do research on geoengineering itself but on the consequences of deployment—for agriculture, terrestrial ecosystems, the oceans, and so on, and for other countries and parts of the world as well as for the United States.

Many agencies and non-federal institutions could play a part. I think it is important that the Department of Defense not undertake research into geoengineering. If this technology is ever to be used, it must be used for peaceful purposes, and our research initiatives must make that pledge credible.

Questions submitted by Representative Ralph M. Hall

Q1. There are several basic questions about the governance of geoengineering that need to be explored before delving into this research. On the international side:

a. If we were to enter into an international agreement to explore cooperative research efforts into geoengineering, which countries would need to be included?

b. Do you envision such an agreement facing resistance similar to previous attempts at global agreements addressing climate change?

c. How would a global partnership be structured?

d. Would certain countries be required to provide more resources than others? If a country provided more resources, would they have more decision-making authority or more input?

e. Should we be looking at this issue as a national security problem, not unlike a rogue state or terrorist group that releases a biological, chemical or nuclear weapon on some unsuspecting populace?

f. Could the actions of a lone"climate savior" have global effects that would rise to this level of concern? Or is the technology really not in a place where this is an issue now? Should we be discussing it for the future?

On the domestic side:

g. Would the decision to deploy such a technology be appropriate for government only? Or, if there is private sector investment and work in this area, should *they have a say in the decision? Are there any safeguards for the private sector to prevent the government from deploying such a technology?*

h. *If we were to deploy such a technology; and it did not work as expected, where would the liability for the unintended consequences lie? With those who developed the technology, or with those who decided to use it?*

A1. Governance-note that, unless stated otherwise, I am taking "geoengineering" here to mean actions taken deliberately to alter the temperature without changing the atmospheric concentration of greenhouse gases. This creates a novel challenge for governance. "Air capture" and storage of carbon dioxide is also important, and addressed below, but this technology poses a very different challenge for governance.

International

a. Since every country will be affected by the deployment of geoengineering, and since research would be undertaken with a view, possibly, to deployment, the international governance arrangements should be open to all countries. My view is that these arrangements should be expressed as a protocol under the Framework Convention on Climate Change, in which case participation would be open to every country that is a party to this Convention (virtually every country in the world is already a party to this agreement). Note that the Framework Convention should be revised to stress the importance of reducing risks. Note also that countries may also wish to negotiate collaborative agreements about specific research initiatives. These would only need to involve the participation of the states involved—perhaps a small number of states. The important thing is that these "minilateral" agreements on research be undertaken in accordance with the very broad governance arrangement noted above.

b. I do not believe that there will be resistance to negotiating such a protocol. Getting countries to reduce emissions is the hardest of all global collective action problems, and so we shouldn't be surprised that we have found this difficult to do. Getting countries to agree on basic rules for geoengineering governance is very different. International negotiations are never easy, but these negotiations will be *easier* than negotiations on limiting emissions.

c. I would recommend that the protocol aim to spell out very broad principles. The focus should be on what countries can agree on rather than on what they cannot agree on. These, I think, should be the main points: (1) that the protocol be open to every party to the Framework Convention to sign and ratify; (2) that the agreement enter into force after being ratified by a substantial number of countries, including a significant number of "geoengineering-capable" states; (3) that every party be obligated to inform all other parties of an intention to deploy geoengineering, including any "field testing"; (4) that deployment be undertaken for peaceful purposes and for purposes that contribute to meeting the objectives of the Convention (which, as I mentioned above, should be revised to stress the importance of reducing risk); (5) that every party be obligated to cooperate to resolve any possible conflicts; (6) that agreements to resolve conflict be made as far as possible by consensus; and (7) that R&D be done openly, and preferably collaboratively, and subject to monitoring/verification. Transparency builds trust.

d. As noted above, agreements to collaborate in doing R&D may involve a small number of states. There are many ways to share the burden of financing. We have many precedents, such as the ITER project, CERN, and the International Space Station. A very simple way to allocate this burden is by reference to the UN scale of assessments. As regards decision-making authority, the agreement should be under the protocol I noted above, which sets the parameters, as it were, for international governance. Subject to this, the principle that is almost certain to be applied is "no representation without taxation."

e. I think the deployment of geoengineering outside of the international framework noted above would be perceived as constituting a possible threat to the security-of other states. Geoengineering should only be undertaken for peaceful purposes, and by agreement-by consensus as far as possible.

f. Any geoengineering undertaken outside of the international framework noted above should be discouraged, and considered as lacking international legitimacy. Any such effort would thus be vulnerable to intervention, discouraging investment in the first place.

Domestic:

g. Under the above international framework, the state deploying geoengineering would be responsible for its consequences, whether that deployment were done by the government or another entity under its control (as in within its territory).

Whether the private sector were involved or had any say would be up to individual states, but the state deploying geoengineering would be responsible for the consequences, under the international framework outlined above. Any safeguards for the private sector would need to be provided by domestic law.

h. Liability would be extremely difficult to determine, which is why it is essential that the decision to deploy be based on consensus insofar as possible. Domestically, risk sharing would likely be a public decision (much like third party liability for nuclear power accidents).

Q2. Several months ago, a paper was published in the Journal of Petroleum Science and Engineering titled,"Sequestering carbon dioxide in a close underground volume" The authors of this study, Christine Ehlig-Economides and Michael J. Economides suggest that "underground carbon dioxide sequestration via bulk CO_2 injection is not feasible at any cost," since the CO_2 *would require up to 500 times more space underground than the carbon did when it was bound as coal, oil or natural gas. (Could we please enter the journal article into the record?)*

a. If this hypothesis is correct, how would this affect your estimation on the feasibility of geoengineering as a viable option from a technological and a cost effectiveness point of view?

b. How would such a hypothesis alter the debate that is currently ongoing about the need to mitigate climate change through reducing emissions?

A2a. There will be physical limits to storage of CO_2 in geologic deposits, in the oceans, and in silicate rock. Depending on the policy being contemplated, these limits may not matter. The cost of direct carbon dioxide removal from the air is very high, and so I think this technology is most likely to be used only if the threat of abrupt and catastrophic climate change appeared very great (carbon capture and storage from the power plant is less costly). I do think this is a very important technology. It is the only true "backstop" technology we have for reducing emissions. It would be a very good technology to have were geoengineering in the form of "solar radiation management" to be tried and found to have serious and undesirable consequences.

A2b. This is an illustration of why we need more research. This finding, if supported by further analysis, would vastly strengthen the case for reducing emissions by means other than underground storage.

Q3. Is it possible that a steep decline in greenhouse gas (GHG) emissions may well cost more than the perceived value of its benefits?

A3. All economic analyses of climate change that I am aware of find that the benefits of reducing greenhouse gas emissions a little vastly exceed the cost. Some studies support steeper reductions. A few commend very substantial reductions immediately. The different conclusions depend on many things, but two factors are crucial. The first is the rate of discount, since the benefits of reducing emissions will be realized decades after the costs have been incurred. The second is the prospect of catastrophic consequences from not reducing emissions. My view is that the second factor is ultimately the most important, and that the prospect of very serious consequences will only grow over time and at an accelerated rate as we do less to limit emissions now. I know of no economic analysis that suggests we should not be developing a substantial, serious, global effort to reduce greenhouse gas emissions.

Q4. In your testimony, you list five things that we should do to mitigate anthropogenic climate change. You state that research into geoengineering should be the last option.

a. Does this mean that you think our research dollars would be betterspent on energy efficiency or renewable energy research?

b. Is there a way to really calculate a return on investment when itcomes to geoengineering?

Aa. We should not put all of our research dollars in one basket. We should spread this money around, so that the returns in every category are roughly equal at the margin. I think the greatest priority today should be to invest in research that can allow us to reduce emissions at lower cost. But we should also spend research dollars on adaptation technologies, direct carbon capture removal and storage, and solar radiation management.

b. As noted above, we need to balance our investments so that they offer a near-equal return at the margin. A convenient way to think of this is to ask which technologies would be deployed were carbon priced at the "social cost of carbon." This concept derives a cost per ton of carbon dioxide by taking into account the effect of emissions on concentrations, concentrations on radiative forcing, radiative forcing on temperature, and temperature on "damages." In the case of "solar radiation management" we cannot make a direct comparison with emission reductions, because SRM would affect temperature via a different mechanism, because it would entail new risks, and because it would not address related environmental problems like ocean acidification. But, in principle, a return can be calculated.

Q5. In previous hearings, we have heard from witnesses that the technologies required to achieve sufficient mitigation action are available and affordable right now.

a. Do you think this is an accurate statement? If so, would you please comment on what those technologies are?

b. Would you consider carbon capture and sequestration technologies available and affordable?

c. Would you consider the installation and use of such technologies available and affordable?

Aa. The technologies required to reduce emissions substantially certainly exist. We could simply shut down all our coal-fired power plants, turn off our natural gas transmission lines, and close every gasoline station. This is feasible. But it's not desirable; it would be too harmful to welfare, given our understanding of the benefit of reducing emissions. So we need to take less drastic measures. We need to conserve energy; we need to reduce emissions per unit of energy; we need to invest more in renewable energy technologies and nuclear power. And we need to invest in complementary technologies for storage and transmission and in R&D to develop new technologies that will allow us to reduce emissions more cheaply in the future.

b. Carbon capture and sequestration is already being done, so this technology is available. However, it is not being done at the scale of a power plant and in the range of environments needed to demonstrate its effectiveness, safety, and cost around the world. This is why more research and development must be spent on pilot projects. Whether this technology is affordable depends on whether we think climate change is a risk worth making sacrifices to avoid. A different way to think about R&D is whether we would like the option to use this technology at some point in the future, and want to find out now whether it works, and whether its operation is efficient and safe. In my view, this should be a top priority for R&D funding.

c. Again, we need to establish a number of such stations around the world, just to demonstrate its effectiveness, safety, and cost. This should be our first priority. We should be doing this now. There is no reason for delay. After we learn from these projects, we'll know if we should encourage or even mandate use of this technology. Based on the engineering cost estimates developed so far, it is likely that economics will favor deployment of this technology (in conjunction with many other efforts) in the very near future. But, again, let's build and operate the pilot plants first. Our efforts to address this great challenge will need to unfold over a very long period of time, but it is long past time to get started.

ANSWERS TO POST-HEARING QUESTIONS

Responses by Jane Long, Deputy Principal Associate Director at Large and Fellow, Center for Global Strategic Research, Lawrence Livermore National Lab

Questions submitted by Chairman Bart Gordon

Q1. Geoengineering is an emerging field, and as such, it does not have a standard, widely agreed upon definition.

a. How is geoengineering being defined today?

b. Discuss the pros and cons of the existing definitions.

c. Lastly, how should geoengineering be defined going forward?

A1. Geoengineering has been defined in several reports as intentional intervention in the climate. However the term itself carries an implication that we know enough to design a modification and implement it, i.e. to "engineer" the geosphere. The term is also used as an umbrella for at least two if not three entirely different types of technology—carbon dioxide removal, solar radiation management and a catch all category for things we largely haven't thought of yet. These categories are different in goal, cost, speed of action and risk. They have little in common except they are all responses to climate conditions we determine are dangerous.

Unfortunately, the term geoengineering has stuck and is probably not easy to lose at this point. What we could do is use better terms for the various categories and make it clear which we are talking about. I suggest we talk about (at least) two categories and call them:

- **Climate remediation:** The act of removing greenhouse gases from the atmosphere and storing them somewhere else such as deep underground.
- **Climate intervention:** The intentional modification of the climate to counteract climate forcing caused anthropogenic emission of greenhouse gases.

Q2. Which Federal research agencies or programs, as well as which non-Federal institutions such as universities, have the capacity to contribute to potential geoengineering research programs?

a. Which agencies or programs should not be involved? Why?

A2. Any institution which is currently doing research in climate science can probably contribute to climate intervention research at some level. The U.S. Global Change program includes thirteen agencies that contribute to data collection and assimilation, modeling and evaluation *(http://www.globalchange.gov/)*. The agencies cooperate in this program and have formed a number of interagency working groups all of which have some application to climate intervention:

- Atmospheric Composition
- Climate Variability and Change
- Communications
- Ecosystems
- Global Carbon Cycle
- Global Water Cycle
- Human Contributions and Responses
- International Research and Coo aeration
- Land Use and Land Cover Change
- Observationsand Monitoring

Some of the major challenges in with climate science are also key to understanding how climate intervention might work. For example, the role of aerosols and clouds are difficult to get right in climate models and are the subject of major research efforts in climate science. These issues correspond exactly the two most prominent ideas for climate intervention: SRM and cloud brightening. So the university and lab research programs that address aerosols and clouds are the right place to start in developing a climate intervention program.

That said, there is a need for much different kinds of research than is currently being carried out. For example, any significant climate intervention research will be controversial and it is best that the entire research process—from the call for proposals to the actual implementation of the research—involve governance, public engagement and international collaboration. The existing research in climate science is not conducted with a need for governance and public engagement although it does involve extensive international collaboration. Most likely, a research program in climate intervention will have to build a new administrative structure to handle this problem and it is not obvious where best to place this activity.

Likewise, any institution doing work in CCS can probably contribute to climate remediation research. For example, DOE's Fossil Energy program conducts work in the capture of CO_2 from flue gas. It would make sense to expand this program to include air capture work.

We will need international collaboration should we ever decide we need to deploy geoengineering. There fore, it would be wise to frame a geoengineering research program as an international effort with collaboration and transparency at its heart. If a U.S. geoengineering research is viewed as a national defense program, it will send a message to the international community that is most likely to interfere with future collaboration. As such, basing this program in the Department of Defense would be unwise.

Q3. Explain the term "adaptive management" and discuss how it could be used with climate change and geoengineering research.

a. What are the advantages and disadvantages of an adaptive management approach to research?

b. Why is adaptive management not being more fully utilized today in federal research projects in these and other research areas?

A3. Adaptive management is a way to run a project when the system you are managing is very complex and you are not sure you can control the outcomes of your management choices. (The alternative to adaptive management would he to make a choice and stick to it no matter what happens.) When we conduct a climate intervention experiment, we will be perturbing a very complex, dynamic climate system and we will not be able to predict the outcome of our interventions with complete certainty. So, it will be wise to observe the results of the intervention and, if things are not going the way we hoped they would, respond with a new decision about what to do. This is a fairly simple and obvious idea, but it is difficult to do in practice.

Imagine how difficult it will be to make a decision to an intervention in the climate by, for example, injecting aerosols into the stratosphere. But for the sake of argument, imagine that we somehow do make that decision and some years later we see little effect on temperature or perhaps it becomes extremely cold or we see abnormal and destructive weather patterns. It is fairly obvious that we should not ignore this data. We should re-evaluate the decision. Maybe we should decrease the injections, maybe we should increase them. Maybe we should counter the bad effects with some other action. These will be very difficult decisions for two major reasons. First, we will not be sure that the negative effects are actually caused by our interventions. They could just be normal climate variability and it will be hard to tell the difference. Second, if we had political trouble making a decision to act, imagine how difficult it will be to change direction.

The ability to relate cause (climate intervention) and effect (a change in the climate) should be a major part of a geoengineering research program. If we are not able to determine whether the actions we have taken are causing a change in the climate, then we are flying blind with a lot at risk. Secondly, we need to social science research on the institutional structure for making adaptive

decisions. For example, adaptively managed projects work best when there is an *a priori* agreement to re-evaluate management choices on a regular prescribed schedule in prescribed process. Research should focus on how best to structure this process.

Questions submitted by Representative Ralph M. Hall

Q1. There are several basic questions about the governance of geoengineering that need to be explored before delving into this research. On the international side:

a. If we were to enter into an international agreement to explore cooperative research efforts into geoengineering, which countries would necessarily need to be included?

b. Do you envision such an agreement facing resistance similar to previous attempts at global agreements addressing climate change?

c. How would a global partnership be structured?

d. Would certain countries be required to provide more resources than others? If a country provided more resources, would they have more decision-making authority or more input?

e. Should we be looking at this issue as a national security problem; not unlike a rogue state or terrorist group that releases a biological chemical or nuclear weapon on some unsuspecting populace?

f. Could the actions of a lone "climate savior" have global effects, that would rise to this level of concern? Or is the technology really not in a place where this is an issue now? Should we be discussing it for the future?

On the domestic side:

g. There are several existing federal laws that could cover some, but not all, aspects of geoengineering. What are the specific gaps in the domestic federal framework that would be needed for us to move forward with this? How much would such a regulatory structure cost to implement?

h. Would the decision to deploy such a technology be appropriate for government only? Or, if there is private sector investment and work in this area, should they have a say in the decision? Are there any safeguards for the private sector to prevent the government from deploying such a technology?

i. Would the domestic decision to deploy a geoengineering technology be similar to the Presidential decision-making power to use nuclear weapons? Or, would this type of deployment benefit from the input of the Congressional and judicial branches of government?

j. If we were to deploy such a technology, and it did not work as expected, where would the liability for the unintended consequences lie? With those who developed the technology, or with those who decided to use it?

Aa. It may be possible to group countries into different categories and involve each category in a different way. At one end of the spectrum, there will be a small number of countries that will have geoengineering research programs (U.K. may be an example). With these countries we should have strong collaboration. Other countries may have scientists involved in our projects. Any country should be able to observe the research and know what we are doing.

b. The dynamics of international agreements for climate intervention may be quite different than for mitigation. It is quite difficult for single countries to commit to mitigation measures on their own. The dynamics of international negotiations on mitigation focus on trying to get everyone to mitigate at the same time. In contrast, international agreements on climate intervention should act to prevent a single country or non-state actor from making a climate intervention on their own and build relationships and institutions that will help us make appropriate global decisions in the future.

c. Global partnerships in research could be structured to share observational obligations, conduct model intercomparisons and conduct collaborative experiments. As well, other agreements might include agreements for consultation, the right to observe and receive research results, and participation in governance exercises.

d. For the case of climate intervention, the costs are quite likely minimal. Thus the use of economic contribution as way to determine who gets to say what is done seems irrelevant. In the case of climate remediation, the negotiation is quite similar to mitigation. The costs are relatively high and everyone benefits from deployment. Thus the framework for, and dynamics of international agreements on climate remediation might be quite similar to the framework and dynamics of mitigation.

e. I do not think that terrorism or rogue state actors are a good analogy for this problem. This is a new international problem and deserves its own careful analysis. What would happen if a single country or group of countries decides that they should act? What would happen if we think we should act? I do not think there is a perfect analogue for this situation in history. The likely motivations are quite different than terrorism and the ability to act is different.

f. I see little danger of an actor perpetrating an effective climate intervention in the immediate future. There are still technical issues to solve and the risks of using intervention today are much greater than the problems we are currently experiencing in the current climate. In the future, if the climate deteriorates and countries become desperate, it could become an issue.

g. We do not have in place a system to govern geoengineering research. This should involve the development of governing principles, public engagement and a process and structure for adaptive management of large field experiments. The costs associated with developing these are probably not large. The difficulty is that we have no historical model that fits this issue, Consequently we need to work hard to develop a thoughtful approach to governance, public engagement and the principles we wish to act under. I think a good approach would be to develop some experiments in research governance and public engagement to evaluate the best course of action.

h. Public sector involvement makes a lot of sense for climate remediation technologies. We can use the power of innovation in the market to develop faster, better, cheaper ways to remove CO_2 from the atmosphere, but only if there is a price for carbon which drives the market to develop this industry. As long as there is no price for carbon, geologic storage of CO_2 could be thought of as a public service, like picking up the garbage. In the case of climate intervention, public sector engagement raises the spector of vested financial interests lobbying for programs that benefit their companies, rather than the future of the Earth. It is my opinion that we should think of all climate intervention technologies—not to mention deployment—as a public good. One idea is to manage climate intervention like a regulated utility. Another might be a non-profit public/private partnership. Public policy research should be part of a geoengineering research program to help illuminate good choices for managing public/private relationships in climate intervention.

i. This question is clearly beyond my expertise, but I don't think there is any perfect analogue for this situation. The questions of who decides, how they decide and when to deploy climate intervention technology is *terra incognito.*

j. My expertise is technical, not legal, but I would agree liability is an issue.

Q2. Several months ago, a paper was published in the journal of Petroleum Science and Engineering titled, "Sequestering carbon dioxide in a close underground volume." The authors of this study, Christine Ehlig Economides and Michael J. Economides suggest that "underground, carbon dioxide sequestration via bulk CO_2-injection is not feasible at any cost," since the CO_2 would require up to 500 times more space underground than the carbon ,did when it was bound as coal, oil or natural gas. (Could we please enter the journal article into the record?)

a. If this hypothesis is correct, how would this affect your estimation on the feasibility of geoengineering as a viable option from a technological and a cost effectiveness point of view?

b. How would such a hypothesis alter the debate that is currently ongoing about the need to mitigate climate change through reducing emissions?

Aa. Evidence to date does not support the hypothesis put forward by Economides and Economides. The actual CO_2 injection cases currently under way do not behave as these authors predict. It is quite likely that their assumptions are not correct. They apparently assume that the reservoirs act like closed systems and the more CO_2 that is injected, the higher the pressure in the reservoir, making it harder and harder to continue to inject CO_2. In practice, the pressure build-ups predicted by Economides and Economides are not observed. The fact that there are four large commercial end-to-end, integrated carbon dioxide capture and facilities currently in operation around disproves the Economides and Economides assertion that carbon dioxide capture and storage cannot work at any price. They have not been observed in pilot projects (e.g., Frio Brine pilot, South Liberty Texas) or in commercial projects (Mississippi's Cranfield project, In Salah in Algeria, or Sleipner in the North Sea). Some reservoirs, for example in the Illinois basin, are thought to be so permeable that pressures may not increase very much at all due to injection. Economides and Economides seem to have an opinion about how CO_2 injection will work that is at odds both with actual data and with a significant number of scientists and engineers involved carbon sequestration. I am aware that scientists in the U.S. and in Europe are working on critiques of the Ehlig-Economides and Economides paper to be submitted to the same journal in which Ehlig-Economides and Economides published. Three useful as yet unpublished analyses of the faults in their paper can be found in JJ Dooley and CL Davidson, 2010. "A Brief Technical Critique of Ehlig-Economides and Economides 2010 'Sequestering Carbon Dioxide in a Closed Underground Volume." "PNNL–19249. Joint Global Change Research Institute, Pacific Northwest National Laboratory, College Park, MD. April 2010, Comments on Economides and Ehlig-Economides, "Sequestering carbon dioxide in a closed underground volume," SPE 124430, Oct. 2009" by the Geologic Carbon Sequestration Program, Lawrence Berkeley National Laboratory, by Oldenburg, Pruess, Birkholzer, and Doughty, Oct. 22, 2009 and finally American Petroleum Institute (API) comments on: Sequestering Carbon Dioxide in a Closed Underground Volume.

b. Whether they are right or wrong, it doesn't change the dire need to mitigate climate change by reducing emissions. It will be very difficult to reduce emissions unless CCS is deployed because it will be difficult to stop generating electricity with coal for some time. CCS is not a solution that will work for ever. It is a way to reduce emissions from coal while alternative energy systems are developed.

Q3. It has been suggested in prior hearings that one of the shortcomings of solar radiation management geoengineering is that it could produce drought in Asia and Africa and threaten the food supply for billions of people. Some scientists have suggested that global climate change could have the same result; others have suggested that it will actually increase agricultural production in some areas of the world.

a. If we were to undertake some type of large-scale geoengineering experiment, how would we be able to differentiate between the effects of global climate change and those from geoengineering and make the necessary modifications to prevent catastrophe?

b. If we were able to differentiate between the effects of global climate change and effects from geoengineering, is it now possible to determine whether a drought is caused by anthropogenic climate change or just natural variability?

A3. These issues were addressed in my written testimony and are abstracted here. A significant issue for geoengineering is to be able to differentiate between the effects of natural climate variability, human induced climate change, and geoengineering induced climate intervention. The science of detection and attribution of human effects on climate has advanced tremendously in the past decades. But the challenge of detecting and attributing changes to intentional, fairly short term interventions has not been met. This must be a focus of research. We cannot now, or perhaps ever, be able to perfectly differentiate various causes from various effects. We can, however, improve our ability to do so.

In the simplest terms, the scientific approach to attribution of human induced climate change—whether through unintentional emissions or intentional climate intervention—is to use climate models to simulate climate behavior in two ways: one with and one without the human activity in question. If the results of the simulations including the human activity clearly match observations better than the results without the activity, then scientists say they have "fingerprinted" the activity as causing a change in the climate. Perhaps the most famous illustration in the International Panel on Climate Change (IPCC) reports shows two sets of multiple model simulations of mean global temperature over the twentieth century, one with and the other without emitted greenhouse gases. On top of this plot, the actual temperature record lines up squarely in the middle of the model results that included greenhouse gas emissions. This plot is a "fingerprint' for human induced warming. Scientists have gone far beyond mean global temperature as a metric for climate change. Temperature profiles in the atmosphere and ocean, the patterns of temperature around the globe and even recently the time of peak stream flow have been used to fingerprint human induced warming.

The science of fingerprinting is becoming more and more sophisticated. Increasingly, scientists are looking at patterns of observations rather than a single number like mean temperature. Patternmatching is a much more robust indicator of causality because it is much harder to explain alternative causality for a geographic or time-series pattern than for a time series of a single parameter. A famous example of this was discerning between global warming caused by emissions versus caused by a change in solar radiation. Solar radiation changes could not account for the observed pattern of cooling of the stratosphere occurring simultaneously with a warming of the troposphere, but this is exactly what models predicted for emission forced climate change. There do exist "killer metrics" like this that tightly constrain the possible causes of climate observations.

Scientists are constantly trying to improve our ability to predict future climate states. Recently, Santer et al. showed that it possible to rank individual models with respect to their particular skill at predicting different aspects of future climate. *http://www.pnas.org/content/106/35/14778.full?sid=e20c4c31-5ab1-4f69-b541-5158e62e4baf).* Some think that the ability to detect and attribute intentional climate intervention will be nearly impossible. The fingerprinting of human induced climate change has been based on decades of data under extremely large human induced perturbations. For climate intervention, we contemplate much smaller perturbations. and would like proof positive of their consequences in a matter of years. Even though this is clearly a big challenge, it is not hopeless. Neither should we expect a panacea. We will be able to identify specific observations that certain models are better at predicting and we will be able to find some "killer metrics" that constrain the possible causes of the observations. In some respects, conclusive results will not be possible and if we ever come to deploy, we will likely have to deal with this. Fingerprinting—detection and attribution of human intervention effects on climate—must be an important area for research if we are to be able to conduct adaptive and successful management of geoengineering.

ANSWERS TO POST-HEARING QUESTIONS

Responses by Granger Morgan, Professor and Department Head, Department of Engineering and Public Policy, and Lord Chair Professor in Engineering, Carnegie Mellon University

Questions submitted by Chairman Bart Gordon

Q1. Geoengineering is an emerging field, and as such, it does not have a standard, widely agreed upon definition.

a. How is geoengineering being defined today?

b. Discuss the pros and cons of the existing definitions.

c. Lastly, how should geoengineering be defined going forward?

A1. Unfortunately, there is today no standard definition of geoengineering. The result in recent years has been that a wide range of very different activities have gotten lumped together under this heading. This is not helpful in promoting reasoned discourse because it allows people to make general assertions that in fact apply to only a subset of what others think they are talking about.

In its report of September 2009, the Royal Society defined geoengineering as "the deliberate large-scale intervention in the Earth's climate system . . .." That report then goes on to introduce two additional terms:

- Carbon dioxide removal, or CDR, defined as techniques that remove greenhouse gases from the atmosphere.
- Solar radiation management, or SRM, defined as techniques that offset the effects of increased greenhouse gas concentrations by causing the earth to absorb less solar radiation.

In most of our recent work, my colleagues and I have stopped using the phrase geoengineering and instead are now using SRM.

All methods of CDR are inherently slow and many are local in scale. The most promising methods of SRM are potentially very fast and are global in scale. In my view, these methods of SRM that present significant new challenges of national and international regulations and governance.

Q2. Which Federal research agencies or programs, as well as which non-Federal institutions such as universities, have the capacity to contribute to potential geoengineering research programs?

a. Which agencies or programs should not be involved? Why?

A2. I argued in my testimony that it would be best if the first phase of research on SRM were supported by the National Science Foundation. I made this argument for two reasons:

1. NSF does a good job of supporting open investigator initiated research and we need a lot of bright people thinking about this topic from different perspectives in an open and transparent way before we get very far down the road of developing any serious programs of field research.
2. In addition to natural science and engineering, NSF supports research in the social and behavioral sciences. Perspectives and research strategies from those fields needs to be brought to bear on SRM as soon as possible.

During the Q&A I was asked why DoE should not be the lead agency on early stages of SRM research. In contrast to work supported by NSF, research programs conducted through DoE often do not engage as wide a range of investigators and institutions. They frequently start with a more focused prior definition of what problems should be addressed and how that should be done. They often do a poorer job of incorporating relevant behavioral social science and do not always draw in the best academic research.

Clearly, the modeling and other capabilities of the DoE national labs, as well as other laboratories, such as NCAR, NASA, Goddard, and GFDL, *should* be used in support of research on SRM. That, however, is different from placing lead responsibility with those agencies.

In my testimony, I also argued that once it becomes clear that we need to be doing some larger scale field studies, then it would be appropriate to engage NASA and or NOAA. I also see no problem with involving the military in providing logistical support to such research, when they have the most appropriate assets.

A key point is that any research undertaken on SRM should be open and transparent. It is for that reason that I believe that it would be entirely inappropriate for the intelligence community to be involved in the experimental aspects of SRM research. We should also work hard to avoid getting ourselves into a situation in which private parties develop an interest in promoting the deployment of SRM because they stand to gain financially from such deployment.

Q3. In your testimony, you discuss the need for an international scientific body to provide oversight for geoengineering research at this time, rather than a formal international agreement to govern research.

a. What types and at what scale would research be conducted under the purview of such a scientific body?

b. At what point would it be prudent for a binding international agreement on geoengineering research to be instituted, if ever?

A3. I believe that it would be premature to seek any sort of formal international accord on SRM today, since there does not appear to be any state or other party about to engage in this activity. Before moving to any formal international negotiation on this topic it would be highly desirable to have completed serious research so that negotiations can be based on a better understanding that we have today. My colleagues and I discuss these issues at greater length in the paper from *Foreign Affairs* that I submitted with my testimony.

I argued in my testimony that "so long as it is public, transparent, and modest in scale, and informally coordinated within the scientific community (e.g., by a group of leading national academies, the international council of scientific unions (ICSU), or some similar group) I believe there should be no constraints on modest low-level field testing, done in an open and transparent manner, designed to better understand what is and is not possible, what it might cost, and what possible unintended consequences might result."

I went on to argue that giving meaning to the phrase "modest low-level field testing" should be top priority for the early phase of a U.S. research program on SRM. The point of the diagrams I showed was to give more concrete meaning to that argument.

The Royal Society is at present taking the lead in facilitating the next round of international discussion among experts and others on how issues of global governance might best proceed. A description of that process is provided below:

The Royal Society 2009 report *Geoengineering the climate* concluded that geoengineering does not present an alternative to greenhouse gas emission reductions, but that it should be researched transparently, responsibly and internationally, as it may be the only option to reduce global temperatures quickly in the event of a climate emergency.

Building on this report, the Royal Society, in partnership with TWAS (the Academy of Sciences for the Developing World), and Environmental Defense Fund (EDF), has turned its focus to the governance of solar radiation management (SRM) approaches to geoengineering with the launch of the **Solar Radiation Management Governance Initiative (SRMGI)**.

A broad spectrum of 'stakeholder partner' organisations will be invited to participate in the SRMGI, representing natural and social sciences, public policy, civil society and private enterprise, and from developed and developing countries. The diversity of partner organisations reflects the fact that there is a wide range of viewpoints on geoengineering, and any governance arrangements for research will have to enjoy broad legitimacy and support if it is to proceed.

The first phase of the SRMGI will run for one year, with the goal of producing a set of clear recommendations for the governance of geoengineering research. These recommendations will be discussed at a two-day international conference at the Royal Society Kavli Centre on 10-11 November 2010. They will be informed by background papers produced by working groups, comprised of individual experts, with further input being provided by partner organisations.

It is my view that this is an appropriate way to proceed. Any move to negotiate some sort of treaty arrangement now, before we have a better technical understanding of SRM, would in my view be premature.

Questions submitted by Representative Ralph M. Hall

Q1. Dr. Morgan, right now, the Department of Energy is heavily engaged in modeling the climate system, biological and atmospheric interactions and the carbon cycle. Yet, in your testimony, you suggest that when it comes to geoengineering, the Department of Energy should not be involved in these activities. Instead, you *recommend that the National Science Foundation, NOAA or NASA be tasked with developing instrumentation and research plans to study solar radiation management events. Why do you think that DOE should not be involved? Do you think they have reached beyond their original mission?*

A1. As I argued in my response to Chairman Gordon's second question above, clearly the modeling and other capabilities of the DoE national labs, as well as those of other laboratories, such as NCAR, NASA, Goddard, and GFDL, should be used in support of research on SRM. That, however, is different from placing lead responsibility for the initial phase of research on SRM with DoE or some other agency.

In contrast to work supported by NSF, research programs conducted through DoE often do not engage as wide a range of investigators and institutions. They frequently start with a more focused prior definition of what problems should be addressed and how. They often do a poorer job of incorporating relevant behavioral social science and do not always draw in the best academic research.

Our nation faces enormous challenges in transforming the energy system: both in lowering the environmental footprint and the cost of producing and moving energy to end users, and in improving efficiency with which we convert that energy into useful services. Given the enormity of the challenges we face, I believe that DOE should focus as much of its attention and resources as possible on advancing these objectives and avoid getting diverted into yet more areas.

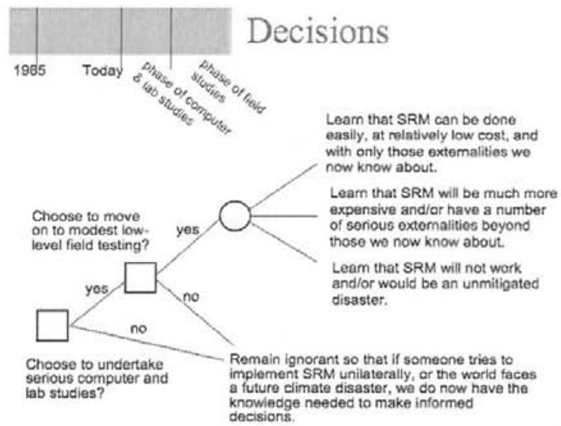
Q2. You mention the need for a more formal international oversight mechanism that will grow as the research continues. Would you suggest a group such as the Intergovernmental Panel on Climate Change being in charge of such a mission? Why or why not?

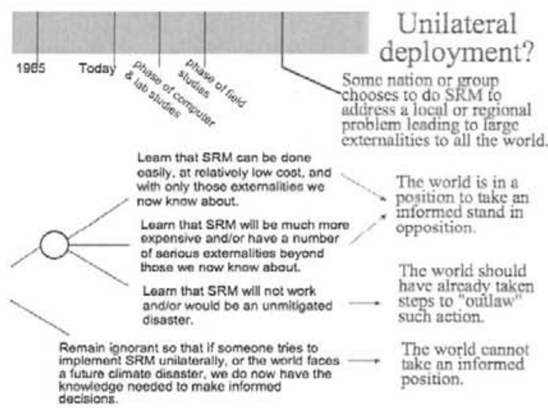
A2. I am not an expert in international relations so this question might better be directed to some of the political scientists with whom I have worked on issues related to SRM. Three who have been thinking about SRM and have somewhat dissimilar views are John Steinbrenner at the University of Maryland, David Victor at UCSD or Ted Parson at Michigan.

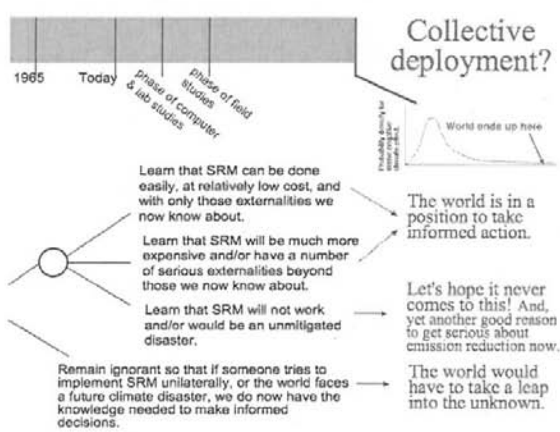
That said, I view the multi-party follow-on study on governance issues related to SRM that has been initiated by the Royal Society to be an excellent next step. In my response to Chairman Gordon's 3rd question, I provided a description of that process.

Q3. In previous hearings on this issue, some witnesses suggested that regardless of how much research we perform ahead of time, we will never really know the true effects geoenginering would have on the planet without actually doing it because of all the possible variables. Is that an accurate statement? How accurate is that for other technological ventures we have undertaken?

A3. Certainly we can never expect to learn *all* the effects that large-scale implementation of SRM might have before its possible implementation. But, a well-designed research program can be expected to provide considerably more understanding and insight than we now possess. The situation we face can be illustrated with a series of simple decision trees as shown on the following page.


Decisions
1965
Today
phase of computer & lab studies
phase of field studies
Learn that SRM can be done easily, at relatively low cost, and with only those externalities we now know about.
Learn that SRM will be much more expensive and/or have a number of serious externalities beyond those we now know about.
Learn that SRM will not work and/or would be an unmitigated disaster.
Choose to move on to modest low-level field testing?
yes
yes
no
no
Choose to undertake serious computer and lab studies?
Remain ignorant so that if someone tries to implement SRM unilaterally, or the world faces a future climate disaster, we do now have the knowledge needed to make informed decisions.


Unilateral deployment?
1965
Today
phase of computer & lab studies
phase of field studies
Some nation or group chooses to do SRM to address a local or regional problem leading to large externalities to all the world.
Learn that SRM can be done easily, at relatively low cost, and with only those externalities we now know about.
Learn that SRM will be much more expensive and/or have a number of serious externalities beyond those we now know about.
The world is in a position to take an informed stand in opposition.
Learn that SRM will not work and/or would be an unmitigated disaster.
The world should have already taken steps to "outlaw" such action.
Remain ignorant so that if someone tries to implement SRM unilaterally, or the world faces a future climate disaster, we do now have the knowledge needed to make informed decisions.
The world cannot take an informed position.


Collective deployment?
1965
Today
phase of computer & lab studies
phase of field studies
World ends up here
Learn that SRM can be done easily, at relatively low cost, and with only those externalities we now know about.
Learn that SRM will be much more expensive and/or have a number of serious externalities beyond those we now know about.
The world is in a position to take informed action.
Learn that SRM will not work and/or would be an unmitigated disaster.
Let's hope it never comes to this! And, yet another good reason to get serious about emission reduction now.
Remain ignorant so that if someone tries to implement SRM unilaterally, or the world faces a future climate disaster, we do now have the knowledge needed to make informed decisions.
The world would have to take a leap into the unknown.

Q4. Several months ago, a paper was published in the Journal of Petroleum Science and Engineering titled, "Sequestering carbon dioxide in a close underground volume." The authors of this study, Christine Ehlig-Economides and Michael J. Economides suggest that "underground carbon dioxide sequestration via bulk CO_2 injection is not feasible at any cost," since the CO_2 would require up to 500 times more space underground than the carbon did when it was bound as coal, oil or natural gas.

a. If this hypothesis is correct, how would this affect your estimation on the feasibility of geoengineering as a viable option from a technological and a cost effectiveness point of view?

b. How would such a hypothesis alter the debate that is currently ongoing about the need to mitigate climate change through reducing emissions?

A4. In April, J.J. Dooley and C.L. Davidson at PPNL prepared an assessment of this paper for the Department of Energy (PNNL–19249). The summary of their report reads in part as follows:

> ". . . the paper is built upon two flawed premises: first, that effective CO_2 storage requires the presence of complete structural closure bounded on all sides by impermeable media, and second, that any other storage system is guaranteed to leak. These two assumptions inform every aspect of the authors' analyses, and without them, the paper fails to prove its conclusions. The assertion put forward by Ehlig-Economides and Economides that anthropogenic CO_2 cannot be stored in deep geologic formations is refuted by even the most cursory examination of the more than 25 years of accumulated commercial carbon dioxide capture and storage experience."

The American Petroleum. Institute has also prepared a critique. The following is an excerpt from the summary of their assessment:

> ". . . the fundamental premise of the paper—that sequestration at the individual project-level will occur in "closed underground volumes"—can be characterized as very conservative, bordering on unrealistic. By making this assumption, the authors are effectively characterizing all geologic formations used for CO_2 storage as sealed, pressure tight containers with storage capacities limited by pressure constraints. While this condition can occur, it is unrealistic to assume it as the "baseline" condition in all potential storage reservoirs.
>
> The oil and gas industry's vast experience clearly shows that truly closed reservoirs are relatively uncommon. Industry experience shows that a majority of producing geologic formations have some form of pressure communication across very broad areas. There is little reason to expect significantly different conditions (i.e. the supposed pressure containment) in saline portions of those same geologic formations or saline reservoirs that under- or over-lay those same formations . . .."

Geological sequestration of carbon dioxide falls under the category of CDR. While it does not appear that the assessment by Ehlig-Economides is correct, its validity has little bearing on the "feasibility" of SRM, the type of geoengineering I discussed. Nor does the volume of available pore space for use in CCS have any relevance to the question of whether we should be reducing CO_2 emissions.

We need to reduce global CO_2 emissions by roughly an order of magnitude over the course of the next few decades if we are to avoid very major, and probably irreversible, climate change. How much pore space may be available to sequester CO_2 has no bearing on that fact.

There is no single technological silver bullet that will achieve a major reduction of CO_2 emissions. Doing that will require a cost-effective portfolio of all available strategies and technologies. The volume of pore space available for sequestration might change the composition of that portfolio but will have no impact on the need to achieve a major reduction in emissions.

Appendix 2:

Additional Material for the Record

Congressional
Research
Service

MEMORANDUM March 11, 2010

To: House Committee on Science and Technology, Subcommittee on Energy and Environment
Attention: Anne Cooper

From: Richard Lattanzio, Analyst in Environmental Policy (7-1754)
Emily Barbour, Legislative Attorney (7-5842)

Subject: **International Governance of Geoengineering**

This memorandum responds to your request for information regarding potential international governance and regulatory mechanisms for geoengineering (or climate engineering) technologies. The memorandum includes a short introduction to geoengineering technologies, a discussion on the criteria that may be used to develop effective international governance structures and instruments, and a summary of existing international regulatory frameworks. This memorandum was requested in preparation for a subcommittee hearing on the governance of geoengineering. Please note that information contained in this memorandum was provided on deadline and may be elaborated upon for use in forthcoming CRS products.

This memorandum does not provide a detailed summary of the science of geoengineering, outline the economic needs for research and development of the technologies,[1] analyze the geoengineering option relative to current climate change policies such as mitigation and adaptation,[2] or assess the scientific, social, legal, and political acceptability of pursuing geoengineering research and deployment.[3] Additionally, because the subcommittee hearing is part of a joint investigation into geoengineering science and governance coordinated by the U.S. House of Representatives and the United Kingdom's House of Commons, this memorandum's discussion of international obligations potentially implicated by geoengineering activities is limited to those contained in customary international law and the international agreements that received close attention from the House of Commons' Science and Technology Committee[4] and the Royal Society in its report on geoengineering on governance.[5] These agreements are

[1] These first two investigations were the purview of the hearings on November 5, 2009 ("Geoengineering: Assessing the Implications of Large-Scale Climate Intervention") and February 4, 2010 ("Geoengineering II: The Scientific Basis and Engineering Challenges") by the House Committee on Science and Technology, Subcommittee on Energy and Environment. See http://science.house.gov/RelatedByTag.aspx?KeywordID=55

[2] Many commentators agree to a large extent with the United Kingdom's Royal Society emphasis that "geoengineering is not an alternative to greenhouse gas emission reductions. Geoengineering may hold longer-term potential and merits more research, but it offers no quick and easy solutions that should distract policy-makers from working toward a reduction of a least 50 percent in global carbon dioxide emissions by 2050." See "Memorandum submitted by the Royal Society" to the United Kingdom House of Commons Science and Technology Committee for a January 13, 2010 hearing on "The Regulation of Geoengineering."

[3] A great deal of literature exists on this debate. Please contact Richard Lattanzio (7-1754) for more information.

[4] *The Regulation of Geoengineering, Hearing before the H. of Commons' Science and Technology Comm.* (2010), *available at* http://www.publications.parliament.uk/pa/cm200910/cmselect/cmsctech/uc221-i/uc22102.htm (last visited Mar. 9, 2010).

[5] The Royal Society, *Geoengineering the Climate: Science, Governance and Uncertainty*, September 2009, at:
(continued...)

as follows: the United Nations Convention on the Law of the Sea, the London Convention and Protocol, the Convention on Biological Diversity, and the United Nations Framework Convention on Climate Change and the Kyoto Protocol. The memorandum also provides a list of some additional multilateral international agreements with global, rather than regional, application that may be implicated by some geoengineering activities. However, this memorandum is not intended as an exclusive list of international frameworks that could support or constrain geoengineering activities, and, therefore, countries considering undertaking geoengineering projects will presumably review their obligations under the full range of bilateral, regional, and multilateral agreements to which they are parties.

For further assistance, please contact Rick at 7-1754 or Emily at 7-5842.

Part I: An Overview of Geoengineering Governance[6]

Introduction to the Science of Geoengineering

Despite concerns that climate change may be more severe and more rapid than estimated by the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report in 2007,[7] progress toward a global reduction of carbon dioxide (CO_2) and other greenhouse gas (GHG) emissions remains slow. Prompted by regard over the slow progress of global GHG reductions, the uncertainties of climate sensitivity, the potential existence of climate thresholds (or "tipping points"), and the political, social, and economic impact of pursuing aggressive mitigation strategies, some in the international community have begun considering alternatives to address potentially catastrophic climate change. One such alternative is the use of geoengineering technologies.

Geoengineering technologies aim to intervene in the climate system through large-scale and deliberate modifications of the Earth's energy balance in order to reduce temperatures and counteract anthropogenic climate change.[8] The methods proposed are diverse and vary greatly in terms of their technological characteristics and possible consequences. They are classified by most commentators into two main groups:

- *Carbon Dioxide Removal (CDR) methods:* technologies or practices that reduce the levels of CO_2 and other GHG emissions in the atmosphere allowing heat radiation to escape more easily into outer space. These methods include, (1) enhancing the uptake and storage of GHG by biological systems through afforestation,[9] adapted land use, production of biomass or biofuels coupled with carbon sequestration, ocean fertilization, and enhanced ocean upwelling; and (2) using physical- or chemical-engineered systems to aid in the sequestration of GHG through enhanced weathering techniques, alkalinity enhancement, ambient air capture, and atmospheric scrubbers.

(...continued)
http://royalsociety.org/geoengineeringclimate/

[6] This section was prepared by Richard Lattanzio, Analyst in Environmental Policy (7-1754).

[7] See IPCC website at: http://www.ipcc.ch/publications_and_data/ar4/syr/en/contents.html

[8] Most commentators refer to the Royal Society report for a definition of geoengineering. This is a composite definition drawn from several passages of the report.

[9] "Afforestation" is the creation of forests on land that has not recently been, or has never been, forest land. "Reforestation" is the reestablishment of forest land after its recent removal.

- *Solar Radiation Management (SRM) methods:* technologies that reduce the net incoming solar radiation received by the planet by deflecting sunlight or by increasing the reflectivity (or "albedo") of the atmosphere. These methods include, (1) modifying land-based albedo through human settlement adjustments, desert or grassland reflectors, or reforestation; (2) modifying troposphere-based albedo through cloud brightening or whitening; (3) modifying upper atmosphere-based albedo through the injection of stratospheric aerosols; and (4) employing space-based techniques for reducing solar radiation including orbiting reflectors or refractors.

Some emerging geoengineering techniques appear technically feasible, though they run the risk of uncertainty regarding their effectiveness, cost, environmental effects, and socio-political impacts. Little research has been done on most of the geoengineering methods considered, and no major directed programs of research are in place. Peer reviewed research and publication is scant, and deployment of the technology — either through controlled field tests or commercial enterprise — has been minimal.[10] Most observers agree that more research is required to test the feasibility, effectiveness, cost, social and environmental impacts, and the possible unintended consequences of geoengineering before deployment. These uncertainties have led some in the international community to consider the need and the role for governance structures to guide research in the short term and to oversee potential deployment in the long term.

Introduction to the Governance of Geoengineering

Geoengineering is an emerging policy area. At present, no international treaties or institutions exist with sufficient mandate to regulate the full spectrum of possible geoengineering activities. While it is likely that some existing national, regional, and international mechanisms may apply to geoengineering practices and their impacts, they have yet to be analyzed or tested with this purpose in mind. Consequently, risk exists that some methods could be researched or deployed unilaterally by individual nation states, corporations, or individuals without appropriate regulation or international agreement. Given the nascent state of understanding in the science, potentially useful techniques may be mistakenly ignored and potentially dangerous proposals may be mistakenly promoted.

Challenges to Crafting Regulation

While technical unknowns exist at each stage in the science of geoengineering — from basic research through implementation and evaluation — most observers believe that the greatest challenge confronting geoengineering governance may be the social, ethical, legal, and political risks associated with it.[11] Some of the most significant policy issues that may complicate the crafting of regulation are as follows:[12]

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[10] Minimal but not absent. In 2008, a German-Indian joint research venture on ocean fertilization produced significant debate among Parties to the London Convention and the Convention on Biological Diversity before being allowed to continue. Commercially, several companies, including Climos, Planktos, and Mantria, have investigated avenues through which to use geoengineering techniques in the carbon markets by selling emission offsets for ocean fertilization and biochar sequestration. These and other examples can be found in Mason Inman's article, "Planning for Plan B," *Nature Reports Climate Change*, Vol 4, January 2010.

[11] Royal Society report, op.cit.

[12] Sources: "Technology control dilemma" as outlined by the Royal Society from a definition in D. Collingridge, *The Social Control of Technology*, Francis Pinter: New York, 1980. "Reversibility" and "encapsulation" as defined by the Royal Society report, op.cit. "Commercial involvement" and "public engagement" as defined by the Royal Society report as well as broached in many of the policy articles debating the acceptability of geoengineering research and implementation.

- *Technology Control Dilemma* refers to the analytical impasse inherent in all innovative technologies wherein potential risks may be foreseen in the design phase but can only be proven and resolved through actual research, development, and demonstration. Ideally, appropriate safeguards are put in place during the early stages of the development of a new technology, but anticipating the evolution of a new technology can be difficult. By the time a technology is widely deployed, it may be impossible to build desirable regulations and risk management provisions without major disruptions.
- *Reversibility* refers to the ability to cease a technology program and have its effects terminate in a short time. In principle, all geoengineering options defined above could be abandoned in short notice, with either an instant cessation of climate effects or with a small time lag after abandonment. However, the issue of reversibility applies to more than just the cessation of the geoengineering activities themselves. Potential scenarios may include the abrupt abandonment of geoengineering management technologies in an environment that also failed to effectively mitigate GHG emissions. Such a scenario could result in a rapid and irreversible climate adjustment through an increase in temperature. Similarly, financial investment in the construction and maintenance of physical infrastructure to support geoengineering may create a strong economic resistance to reversibility.
- *Encapsulation* refers to whether a technology program is modular and contained or whether it involves the release of materials into the wider environment. Encapsulated technologies are often viewed as more "ethical" in that they are not seen as polluting. But encapsulated technologies may still have environmental impacts depending on the nature, size, and location of the application. As such, regulatory consequences may arise as much from the indirect impacts of activities on species and habitat as from the direct impacts of released materials on atmospheric and oceanic ecosystems.
- *Commercial Involvement* refers to the conditions of private sector engagement in the development and promotion of geoengineering. Involvement may be positive, in that it mobilizes innovation and capital investment, which could lead to the development of more effective and less costly technology at a faster rate than the public sector. However, commercial involvement could by-pass or neglect risk assessment related to the socio-economic environmental and regulatory dimensions of geoengineering in favor of what one commentator refers to as "irresponsible entrepreneurial behavior."[13] Private sector involvement would likely demand some form of GHG emission pricing to spur investment, as well as considerations of ownership models, intellectual property rights, and trade and transfer mechanisms for the dissemination of the technologies.
- *Public Engagement* refers to the wider dialogue between scientists, policymakers, the public, and civil society. The consequences of geoengineering — including the risks discussed above — could be felt by people and communities across the world. Public attitudes toward geoengineering, and public engagement in the formation and development of proposed governance, could have a critical bearing on the future of the enterprise. Perceptions of risks, levels of trust, transparency of actions, and economies of investment could play a significant role in the political feasibility of geoengineering.

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[13] See John Virgoe's comments in the "Uncorrected Transcript of Oral Evidence" presented before the U.K. House of Commons Science and Technology Committee on January 13, 2010. Please note that the uncorrected transcript is not yet approved as a formal record of the proceedings. Transcript can be found at: http://www.parliament.uk/parliamentary_committees/science_technology/s_t_geoengineering_inquiry.cfm

Criteria for Crafting Regulation

Some technical characteristics of geoengineering have been used by most commentators as criteria to aid in determining the structure and extent of any potential international regulatory regime.[14] These criteria are as follows:

- The extent to which the impacts of geoengineering *are international or transboundary in scope*;
- The extent to which the impacts of geoengineering *dispense hazardous material into the environment*; and,
- The extent to which the impacts of geoengineering *directly intervene in the balance of the ecosystem*.

Consequently, different aspects of geoengineering technologies may require different regulations. For example:

- *Different technologies may require different regulatory regimes:* To the extent that most CDR technologies are similar to familiar and existing ones, many could be adequately controlled by existing national legislation. Air capture technologies are similar to those of carbon capture and sequestration for power generation. Biochar and biomass sequestration face similar life cycle analyses and regulatory issues as biofuels. Ecosystem impacts of enhanced terrestrial weathering would likely be contained within national boundaries. Enhanced weathering in oceans and ocean fertilization techniques are the only CDR technologies that may require new regulatory structures due to risks associated with ecosystem interventions that could cross national boundaries. For SRM technologies, however, the scope, dispersions, and interventions are more likely to cross national boundaries. While land surface albedo modification could potentially be managed under national regulatory frameworks, all other technologies may trigger transboundary issues. Some existing treaties address atmosphere and space but have rarely been tested for enforcement.
- *Different stages of the research cycle may require different regulatory regimes:* Geoengineering development involves several stages. Regulatory frameworks must be flexible enough to cover the full cycle (e.g., from assessment through research, modeling, laboratory trials, field trials, implementation, monitoring, and evaluation). Transboundary environmental impacts grow along this cycle, and negative social and economic consequences may be felt as early as small-scale field trials.
- *Different environments for potential research or deployment may require different regulatory regimes:* Legal classifications with respect to geoengineering technologies often relate to the differing environments — space, atmosphere, ocean, land — in which the techniques are deployed. This approach allows for the different jurisdictions and different resource ownership arrangements. Land-based and lower atmosphere activities are placed under sovereign rights; but for the open ocean, upper atmosphere, or space, effective legal instruments are scarcer.

[14] Royal Society memorandum to the U.K. House of Commons, op.cit.

Potential Regulatory Instruments

Guidelines for Regulation

Many observers note that certain baseline characteristics within the science of geoengineering lend themselves to certain governance or regulatory guidelines. Some of the characteristics they mention are as follows:

- Because the climate is global, a regulatory framework for geoengineering should likewise be international and transboundary.
- Because the range of stakeholders potentially affected by geoengineering is broad, a regulatory framework should be accessible, inclusive, and equitable to all nations, sub-national groups, non-governmental organizations, corporations, and civil societies.
- Because the number of actors potentially employing geoengineering techniques may be small in comparison to the number of those affected, a regulatory framework should be open and transparent with respect to the exposure to risk.
- Because the global impacts of geoengineering — both its benefits and damages — may be unevenly distributed, a regulatory framework should consider cost structures, ownership models, and compensation assessments.
- Because the technology is new and unproven, a regulatory framework should be flexible in the light of ongoing scientific and technical evidence.
- Because the impacts of geoengineering are uncertain, a regulatory framework should be able to respond rapidly to emerging situations including foreseen and unforeseen risks and to be withdrawn fully if new situations so require.

While many of these guidelines appear rational, various social, economic, and political considerations may open the door for alternative regulatory interpretations. In the sections that follow, a few regulatory frameworks are outlined and alternatives are mentioned where noteworthy.

1. No Regulation

It should be noted that one possible response to the rise of interest in geoengineering technologies is for governments to fully refrain from any regulatory or governance mechanism. Advocates of an unregulated response may either see private industry and corporations as the best avenue through which to pursue geoengineering research and entrepreneurship, or, conversely, consider government involvement as an unwanted stamp of acceptability on a deleterious technology. Public opinion and civil society engagement may also sour to either the technological uncertainty of the science or the cost considerations of research and regulation. These concerns should be balanced against the many potential risks of an unregulated program (as outlined in the previous paragraph) to evaluate the extent of government support for geoengineering enterprises and determine the maximum threshold of abstention before government interventions.

2. International Treaties and Agreements

Based on experiences with other international environmental issues, many commentators propose the need for a legally binding regulatory treaty along with a careful global assessment that gives all nations the opportunity to participate formally in evaluating the risks and benefits of geoengineering science.

Treaty instruments can negotiate, codify, and enforce normative standards on an emerging science. They undergo extensive review and ratification by governments before entering into force, and they have the potential to provide a framework under which future discussions and institutions can develop. While there are no legally binding treaties currently in place with geoengineering – specific provisions, existing treaties and rules of customary international law suggest there are some principles of shared environmental and development practice that could form a basis of regulation. Accordingly, governments could choose to enhance these principles' applicability to geoengineering by expanding existing international agreements and/or forming new ones. (Please refer to Part II of this memorandum, "Customary International Law" for further discussion).

However, the strengths of international treaties may also be their weakness.[15] Treaties are based on a process that is inherently conservative. Nations often negotiate by adjusting their commitments to a level where they are sure that compliance is technically, economically, socially, and politically feasible. If commitments are too high, nations may seek favorable (i.e. vague) language, or, conversely, refuse to join.[16] When an international situation is new and evolving or if the framing creates strongly opposing interests (such is the potential of geoengineering regulation), a common outcome of treaty negotiation is stalemate. Moreover, international agreements, particularly those involving compliance mechanisms and the establishment of new international institutions, can be viewed as infringing with countries' sovereignty, and thereby interfering with states' ability to experiment with domestic measures that best address local needs and capabilities.

Some commentators suggest that a treaty negotiation on the science of geoengineering, as it currently stands, may lead to a moratorium on research and deployment activities. A proposed moratorium could arise because the majority of countries currently lack the capacity and political incentive to geoengineer and may believe there is little to gain from permitting other states to experiment. Proponents of a ban on certain forms of geoengineering currently include several environmental groups and developing country NGOs.[17] In general, advocates of this kind of moratorium argue that: (1) geoengineering research would distract from the global goal of emission reductions (the "moral hazard" argument); (2) geoengineering could be used by governments and industry as a "time buying" strategy to avoid mitigation commitments; (3) the underlying science is too risky; (4) the potential impacts are too uneven, or, disproportionately weighted toward vulnerable developing countries in the tropics; and (5) geoengineering techniques may be co-opted by commercial or unethical interests.

Other commentators suggest that a moratorium on geoengineering technologies is ill-advised. From their perspective, a moratorium would (1) inhibit research, some of which has been ongoing for decades in the context of marine ecology, oceanographic studies, and atmospheric meteorology; (2) make it difficult to accumulate the information needed to make informed judgments about the feasibility and the acceptability of the proposed technology; and (3) likely deter only those countries, corporations, and

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[15] The following critique of treaty instruments is taken from several articles by authors such as David Victor, Kal Raustiala, Eugene Skolnikoff, and Lee Lane. See specifically: David Victor, "On the Regulation of Geoengineering," *Oxford Review of Economic Policy*, Vol. 24, No. 2, 2008, pp. 322-336; as well as comments made in the Royal Society report, op.cit.

[16] Such was the situation in negotiations leading to the 1992 Convention on Biological Diversity, which, as outlined by Victor, op.cit., "contained European-inspired language that was hostile to genetically engineered crops and developing country-inspired language that demanded complicated revenue-sharing for some kinds of germplasm collections. The USA, world leader in these investments, simply refused to join the treaty."

[17] The following arguments are taken from one such organization, The Action Group on Erosion, Technology, and Concentration (ETC Group) in its "Memorandum submitted by the ETC Group" to the United Kingdom House of Commons Science and Technology Committee for a January 13, 2010 hearing on "The Regulation of Geoengineering."

individuals who would most likely develop the technology in a responsible fashion, thus failing to discourage potentially dangerous experimentation by less responsible parties.

3. International Research Consortia

Some commentators have suggested that forming an international scientific consortium would reduce the potential disadvantages of working towards an international system for geoengineering governance at this stage. They posit that an international consortium could explore the safest and most effective forms of geoengineering while also building a community of responsible researchers.[18] Prior international scientific collaborations have shown that research consortia are generally well-equipped to:

- Set research priorities at the initial stages of an emerging technology;
- Coordinate existing research, identify new research agendas, and develop effective and objective assessment frameworks to inform the initial stages of regulation;
- Collaborate with representation from the scientific, policy, commercial, regulatory and non-governmental communities to provide independent oversight of evolving regulatory issues concerning an emerging technology; and,
- Formulate, develop, and socialize an international and voluntary code of practice to govern research in an emerging technology.

Building comprehensive international assessments and effective international organizations to govern transboundary geoengineering activities may be difficult because of how little is currently understood about the technical, economic, social, and political components of geoengineering. At this point, there are no international organizations with a direct or indirect mandate to regulate the full spectrum of possible geoengineering activities. However, it is theoretically possible that existing institutions could fit this purpose if their charters were modified and expanded, but it is unclear if this would be the most effective way of achieving comprehensive international regulation of geoengineering activities. Bolstering this uncertainty is debate over the ideal form of an international body charged with geoengineering governance. Whereas some believe the current issues involved in geoengineering are ill-suited for resolution by consensus-based organizations, others caution against populating an international governing body with representatives from only a few countries, regions, or fields.[19] It is unclear at this point how this kind of international body would balance the need for international research and governance with the technical, political, and ethical uncertainties posed by a controversial, emerging technology.[20]

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[18] As recommended by the Royal Society, with collaborations such as the European Organization for Nuclear Research (CERN) and the Human Genome Project used as example. See Royal Society report, op.cit.

[19] Victor, op.cit. and the ETC Group, op.cit.

[20] Given the fundamental purpose of geoengineering, many commentators point to the United Nations Framework Convention on Climate Change as a potential governing organization. Some have suggested that the Intergovernmental Panel on Climate Change (IPCC) could provide a technical framework to establish whether there is sufficient scientific justification for research on different techniques and, if so, where effort should be focused. International global programs, such as the World Meteorological Organization (WMO), and those co-sponsored by International Council for Science (ICSU), International Geosphere-Biosphere Programme (IGBP); World Climate Research Programme (WCRP); International Human Dimensions Programme on Global Environmental Change (IHDP) and Diversitas; grouped under the Earth System Science Partnership, (ESSP)) could also coordinate relevant research and provide independent international assessments adapted for the purposes of geoengineering.

Part II: A Survey of Selected International Obligations and Regulatory Frameworks[21]

The following section outlines information regarding existing international obligations and treaty frameworks that might support or constrain the implementation or research of transboundary geoengineering projects. Because geoengineering is an umbrella term for a broad array of methods of global climate adjustment, some largely theoretical and others well-understood, it is very likely that particular projects may be affected by multiple international obligations and regulatory frameworks, including some that are not identified in this memorandum. This section limits its discussion of sources of relevant international obligations to those that received heightened consideration in the Royal Society's report on geoengineering and governance: customary international law, the United Nations Convention on the Law of the Sea, the London Convention and Protocol, the Convention on Biodiversity, and the United Nations Framework Convention on Climate Change and the Kyoto Protocol. It also supplements the Royal Society's report with a list of several other multilateral treaties with global, rather than regional, application that countries could use to constrain or support the research and deployment of geoengineering projects. However, this section does not provide a comprehensive list or discussion of relevant international obligations, frameworks, or institutions.

Customary International Law

Customary international law results from a general and consistent practice by nation states which are followed from a sense of legal obligation.[22] In other words, obligations under customary international law arise from the combination of: (1) "general practice" and (2) *opinio juris*, (i.e., the belief that such practice is based upon a legal obligation).[23] Duties established by customary international law are generally deemed binding on states that have not persistently objected to it.[24] For purposes of U.S. domestic law, the legal significance of customary international law is unclear, but does not take precedence over a conflicting statute.[25]

Environmental Obligations under Customary International Law

While it can be difficult to determine when a widespread state "practice" evolves into a "duty" imposed by customary international law, there are several duties that should be emphasized for the purposes of this memorandum. First, customary international law establishes a duty not to cause significant transboundary harm.[26] Customary international law also arguably obligates states, to the extent practicable, to take measures necessary to prevent, reduce, and control pollution that is causing or threatening to cause

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[21] This section was prepared by Emily Barbour, Legislative Attorney (7-5842).

[22] RESTATEMENT (THIRD) OF FOREIGN RELATIONS LAW § 102 (1987).

[23] LORI F. DAMROSCH ET. AL., INTERNATIONAL LAW: CASES AND MATERIALS 59 (5th ed. 2009).

[24] RESTATEMENT (THIRD), *supra* note 22, at 102 n.2.

[25] There does not appear to be an instance in which a U.S. statute or presidential action was struck down by a reviewing U.S. court solely on the basis that it conflicted with customary international law. For further discussion, see CRS Report RL32528, *International Law and Agreements: Their Effect upon U.S. Law*, by Michael John Garcia.

[26] RESTATEMENT (THIRD), *supra* note 22, at § 601(1) (stating that a nation is generally obligated to take "such measures as may be necessary, to the extent practicable under the circumstances, to ensure that activities within its jurisdiction or control...are conducted so as not to cause significant injury to the environment of another state.")

significant injury to the marine environment.[27] This obligation, along with several other rules of customary international law, mirror provisions in the United Nations Convention on the Law of the Sea, which is discussed below.[28]

Customary International Law and the Effect of Treaties

In addition to establishing substantive obligations, customary international law also informs the legal significance given by states to international agreements. Customary international law, as reflected in the Vienna Convention on the Law of Treaties ("VCLT") recognizes that signatories of an international agreement must refrain from acts that would defeat the object and purpose of that agreement unless the state makes clear its intent not to ratify the treaty.[29] The VCLT also codifies the customary rule that a treaty may not create rights and obligations for a non-Party without its consent.[30] In other words, countries that are not parties to an international agreement may not be bound to adhere to it.

Selected International Agreements

The status of U.S. accession and/or ratification to the treaties discussed on the following pages should be viewed in light of the two principles of international law just discussed. The United States has signed most of the treaties and protocols discussed in detail below, but has only ratified or acceded to two: the Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter (the "London Convention") and the United Nations Framework Convention on Climate Change ("UNFCCC"). Therefore, customary international law dictates that the United States should refrain from acts that would defeat the object and purpose of each agreement it has signed, but, in the context of the agreements discussed below, it is only bound to strictly comply with the obligations set out in the London Convention and UNFCCC.

United Nations Convention on the Law of the Sea

The United Nations Convention on the Law of the Sea ("UNCLOS") establishes a legal regime governing activities on, over, and under the world's oceans. It opened for signature in December 1982 and entered into force on November 16, 1994. A large part of the UNCLOS is concerned with defining states' jurisdiction over the oceans and rights of access to the ocean. For example, the UNCLOS permits coastal states to define and exercise sovereignty over a territorial sea that does not extend beyond 12 nautical miles from the coastal state.[31] It also establishes a 200-nautical mile exclusive economic zone ("EEZ"), in which coastal states exercise jurisdiction over marine science research, environmental protection, natural

[27] *Id.* at § 603(2).

[28] *See e.g. id.* at §§ 511-517.

[29] RESTATEMENT (THIRD), *supra* note 22, at § 312(3); VCLT, Art. 18. The United States signed the Vienna Convention on the Law of Treaties (VCLT), but the VCLT has not received the Senate's advice and consent and, consequently, the United States is not a Party to the VCLT. Nevertheless, the United States considers most of the VCLT to constitute customary international law on the law of treaties. *See, e.g.*, Fujitsu Ltd. v. Federal Exp. Corp., 247 F.3d 423 (2d Cir. 2001) ("we rely upon the Vienna Convention here as an authoritative guide to the customary international law of treaties ... [b]ecause the United States recognizes the Vienna Convention as a codification of customary international law ... and [it] acknowledges the Vienna Convention as, in large part, the authoritative guide to current treaty law and practice") (internal citations omitted).

[30] VCLT, Art. 34; RESTATEMENT (THIRD), *supra* note 22, at § 324(1).

[31] UNCLOS, Art. 3.

resources, and certain economic activities.[32] The UNCLOS also guarantees that all states are entitled to lay submarine cables and pipelines on the bed of the high seas and enjoy the traditional freedoms of navigation, overflight, scientific research, and fishing on the high seas.[33] These states also bear the burden of cooperating in the repression of piracy occurring on the high seas and taking necessary measures to conserve the living resources of the high seas.[34]

Disputes under the UNCLOS can be submitted to the International Tribunal for the Law of the Sea, established by the UNCLOS, the International Court of Justice, or to arbitration.[35] Procedures may be superseded if the parties to the dispute are also members of an international agreement that contains a previously accepted procedure to reach a "binding decision."[36]

U.S. Action

The United States has neither signed nor become a party to the UNCLOS. On October 31, 2007, the Senate Foreign Relations Committee voted to recommend Senate advice and consent to U.S. adherence to the Convention. In her confirmation hearing before the Senate Committee on Foreign Affairs on January 13, 2009, Secretary of State Hillary Clinton acknowledged that U.S. accession to the UNCLOS would be a priority for the Obama Administration.

Action by Selected Other Countries and Entities

China became a party to the UNCLOS in 1996.

The European Union became a party to the UNCLOS in 1998 via an act of formal confirmation.

India became a party to the UNCLOS in 1995.

Japan became a party to the UNCLOS in 1995.

Russia became a party to the UNCLOS in 1997.

A complete list of Parties to the UNCLOS is available at http://www.un.org/Depts/los/reference_files/status2010.pdf.

Selected Provisions with Potential Relevance to Geoengineering

Article 192 of the UNCLOS imposes a general obligation on states to protect and preserve the marine environment. In addition, the UNCLOS creates specific obligations to preserve particular marine animals. A thorough review of these "living resources provisions" can be found in CRS Report RL32185, *U.N. Convention on the Law of the Sea: Living Resources Provisions*, by Eugene H. Buck. These provisions could be implicated by ocean fertilization and some other geoengineering activities if they have a

[32] *Id.* at Arts. 55-57.

[33] *Id.* at Arts. 87, 112.

[34] *Id.* at Arts. 100, 117.

[35] *Id.* at Art. 287.

[36] UNCLOS, Arts. 282.

negative effect on the marine ecosystem. In addition to the living resources provisions discussed in that report, a large-scale ocean fertilization project could also implicate the provisions identified below.

Articles 56 and 240: Marine Research

Geoengineering research conducted in or on the oceans would likely implicate several UNCLOS provisions, including Article 56 and Articles 238 through 241.

Article 56 of the UNCLOS gives the coastal member state the jurisdiction over marine scientific research within its EEZ, but also imposes a duty on the state to exercise this jurisdiction in a manner compatible with the provisions of the UNCLOS and with regard to the rights and duties of other states.

Article 238 gives all member states, regardless of their geographic location, as well as competent international organizations, the right to conduct marine scientific research subject to the rights and duties of other states. Article 240 of the UNCLOS provides a list of principles for the conduct of marine scientific research, including that marine scientific research must not unjustifiably interfere with other legitimate uses of the sea.

Articles 194 and 207-212: Duty to Prevent, Reduce, and Control the Spread of Pollution

Article 194 of the UNCLOS imposes a duty on member states to take, individually or jointly, measures that are necessary to prevent, reduce, and control pollution of the marine environment from any source. The UNCLOS defines pollution as any human-driven introduction of substances or energy into the marine environment that results *or is likely to result* in deleterious effects such as harm to living resources and marine life, hazards to human health, hindrance to marine activities, or impairment of sea water quality.[37] Article 194 requires member states to take measures to ensure that activities under their jurisdiction are conducted so as not to cause damage by pollution to other states and their environment and that pollution arising from incidents or activities within their jurisdiction does not spread beyond the areas where they exercise sovereign rights. This provision could be implicated by a geoengineering project if it entails polluting the marine environment, by land, sea, or air. In addition to, arguably, mandating that a state not engage in that activity, once a geoengineering project resulted in the pollution of the ocean environment, Article 194 would impose a duty on the member state responsible for that pollution to control and limit its spread.

In addition to Article 194, there are several other pollution-specific provisions, including Articles 207 through 212, each which deal with pollution from different sources including pollution from land-based sources, pollution by dumping, pollution from vessels, and pollution from or through the atmosphere. Consequently, while ocean fertilization might be the geoengineering project most easily associated with a potential to implicate the UNCLOS's pollution provisions, both land and air-based geoengineering projects would implicate these provisions if they introduced new substances or energy into the marine environment that caused or was likely to cause harm to marine animals, ecosystems, or water quality. In particular, ocean-based enhanced weathering techniques, ocean-based albedo enhancement techniques, and geoengineering activities that may lead to ocean acidification could implicate these provisions depending upon the nature of their intervention.

[37] UNCLOS, Art. 1.1(4).

Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter and the "London Protocol"

The Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter ("London Convention") was opened for signature in December 1972 and entered into force in August 1975. Contracting Parties pledge to take all possible steps to prevent the pollution of the sea by substances that are liable to create hazards to human health, harm living resources and marine life, or interfere with other legitimate uses of the sea.[38] "Dumping" is defined for purposes of the Convention as any deliberate disposal of substances and materials into the sea by or from ships or aircraft other than what is (1) incidental to the normal operation of ships and aircraft; or (2) placed into the sea for a purpose other than disposal that is not contrary to the aim of the Convention.[39] Several amendments were added to the London Convention between 1978 and 1993 dealing with the dumping of incinerated and radioactive wastes.

The London Protocol was agreed to in 1996 as a means of modernizing and eventually replacing the London Convention. It entered force in March 2006. The Protocol reiterates and expands upon many of the obligations discussed in the London Convention. It is notable for taking a "precautionary approach" to environmental protection from marine pollution by dumping. In addition, rather than continuing the London Convention's approach to banning the dumping of a set of substances, it reverses that approach, banning the dumping of *all* substances except for a particular set of substances.[40] In 2006, an amendment to the protocol added carbon dioxide streams from carbon dioxide capture processes to the London Protocol's list of substances that may be dumped.

U.S. Action

The United States ratified the Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter ("London Convention") in 1974, but it has not become a party to the *Protocol* to the Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter ("London Protocol"). The London Protocol was signed by the United States on March 31, 1998 and submitted to the Senate on September 4, 2007. The State Department identified the London Protocol as a treaty "on which the Administration supports Senate action at this time" in a May 11, 2009 letter to the Chairman of the Senate Committee on Foreign Relations.[41]

Action by Selected Other Countries and Entities

China became a party to the London Convention in 1985 and the London Protocol in 1996.

The European Union has not become a party to either the London Convention or the London Protocol, but many European countries have. The European states that are parties to *both* are: Belgium, Bulgaria,

[38] London Convention, Art. 1.

[39] *Id.* at Art. 19.1.

[40] These possibly accepted substances include: dredged material, sewage sludge, fish waste, man-made structures at sea, inert inorganic geological material, organic material of natural origin, and bulky items primarily comprising iron, steel, concrete and similar materials for which concern is physical impact and dumping is the most practicable means of disposal. London Protocol, Annex 1.

[41] Letter from Richard Verma, Assistant Secretary for Legislative Affairs, U.S. Department of state, to Senator John Kerry, Chairman of the Senate Committee on Foreign Relations (May 11, 2009) *available at* http://www.globalsolutions.org/files/general/White_House_Priorities_List.pdf.

Denmark, France, Germany, Iceland, Ireland, Italy, Luxembourg, the Netherlands, Norway, Slovenia, Spain, Switzerland, and the United Kingdom.

India is not a party to either agreement.

Japan became a party to the London Convention in 1980 and to the London Protocol in 2007.

Russia has been a party to the London Convention since 1975 but has not become a party to the London Protocol.

A list of the parties of the London Convention is available at http://www.imo.org/includes/blastDataOnly.asp/data_id%3D23854/2.pdf. A list of the parties of the London Protocol is available by following the "37 Parties" hyperlink at http://www.imo.org/home.asp?topic_id=1488.

Selected Provisions with Potential Relevance to Geoengineering

Article 19 of the London Convention and Article 1 of the Protocol: Dumping Defined

Both the London Convention and London Protocol are implicated when a substance is dumped into the oceans. However, geoengineering projects that intentionally dump substances into the ocean for a purpose *other than disposal* may fall outside of the London Convention's definition of dumping if the purpose of the dumping is not contrary to the aim of the Convention.[42] For example, as discussed below, ocean fertilization research activities have been deemed not to constitute dumping under the London Convention and Protocol.[43]

Articles 5-6 of the London Convention and Article 4 of the Protocol: Bans and Permits

Article 5 of the London Convention bars particular substances from being dumped, and Article 5 places constraints on the dumping of other enumerated substances. The barred substances are listed under Annex 1[44] while those subject to special requirements are listed in Annex 2.[45] Among the constraints placed on the dumping of Annex 2 substances is the requirement that they may not be dumped in "significant" amounts absent a permit.[46] The substances that the London Convention requires be dumped only in limited circumstances include those that, while not considered inherently harmful, *may become* harmful or seriously likely to reduce amenities due to the *quantities* in which they are dumped.

[42] *See* London Convention, Art. 19.1; *see also* London Protocol, Art. 1.4 (adopting a very similar definition of dumping).

[43] *See infra* notes 55-59 and accompanying text.

[44] These substances include: organohalogen compounds, compounds which may form organohalogens in the marine environment, organosilicon compounds, compounds which may form organosilicons in the marine environment, substances that the Contracting Parties agreed are likely to be carcinogenic under the conditions of disposal, mercury, mercury compounds, cadmium, cadmium compounds, persistent plastics, persistent synthetic materials which may float or remain in suspension and seriously interfere with fishing, navigation or other legitimate uses of the sea.

[45] London Convention, at Arts. 5-6. These substances include: arsenic, lead, copper, zinc, cyanides, flourides, pesticides, containers, scrap metal, tar-like substances, other bulky wastes likely to present a serious obstacle to fishing or navigation, substances which may become harmful due to the quantities in which they are dumped or are seriously likely to reduce amenities.

[46] London Convention, Art. 6.

The London Protocol has take a more restrictive approach than the London Convention, banning all dumping *except* for that of the substances listed in Annex 1.[47] However, even dumping of the permissible substances must be done in compliance with the permit requirement and other conditions specified in Annex 2.[48]

Article 3.1 of the London Protocol: The Precautionary Approach

The precautionary approach to environmental protection from dumping is outlined in Article 3.1, which states that Contracting Parties must take "appropriate preventative measures" when there is reason to believe that wastes or other matter introduced into the marine environment are "likely to cause harm even when there is no conclusive evidence" to that effect. It further states that, in implementing this duty, Contracting Parties must not transfer the damage or likelihood of damage from one part of the environment to another or transform one type of pollution into another.[49]

Article 6 of the London Protocol: Exceptions to the General Ban

Contracting Parties considering a geoengineering project that might implicate the London Protocol should note its exceptions to the general ban on dumping.[50] In particular, Article 6.2 permits Contracting Parties to issue a permit as an exception to the general ban "in emergencies posing an unacceptable threat to human health, safety, or the marine environment and admitting of no other feasible solution." Arguably, such a permit could entitle a Contracting Party to engage in a geoengineering project that would otherwise violate the London Protocol's general ban. However, in order to make use of this exception, the Contracting Party must consult with other countries that are likely to be affected as well as certain international organizations.[51]

Article 14 of the London Protocol: Scientific Research

The London Protocol requires Contracting Parties to take appropriate measures to promote and facilitate scientific and technical research on the prevention, reduction, and elimination of sources of marine pollution.[52] Consequently, if carbon dioxide emissions or imbalances are considered a source of marine pollution, one could argue that the London Protocol *supports* research into geoengineering projects to stabilize the amount of carbon dioxide in the climate system.[53]

2006 Amendments

Finally, the 2006 amendments to the London Protocol could be particularly relevant to geoengineering projects involving the sequestration of carbon dioxide. These amendments entered into force on February 10, 2007 and provide guidance on the means by which sub-seabed geological sequestration of carbon dioxide can be conducted. The International Maritime Organization (IMO), which is the international organization charged with developing and maintaining a comprehensive transboundary maritime regulatory framework, described these amendments as creating a basis in international environmental law

[47] London Protocol, Art. 4.1.1.

[48] *Id.* at Art. 4.1.2.

[49] *Id.* at Art. 3.1.

[50] *See id.* at Art. 6.

[51] *Id.* at Art. 6.2.

[52] London Protocol, Art. 14.

[53] *Id.* at Art. 6.2.

to regulate carbon capture and storage in sub-seabed geological formations.[54] They state that carbon dioxide streams may only be considered for dumping if (1) disposal is into a sub-seabed geological formation; (2) the substances dumped consist overwhelmingly of carbon dioxide; and (3) no other wastes or matter were added to them for the purpose of disposing of them.

2008 Resolution: Ocean Fertilization

In 2008, the Contracting Parties adopted Resolution LC-LP.1[55] agreeing that the scope of *both* the London Convention and the London Protocol includes ocean fertilization activities, which has been identified as a potential geoengineering project. The resolution defines "ocean fertilization" as "any activity undertaken by humans with the principle intention of stimulating primary productivity in the oceans."[56] It specifically excludes ocean fertilization *research* from the London Convention and London Protocol's definition of dumping by stating that ocean fertilization is a placement of matter for a purpose other than mere disposal.[57] It urges Contracting Parties to use the "utmost caution and the best available guidance" to evaluate scientific research proposals for ocean fertilization and says that ocean fertilization activities *other than research* should not be allowed given the present state of knowledge.[58] The Scientific Groups under the London Convention and Protocol, which act as scientific advisers to the Parties, will, pursuant to this resolution, develop an assessment framework by which Contracting Parties can assess ocean fertilization research proposals to determine their consistency with the Convention and the Protocol.[59]

Convention on Biological Diversity

The Convention on Biological Diversity ("CBD") was opened for signature in June 1992 and entered into force in December 1993. Its key principle is that countries have both the sovereign right to exploit their own resources pursuant to their own domestic policies and the responsibility to ensure that activities within their control do not cause damage to the environment of other states or to areas beyond the limits of national jurisdiction.[60] Rather than limiting its provisions to *conservation*, the CBD seeks to balance conservation objectives with development objectives. It calls upon Parties to develop national strategies, plans, and programs for the conservation and sustainable use of biodiversity; to identify components of biodiversity important for its conservation and use; to establish a system of protected areas where special measures need to be taken to conserve biodiversity; and to regulate or manage biological resources important for biodiversity with a view to ensuring their conservation and sustainable use.[61]

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[54] Press Release, International Maritime Organization, New International Rules to Allow Storage of CO_2 under the Seabed, http://www.imo.org/Newsroom/mainframe.asp?topic_id=1472&doc_id=7772 (last visited Mar. 8, 2010).

[55] *Available at* http://www.imo.org/includes/blastDataOnly.asp/data_id%3D24337/LC-LP1%2830%29.pdf.

[56] Resolution LC-LP.1, Art. 2.

[57] *Id.* at Art. 3.

[58] *Id.* at Arts. 6, 8.

[59] *Id.* at Arts. 5, 6.

[60] CBD, Art. 3.

[61] *Id.* at Arts. 6-8.

U.S. Action

The United States has signed but has not become a party to the Convention on Biological Diversity ("CBD"). In 2009, the State Department identified the Convention on Biological Diversity as a treaty on which the Obama Administration is *not* seeking Senate action.[62]

Action by Selected Other Countries and Entities

China became a party to the CBD in 2000.

The European Union became a party to the CBD in 2000.

India became a party to the CBD in 2001.

Japan has signed but not become a party to the CBD.

Russia has signed but not become a party to the CBD.

A complete list of Parties to the CBD can be found at http://www.cbd.int/convention/parties/list.

Selected Provisions with Potential Relevance to Geoengineering

Article 4: Jurisdictional Scope

Unlike some of the other treaties discussed in this memorandum, which apply largely to areas outside of national jurisdiction, in the case of "components of biological diversity," the provisions of the CBD apply to areas *within* the limits of a Party's national jurisdiction.[63] The CBD also applies to "processes and activities" carried out within the limits of a Party's national jurisdiction regardless of where the effects of those processes or activities occur.[64]

Article 8: In-situ Conservation

Under Article 8, Contracting Parties must establish a system and guidelines for the selection of protected areas where special measures need to be taken to conserve biological diversity.[65] They must also, to the extent possible and appropriate, rehabilitate and restore degraded ecosystems and promote the recovery of threatened species. [66] Perhaps most importantly for geoengineering projects, they must regulate, manage, or control the risks associated with the use and release of living modified organisms which are likely to have adverse environmental impacts and must prevent the introduction of, control, or eradicate alien

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[62] *Supra* note 41, at 5.

[63] CBD, Art. 4.1(a). The components of biological diversity seem to include the categories identified in Annex I. These categories include, for example, ecosystems and habitats that contain high diversity or large numbers of threatened species, and species and communities that are threatened, wild relatives of domesticated species, or important to research into the conservation and sustainable use of biological diversity. CBD, Annex 1.1-1.2. Article 7 also asks the Contracting Parties to identify "components of biological diversity important for its conservation and sustainable use" having regard to the list of categories set down in Annex I. *Id.* at Art. 7(a).

[64] *Id.* at 4.1(b).

[65] CBD, Art. 8(a)-(b).

[66] *Id.* at Art. 8(f).

species that threaten ecosystems, habitats, or species.[67] These requirements could constrain if not prohibit certain geoengineering projects that involve releasing living organisms, such as algae, into new ecosystems to sequester carbon.

Article 12: Research and Training

Article 12 requires Contracting Parties to promote and encourage research which contributes to the conservation and sustainable use of biological diversity. In doing so, the Contracting Parties must take into account the decisions of the Conference of the Parties reached in response to recommendations of the Subsidiary Body on Scientific, Technical, and Technological Advance.[68] Accordingly, this provision has the potential to be used to support geoengineering research projects if those projects were recommended by the Subsidiary Body on Scientific, Technical, and Technological Advance.

2008 Decision of the Conference of the Parties: Climate Change and Ocean Fertilization

The Ninth Meeting of the Conference of the Parties to the CBD ("COP") decided that reviews of programs of work of the CBD should assess the impacts of climate change. In its decision on biodiversity and climate change, the Conference urged Parties to "enhance the integration of climate-change considerations related to biodiversity in their implementation of the Convention."[69]

In addition, the COP noted the work of the London Convention and the London Protocol regarding ocean fertilization and requested that its own Parties act to ensure that ocean fertilization activities do not take place until either there is adequate scientific basis on which to justify such activities or the activities are small-scale scientific research studies within coastal waters.[70] The Royal Society criticized the move by the COP on the grounds that the definition of "coastal waters" was ambiguous and that small-scale near-shore studies are meaningless for ocean fertilization field trials.[71] For its part, the Secretariat of the Convention on Biological Diversity has published two reports analyzing the possible effects of ocean fertilization on biodiversity, both of which are available on its website at http://www.cbd.int/ts.

United Nations Framework Convention on Climate Change and the Kyoto Protocol

The United Nations Framework Convention on Climate Change ("UNFCCC") opened for signature in 1992 and entered into force in 1994. In its report on geoengineering and governance, the Royal Society noted that, in combination with the Kyoto Protocol, the UNFCCC has a significant institutional structure for the international governance of climate change and its secretariat already cooperates with that of two other environmental conventions (the CBD and the UN Convention to Combat Desertification) on mutually supportive activities.[72] Under the UNFCCC, Parties are required to: (1) gather and share information on greenhouse gas ("GHG") emissions, national policies, and best practices, (2) launch national strategies for addressing GHG emissions and adapting to expected impacts, and (3) cooperate in preparing for adaptation to the impacts of climate change. The UNFCCC does not set binding targets for GHG emissions. Instead, it provides a structure for international consideration of the issue of climate

[67] *Id.* at Art. 8(g)-(h).

[68] *Id.*

[69] UNEP/CBD/COP/9/29, Decision IX/16, "Climate Change and Biodversity," *available at* http://www.cbd.int/doc/decisions/cop-09/full/cop-09-dec-en.pdf.

[70] *Id.*

[71] THE ROYAL SOCIETY, *supra* note, at 37.

[72] *Id.* at 41.

change and states that climate change is of "common concern to humankind" but that any international response should take into account, among other factors, countries' "respective capabilities."

The Kyoto Protocol was opened for signature in 1997 and entered into force in 2005. It is designed to implement the UNFCCC by committing its industrialized state Parties ("Annex 1" countries) to legally binding reductions in emissions of greenhouse gases. Specifically, the Kyoto Protocol requires Annex I countries to reduce their aggregate greenhouse gas emissions by 5% below 1990 levels by 2012. This goal is often-called the "first round" of emissions targets under the Kyoto Protocol. One of the goals the 2009 Copenhagen Conference was to develop a "second round" emissions targets for Annex 1 Parties. However, this goal was not achieved.[73]

Like the UNFCCC, the Kyoto Protocol calls on *all* Parties to take certain steps relating to national and regional programs to mitigate climate change, the promotion and transfer of environmentally sound technologies, and the identification of domestic greenhouse gas sinks. The Kyoto Protocol established a Compliance Committee responsible for, among other duties, applying consequences for Parties that do not meet their commitments. For more on the obligations contained in the Kyoto Protocol, read CRS Report RL33826, *Climate Change: The Kyoto Protocol, Bali "Action Plan," and International Actions*, by Jane A. Leggett.

While the Copenhagen Conference did not set a "second round" of emissions reduction targets for Annex 1 Parties of the Kyoto Protocol, it did produce a non-binding political outcome, the Copenhagen Accord, with which Parties may indicate their intent to associate. The Accord represents a bottom-up approach to climate change: Annex 1 Parties of the UNFCCC are asked to develop their own individual emissions targets for 2020 and to measure, report, and verify their progress towards these targets pursuant to guidelines adopted by the UNFCCC Conference of the Parties ("COP").[74] Similarly, non-Annex 1 Parties are asked to develop "mitigation actions" for the reduction of GHG emissions, though not emissions *targets*, and measure, report, and verify their implementation of these actions.[75]

U.S. Action

The United States ratified the United Nations Framework Convention on Climate Change ("UNFCCC") in 1992. It signed but has not become a party to the Kyoto Protocol. It has indicated its intent to associate with the Copenhagen Accord.

Action by Selected Other Countries and Entities

China has been bound by the UNFCCC since 1993 and the Kyoto Protocol since 2002. It has indicated its intent to associate with the Copenhagen Accord.

The European Union has been bound by the UNFCCC since 1993 and the Kyoto Protocol since 2002. It has indicated its intent to associate with the Copenhagen Accord.

[73] Under the "Bali Road Map" developed by the 2007 UN Climate Change Conference, there were two goals of Copenhagen Conference: (1) set post-2012 emissions targets for Annex 1 Parties of the Kyoto Protocol and (2) reach a new agreed outcome among *all* UNFCCC Parties regarding greenhouse gas (GHG) mitigation targets or actions. While Copenhagen failed to achieve the first goal, some have argued it did achieve the second, even though the agreed outcome, the Copenhagen Accord, is a non-binding political agreement.

[74] Copenhagen Accord, Art. 4.

[75] *Id.* at Art. 5.

India has been bound by the UNFCCC since 1993 and the Kyoto Protocol since 2002. It has indicated its intent to associate with the Copenhagen Accord.

Japan has been bound by the UNFCCC since 1993 and the Kyoto Protocol since 2002. It has indicated its intent to associate with the Copenhagen Accord.

Russia has been bound by the UNFCCC since 1994 and the Kyoto Protocol since 2004. It has indicated its intent to associate with the Copenhagen Accord.

A list of the parties of the UNFCCC and Kyoto Protocol is available at http://unfccc.int/parties_and_observers/items/2704.php. For accession information on developed countries, follow the "Annex I" hyperlink, and for accession information on developing countries, follow the "Non-Annex I" hyperlink.

For links to the submissions of Annex I parties relating to the Copenhagen Accord, visit http://unfccc.int/home/items/5264.php, and, for links to the submissions of non-Annex I parties, visit http://unfccc.int/home/items/5265.php.

Selected Provisions with Potential Relevance to Geoengineering

Article 4 of the UNFCCC: Commitments

Under Article 4 of the UNFCCC, Parties must formulate, implement, and update national, and where appropriate, regional programs containing measures to mitigate climate change as well as measures to facilitate adequate adaptation to climate change.[76] When a Party implements this mandate, it must communicate information related to that implementation to the Conference of the Parties.[77] Consequently, if a UNFCCC Party is using geoengineering currently as a national measure to mitigate or adapt to climate change, it needs to communicate that to the Conference of the Parties.

In addition, Article 4 requires Parties to promote and cooperate on the sustainable management, conservation, and enhancement of sinks and reservoirs of greenhouse gases, which includes biomass, forests, and oceans.[78] In the context of some potential geoengineering projects, a conflict could arise between *enhancing* a greenhouse gas sink or reservoir and either conserving it or managing it sustainably since, by enhancing the capacity of a sink or reservoir to absorb carbon dioxide, one may degrade it. However, Article 4.1(f) requires Parties to employ climate change measures "with a view to minimizing adverse effects" on the environment, the economy, and public health. This provision would arguably weigh in favor of an interpretation of enhancement that would exclude geoengineering projects with potentially numerous or severe adverse effects.

Article 4 also requires Parties to cooperate in preparing for adaptation to the impacts of climate change.[79] One could, potentially, argue that geoengineering is a form of this transboundary cooperation and frame

[76] UNFCCC, Art. 4.1(b); *see also* Art. 4.2(a) (reiterating this commitment for *developed* countries).

[77] UNFCCC, Art. 4.1(j).

[78] *Id.* at Art. 4.1(d); *see also* Art. 4.2(a) (reiterating this commitment for *developed* countries).

[79] UNFCCC, Art. 4.1(e).

geoengineering projects as *adaptation* to climate change rather than measures to *mitigate* climate change. The UNFCCC does not define adaptation to definitively preclude this position.[80]

Article 4 requires Parties to cooperate in the full, open, and prompt exchange of relevant scientific, technological, and other information related to the climate system and climate change and to the consequences of various response strategies.[81] This provision would appear to mandate that any UNFCCC Party that engaged in geoengineering research exchange information resulting from that research with the other Parties.

Article 4 reiterates these commitments for developed countries, effectively asking them to take policies and measures that "will demonstrate that developed countries are taking the lead in modifying longer-term trends in anthropogenic emissions."[82] This language could be interpreted to place developed countries in a leadership position on geoengineering projects. It also leaves open the door for developed countries to implement climate change policies and measures *jointly* and assist other Parties in combating climate change.[83]

Article 5 of the UNFCCC: Research and Systematic Observation

As for research, the UNFCCC requires Parties to promote access to data and analyses obtained from areas beyond national jurisdiction.[84] This could be read to require the sharing of information from a Party's geoengineering project on the high seas or in outer space, for example, with other Parties.

Article 3.3 of the Kyoto Protocol and Provisions of the Copenhagen Accord: Carbon Sinks

One of the most contentious issues in the negotiations over Kyoto Protocol rules is how to give nations credit for carbon sinks: forest or land uses that absorb carbon from the atmosphere so as to reduce the net additions a country makes to carbon dioxide levels in the atmosphere. Article 3.3. of the Kyoto Protocol states that the net changes in greenhouse gas emissions resulting from human-induced land-use change and forestry activities may be used to meet the emission reduction targets of each Annex I country. However, Article 3.3 appears to only permit net emissions changes to be used to meet reduction targets when they result from changes in *land*-uses or *forestry* (either afforestation, reforestation, or deforestation). The opportunity presented by Article 3.3 for geoengineering projects to be used to meet Kyoto Protocol targets, therefore, does not seem to exist for *air* or *ocean* geoengineering activities.

The Copenhagen Accord provides much less explicit guidance on the role of carbon sinks, and countries' use and enhancement of those sinks, in meeting its submitted commitments on emissions targets or, for developing countries, mitigation actions. Article 6 of the Copenhagen Accord states that the Parties "recognize the crucial role of reducing emissions from deforestation and forest degradation." In Article 7 states the Parties decision "to pursue various approaches...to enhance the cost-effectiveness of, and to promote mitigation actions." Finally, Article 11 states that the Parties will "establish a Technology Mechanism to accelerate technology development and transfer in support of action on adaptation and mitigation..." Given the generality of these statements, they can be read to promote some geoengineering

[80] *See id.*, Art. 1.

[81] *Id.* at Art. 4.1(h).

[82] UNFCCC, Art. 4.2(a) (emphasis added).

[83] *Id.*

[84] *Id.* at Art. 5 (b).

projects and geoengineering-technology transfer, but, at this early stage, the extent of that promotion is far from clear.

Countries considering researching or implementing a geoengineering project under the auspices of a UNFCCC-related agreement's provisions on carbon sinks will presumably review methodology reports and guidelines issued by the Intergovernmental Panel on Climate Change ("IPCC"). These are generally considered the worldwide standard for best practice in emissions inventories and frequently used by UNFCCC Parties.

Table: Table of Selected Parties to International Agreements Discussed

	United States	China	European Union	India	Japan	Russia
UNCLOS		X	X	X	X	X
London Convention	X	X	By Country		X	X
London Protocol		X	By Country		X	
CBD		X	X	X		
UNFCCC	X	X	X	X	X	X
Kyoto Protocol		X	X	X	X	X
Copenhagen Accord	A	A	A	A	A	A

Source: Congressional Research Service

Notes: An 'X' indicates that the country is a party to the international agreement; an 'A' indicates that it has stated its intent to associate with the agreement. The European Union did not ratify the London Convention and London Protocol as a single unit, leaving the individual nations to decide whether to ratify/accede to the agreements.

Selected Other Multilateral Treaties with Possible Ramifications for Geoengineering

Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space ("Outer Space Treaty")[85]

The Agreement Governing the Activities of States on the Moon and Other Celestial Bodies ("Moon Treaty")[86]

United Nations Convention to Combat Desertification ("UNCCD")[87]

[85] More information available at http://www.oosa.unvienna.org/oosa/SpaceLaw/outerspt.html

[86] More information available at http://www.oosa.unvienna.org/oosa/SpaceLaw/moon.html

[87] More information available at http://www.unccd.int

Convention on the Prohibition of Military or Other Hostile Use of Environmental Modification Techniques ("ENMOD")[88]

Convention on Long-range Transboundary Air Pollution ("CLRTAP")[89]

Convention on the Conservation of Antarctic Marine Living Resources ("CCAMLR")[90]

Convention on Fishing and Conservation of the Living Resources of the High Seas[91]

[88] Text available at http://www.un-documents.net/enmod.htm

[89] More information available at http://www.unece.org/env/lrtap

[90] More information available: http://www.ccamlr.org

[91] Text available at http://untreaty.un.org/ilc/texts/instruments/english/conventions/8_1_1958_fishing.pdf