



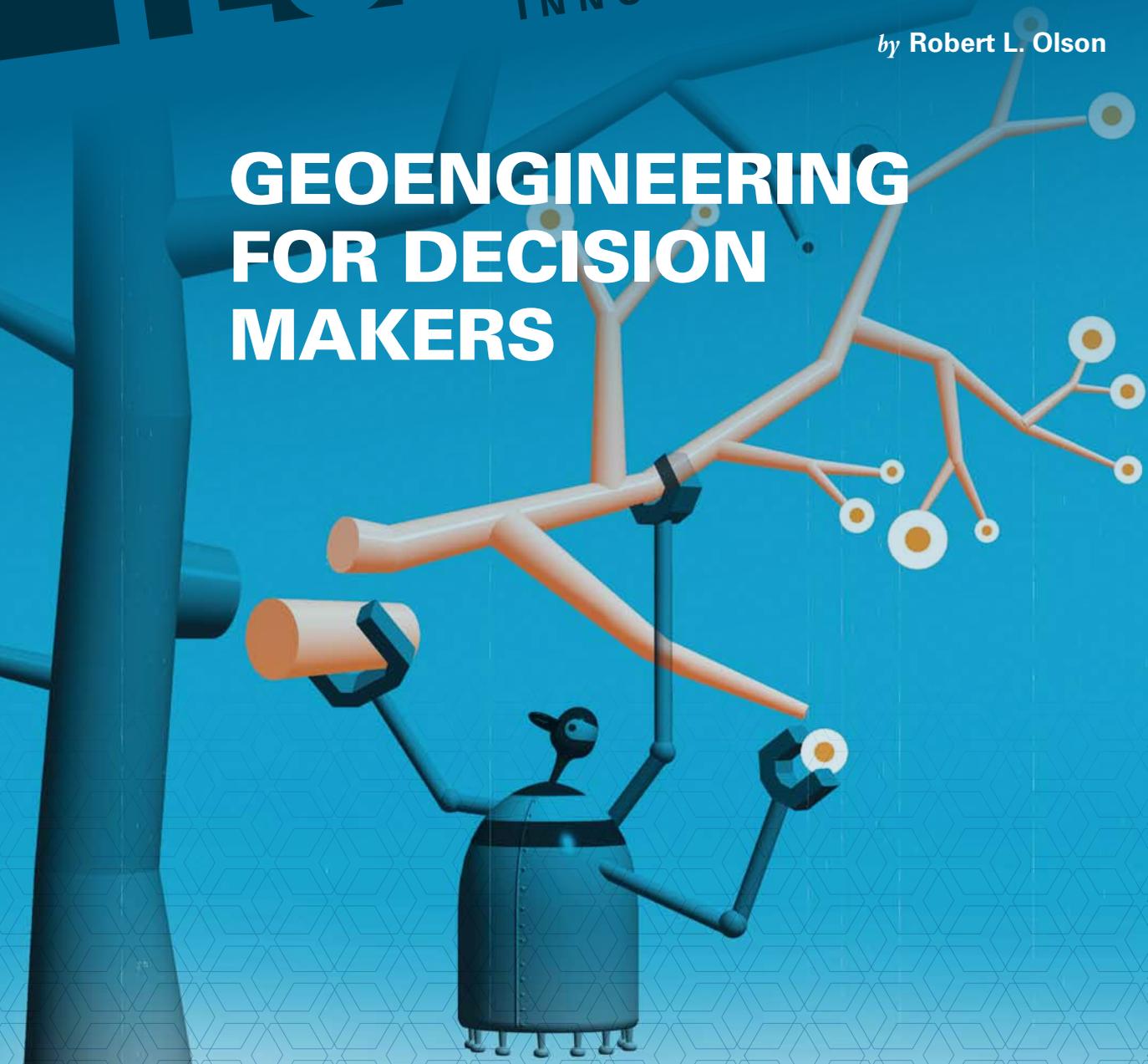
Woodrow Wilson
International
Center
for Scholars

STIP 02
NOVEMBER 2011

SCIENCE+ TECHNOLOGY INNOVATION PROGRAM

by Robert L. Olson

GEOENGINEERING FOR DECISION MAKERS



Suggested citation:

Washington, DC: Science and Technology Innovation Program, Woodrow Wilson International Center for Scholars, November 2011.

<http://www.wilsoncenter.org/publication-series/technology-assessment>



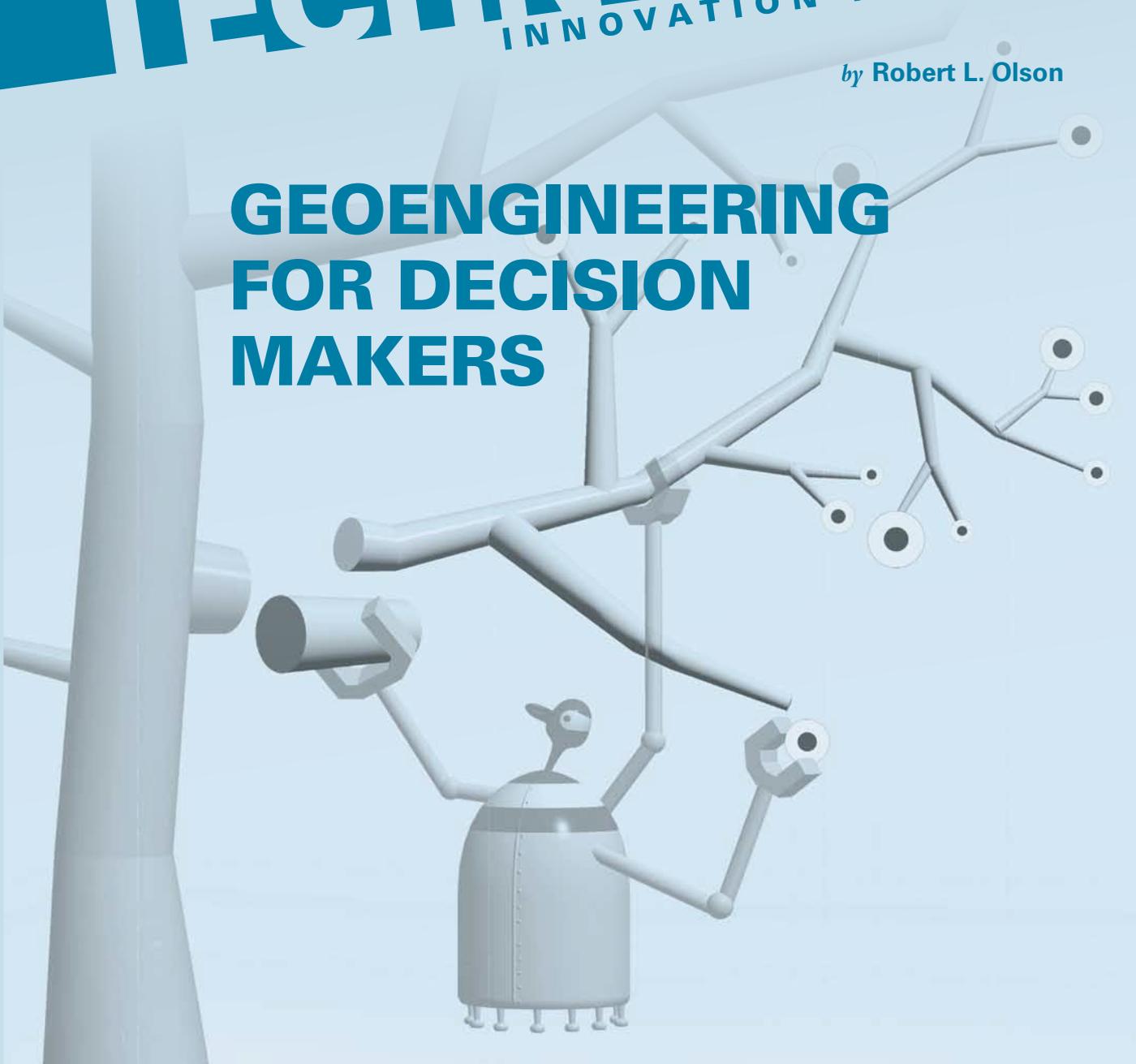
Woodrow Wilson
International
Center
for Scholars

SCIENCE + TECHNOLOGY

INNOVATION PROGRAM

by Robert L. Olson

GEOENGINEERING FOR DECISION MAKERS



Contents

v	Abbreviations and Acronyms
vi	About the Author
vii	Acknowledgments
viii	Executive Summary
1	Introduction
	The Larger Context
	Climate Change Management
	Geoengineering Methods
	History of Geoengineering
9	1. Major Concerns about Geoengineering
	Unintended Negative Consequences
	Potential Ineffectiveness
	Risk of Undermining Emissions-Mitigation Efforts
	Risk of Sudden Catastrophic Warming
	Equity Issues
	Difficulty of Reaching Agreement
	Potential for Weaponization
	Reduced Efficiency of Solar Energy
	Danger of Corporate Interests Overriding the Public Interest
	Danger of Research Driving Inappropriate Deployment
19	2. Can We Reduce Greenhouse Gas Emissions Fast Enough?
	Climate Trends
	Dangerous Climate Change
	Tipping Points
	Preventing Dangerous Climate Change

27 3. Geoengineering Scenarios

Scenarios

Failure Modes

31 4. Geoengineering Governance

Should R&D on Geoengineering Be Supported?

Importance of Upstream Governance

Field Experiments and Deployment

41 5. Recommendations for Decision Makers

Boxes

- 3** Box 1: Is Geoengineering Being Defined Too Narrowly?
- 8** Box 2: Recent Controversies
- 36** Box 3: The Asilomar International Conference on Climate Intervention Technologies
- 38** Box 4: UN Convention on Biological Diversity Moratorium on Geoengineering Experiments

Figures

- 4** Fig 1: Climate Change Management
- 6** Fig 2: U.S. Media Coverage of Geoengineering: 2005-2010
- 33** Fig 3: Upstream Governance Strategies

Tables

- 10** Table 1: Solar Radiation Management Technologies (SRM)
- 12** Table 2: Carbon Dioxide Removal Technologies (CDR)
- 14** Table 3: Ranking the Cooling Power of Geoengineering Options

Abbreviations & Acronyms

CDC	Centers for Disease Control and Prevention
CDR	carbon dioxide removal
CRS	Congressional Research Service
CTA	constructive technology assessment
ECAST	Expert & Citizen Assessment of Science & Technology Network
DBT	Danish Board of Technology
GAO	Government Accountability Office
GHG	greenhouse gas
NAS	National Academy of Sciences
NCTF	National Citizens' Technology Forum
NIH	National Institutes of Health
NISEnet	Nanoscale Informal Science Education Network
NRC	National Research Council
OSTP	White House Office of Science and Technology Policy
OTA	Office of Technology Assessment
pTA	participatory technology assessment
PTA	Parliamentary Technology Assessment
R&D	research and development
S&T	science and technology
SRM	solar radiation management
STIP	Science and Technology Innovation Program
STS	science, technology and society
TA	technology assessment
WWViews	World Wide Views on Global Warming

About the Author

Robert L. Olson is a Senior Fellow at the Institute for Alternative Futures. He was previously the Institute's Director of Research and a member of its founding Board of Directors. Much of his recent work has focused on the environmental future, including projects with the U.S. Environmental Protection Agency (EPA) to bring greater foresight into the Agency's planning. He is a member of the National Advisory Council for Environmental Technology and Policy (NACETP) and the primary author of the NACEPT report *The Environmental Future*. He is the author of *Exploring the Future*, editor of *Mending the Earth* and co-editor with David Rejeski of *Environmentalism and the Technologies of Tomorrow*. Formerly he served as a consultant to the Director and a Project Director at the Office of Technology Assessment of the U.S. Congress. He was for several years a Fellow of the Center for Cooperative Global Development at the American University and has been a Resident Fellow at the University of Illinois Center for Advanced Study.

Acknowledgments

Many people assisted in developing and reviewing this report. First and foremost was *David Rejeski*, Director of the Science and Technology Innovation Program at the Woodrow Wilson International Center for Scholars, who suggested the idea for the report and contributed heavily to the development of ideas about the upstream governance of geoengineering. The work benefited greatly from the comments of several reviewers. *Robert J. Berg* made suggestions about geoengineering governance and several other topics covered in the paper, drawing on his background as a Senior Advisor to a number of parts of the United Nations (UN), including his role in proposing and co-authoring the UN's Millennium Development Goals and his involvement in a UN expert group concerned with the governance implications of climate change. *David Keith* at the University of Calgary in Canada, one of the leading experts on geoengineering and on the interface between climate science, energy technology and public policy, helped fine tune several of the report's recommendations. *Philip Rasch*, the Chief Scientist for Climate Science at the Department of Energy's Pacific Northwest National Laboratory (PNNL) made many suggestions for making the report more balanced and clarified some technical issues. *Braden Allenby*, Professor of Civil and Environmental Engineering and of Law at Arizona State University, challenged the conventional approach to geoengineering, the way it is defined and the range of technologies that are treated as relevant, and stressed the larger context of moving toward a future where humans take greater responsibility for the management of Earth systems. *Gayle Hagler* at the EPA's National Risk Management Laboratory helped refine a number of assertions made in the report, including many of the technical points concerning climate change. *Clement Bezold*, Founder and Chairman of the Board of the Institute for Alternative Futures, contributed ideas about alternative scenarios for the future of geoengineering, both in reaction to a draft and in our work together on a geoengineering report being developed by the U.S. Government Accounting Office. I would also like to thank *Walter Truett Anderson* for bringing me into some informal but scholarly discussions of geoengineering governance that kindled my interest in the subject.

Executive Summary

Geoengineering involves intentional, large-scale interventions in the Earth's atmosphere, oceans, soils or living systems to influence the planet's climate. Geoengineering is not a new idea. Speculation about it dates at least to 1908, when Swedish scientist Svante Arrhenius suggested that the carbon dioxide released from burning fossil fuels might help prevent the next ice age. Until recently, proposals for using geoengineering to counteract global warming have been viewed with extreme skepticism, but as projections concerning the impact of climate change have become more dire, a growing number of scientists have begun to argue that geoengineering deserves a second look.

Below are 10 of the major concerns about geoengineering that policy makers need to be aware of and give due consideration. These concerns apply mainly to Solar Radiation Management (SRM), the form of geoengineering that attempts to cool the climate by reflecting a small amount of solar radiation back into space. SRM involves significantly higher risks than the other form of geoengineering, Carbon Dioxide Removal (CDR) which involves removing carbon dioxide from the atmosphere and storing it in the ocean, plants, soil or geological formations

- **Unintended Negative Consequences** – We may know too little about the Earth's geophysical and ecological systems to be confident we can engineer the climate on a planetary scale without making an already bad situation even worse;
- **Potential Ineffectiveness** – Some proposed CDR methods are so weak that they would produce useful results only if sustained on a millennial timescale;
- **Risk of Undermining Emissions-Mitigation Efforts** – If politicians come to believe that geoengineering can provide a low-cost “tech fix” for climate change, it could provide a perfect excuse for backing off from efforts to shift away from fossil fuels;
- **Risk of Sudden Catastrophic Warming** – If geoengineering is used as a substitute for emissions reduction, allowing high concentrations of CO₂ to build up in the atmosphere, it would create a situation where if the geoengineering ever faltered because of wars, economic depressions, terrorism or any other reasons during the millennium ahead, a catastrophic warming would occur too quickly for human society and vast numbers of plant and animal species to adapt;
- **Equity Issues** – Geoengineering efforts might succeed in countering the warming trend on a global scale, but at the same time cause droughts and famines in some regions;

- **Difficulty of Reaching Agreement** – It could be harder to reach global agreements on doing geoengineering than it is to reach agreements on reducing carbon emissions;
- **Potential for Weaponization** – Geoengineering research could lead to major advances in knowledge relevant for developing weather control as a military tool;
- **Reduced Efficiency of Solar Energy** – For every 1 percent reduction in solar radiation caused by the use of SRM geoengineering, the average output of concentrator solar systems that rely on direct sunlight will drop by 4 to 5 percent;
- **Danger of Corporate Interests Overriding the Public Interest** – Dangers include a lack of transparency in SRM technology development and the possibility that the drive for corporate profits could lead to inappropriate geoengineering deployments;
- **Danger of Research Driving Inappropriate Deployment** – Research programs have often created a community of researchers that functions as an interest group promoting the development of the technology that they are investigating.

As problematic as geoengineering is, a growing number of scientists now view global climate change as such a serious threat that they feel no option for dealing with it, including geoengineering, can be taken off the table. There is no longer any doubt that the average temperature of the Earth's atmosphere and oceans is rising. There is an overwhelming consensus in the scientific community that human activities are significant contributors to this temperature increase, even if other dynamics are also at work. There are still uncertainties about how fast the climate will change and even larger uncertainties about the impacts climate change could have in different parts of the world. But there is substantial agreement that the impacts could become dangerous over the decades ahead. The greatest danger is that we could pass "tipping points" of self-amplifying, irreversible change into a much hotter world.

Several of the best climate studies suggest that stabilizing the amount of carbon dioxide and other greenhouse gases below the level that risks dangerous climate change will require a social mobilization and technological transformation at a speed and scale that has few if any peacetime precedents. If correct, and the needed mobilization does not occur in the years immediately ahead, then decision makers later in the century could find themselves in a situation where geoengineering is the only recourse to truly dangerous climate change. The most fundamental argument for R&D on geoengineering is that those decision makers should not be put in a position of either letting dangerous climate change occur or deploying poorly evaluated, untested technologies at

scale. At the very least, we need to learn what approaches to avoid even if desperate. As concerns about climate change grow and the possibility that we may have to resort to geoengineering to avert a climate catastrophe begins to be taken more seriously, several different viewpoints are emerging about how geoengineering should or could be developed and used. Most of this range of opinion can be described in terms of six scenarios of how events could unfold:

- **No Geoengineering** – Whether from inertia or opposition, little R&D is done and we rely on mitigation and adaptation to deal with climate change.
- **Safe Carbon Dioxide Removal Only** – CDR technologies are developed to complement emissions reduction, but the use of SRM technologies is rejected as too problematic.
- **Technology Transformation** – A burst of private sector innovation and large increases in government spending for R&D create breakthroughs in energy technology that make it possible to reduce carbon emissions quickly, making SRM geoengineering unnecessary.
- **Insurance Policy** – A growing concern that it may not be possible to avoid dangerous climate change with emissions reduction alone leads to increasingly urgent efforts to develop SRM as an insurance policy against climate catastrophe.
- **Needed Soon** – Rapidly rising methane emissions from melting arctic permafrost convinces scientists that SRM geoengineering needs to be used as soon as possible to prevent the world from passing an irreversible climate tipping point.
- **Do It All** – As events drive home the reality of climate change there is a major international effort to cut carbon emissions and substantial R&D funding for both CDR and SRM.

Each of these scenarios is different with respect to decisions made by society, costs to society, risks to society, and potential benefits to society. Wise and adaptive decision making will be needed to avoid a variety of potential “failure modes.” The nature of the governance process we develop for making those decisions will be a major factor shaping how the future unfolds.

The report reviews the challenges of geoengineering governance and argues for giving much greater attention to *upstream governance* strategies such as ethical, legal and social implications (ELSI) studies, lab-scale intervention, and participatory technology

assessment (PTA) that are applicable early on, beginning even with theoretical studies, modeling, and laboratory experiments. The report also examines the challenge of *downstream governance* where agreed upon processes will be needed for approving large-scale field experiments as well as actual deployments, if they should prove necessary. Further, it suggests a number of principles that decision makers can follow going forward. These principles are as follows:

- Always consider geoengineering issues in a broader context of *climate change management*, which includes emissions reduction as the primary strategy and adaptation as the secondary strategy, with geoengineering as a third strategy to use only if clearly needed.
- Address the climate problem and geoengineering in the context of related challenges, such as energy security, vulnerability to terrorism, water scarcity and food security, ocean health, economic competitiveness and job creation.
- Commit the U.S. fully to leadership in creating an advanced 21st-century energy infrastructure that incorporates major improvements in energy efficiency and dramatic reductions in carbon dioxide emissions.
- Support significantly greater funding for energy research and development (R&D) on high-risk, high-reward energy supply options that could be game changers if they prove feasible.
- Do not take geoengineering off the table as an option for helping to address the climate problem, but do not allow funding for geoengineering-related activities to reduce support for or divert funding from R&D on energy efficiency and carbon-free energy sources, climate science research or adaptation efforts.
- Do not allow geoengineering to be used as a source of carbon offsets.
- Distinguish between the two different approaches to geoengineering — carbon dioxide removal (CDR) and solar radiation management (SRM). In general, SRM poses greater risks and requires more evaluation and regulation.
- Never treat SRM methods – especially the more powerful ones such as stratospheric aerosols, cloud brightening and space-based approaches – as a substitute for emissions mitigation.
- Do not consider deployment of stratospheric aerosols, cloud brightening or space-based methods in the near term.

- In R&D on SRM methods, give more attention to the idea of regional geoengineering or “geoadaptation,” which could have more localized, “where needed” effects and be especially important for use in polar areas to limit permafrost thawing, ice sheet melting, and sea level rise.
- Acknowledge that many geoengineering methods have significant uncertainties about their likely costs, effectiveness and risks, and support rigorous and fully transparent research efforts to reduce these uncertainties.
- Learn as much as possible, as soon as possible, about geoengineering’s potential environmental impacts and its ethical, legal and social implications, using a portfolio of upstream governance approaches.
- Insist that all SRM research be in the public domain, and stand firm in a commitment to openness, transparency and accessibility.
- Recognize that developing needed agreements on large-scale testing will be easier to the extent that research is internationalized from an early stage. Support the development of a coordinated, fully transparent international effort in which the work of individual scientists and national programs is integrated into an international framework.
- A moratorium on large-scale or “climate impact” testing should be put in place until a legitimate international process for approval and oversight has been agreed upon.
- Begin working to develop the “downstream” governance arrangements that will be needed for authorizing both large-scale testing and actual deployment. As a first step, organize informal international dialogues where participants can think together and share concerns without having to take positions or votes.

Introduction

In his book *Against All Enemies*, former counter-terrorism czar Richard Clarke described the small group of international security experts who were running around Washington, D.C., in 2000 and 2001 with their “hair on fire” trying to warn policy makers of the growing likelihood of a major terrorist attack on the United States. Today, it is the scientists working on climate change with their hair on fire, pleading with governments around the world to face up to the magnitude of the climate challenge and warning that we may be approaching a “tipping point” where the problem will go out of control.

These scientists have good cause for alarm. On the one hand, climate change appears to be moving faster than in even the gloomiest scenarios described in *Climate Change 2007*, the fourth assessment report of the Intergovernmental Panel on Climate Change (IPCC).¹ On the other hand, the UN Climate Summit in Copenhagen was a near failure; the U.S. Congress has failed to pass even weak climate legislation; and charges that climate scientists have been hiding data, covering up errors and suppressing alternative views have damaged

public trust in the scientific enterprise. All this is causing growing concern about whether greenhouse gas (GHG) emissions can be reduced rapidly enough to prevent dangerous, highly disruptive climate change. Most political leaders now acknowledge that climate change is a real and important issue, but as former Vice President Al Gore put it at the 2007 UN climate conference in Bali, “The truth is that the maximum now considered possible ... is still far short of the minimum that will really solve the problem.”²

Concerns about rapid climate change, slow political progress in reducing emissions and unsettling uncertainties about dangerous climate

As conventionally defined, geoengineering involves intentional, large-scale interventions in the Earth’s atmosphere, oceans, soils or living systems to cool the Earth.

tipping points are leading some scientists and policy makers to consider the possibility of combining efforts to reduce greenhouse gas emissions with another approach to limiting climate change – geoengineering.

As conventionally defined, geoengineering involves intentional, large-scale interventions in the Earth's atmosphere, oceans, soils or living systems to cool the Earth. The U.S. National Academy of Sciences defines it as “options that would involve large-scale engineering of our environment in order to combat or counteract the effects of changes in atmospheric chemistry.”³

The Larger Context

Many people who are skeptical about climate change find it hard to believe that humans can have any significant impact on the functioning of our entire planet with its vast oceans and land areas. It is important, therefore, to understand that we are already engaged in planetary-scale interventions that are often unintentional or destructive.

For example, the stratospheric ozone layer that protects the Earth from damaging levels of ultraviolet radiation was severely depleted by the production of chlorofluorocarbon (CFC) compounds that were inert in the lower troposphere but turned out to be photochemically reactive in the stratosphere. The impacts on human society and the biosphere could have been disastrous if satellite images of the “ozone hole” over Antarctica had not catalyzed efforts to restrict CFC production and protect the ozone layer. Fossil fuel burning has pushed the concentration of carbon dioxide (CO₂) in the atmosphere up by more than a third since pre-industrial times. Industrial processes are fixing nitrogen at a rate equal to that of nature, and the resulting over-fertilization has already created hundreds of “dead zones” in the world's oceans. Human actions consume or destroy roughly half

of nature's photosynthetic output each year, leaving too little for other species. Over half of all the accessible fresh water running off the continents to the sea is intercepted for human use. Rivers like the Colorado, Yellow, Ganges and Nile are so heavily used that they no longer reach the oceans in the dry season. Half the world's wetlands, tropical forests and temperate forests have disappeared as a result of human activity. An estimated 90 percent of large predator fish are gone. Because of human-caused habitat destruction, pollution and climate change, species around the world are disappearing at rates about a thousand times faster than normal.⁴

In brief, we are engineering the Earth, often to its detriment. The key question posed by climate change is whether we can intentionally back off our emissions of carbon dioxide and other greenhouse gases that are destabilizing the Earth's climate. The key question posed by geoengineering is whether it is acceptable to consider making new, more intentional and systematic large-scale interventions in Earth systems to protect humans and other species from dangerous climate change.

The larger context for thinking about climate change and geoengineering is our entry into what atmospheric chemist Paul Crutzen first called the “Anthropocene Epoch.”⁵ Or, as Brad Allenby at Arizona State University puts it, we have gone from “the Earth” to “the anthropogenic Earth,” in which the dynamics of major natural systems are increasingly affected by human activity.⁶ Political scientist Walter Truett Anderson was among the first to develop this perspective in a comprehensive manner. His 1987 book *To Govern Evolution: Further Adventures of the Political Animal* portrays the human species – confronted with the recognition of its increasing impacts on the Earth's atmosphere and ecosystems – finding itself in an unavoidable, challenging new role of growing responsibility for the welfare and future evolution of life on the planet.⁷

BOX 1.**Is Geoengineering Being Defined Too Narrowly?**

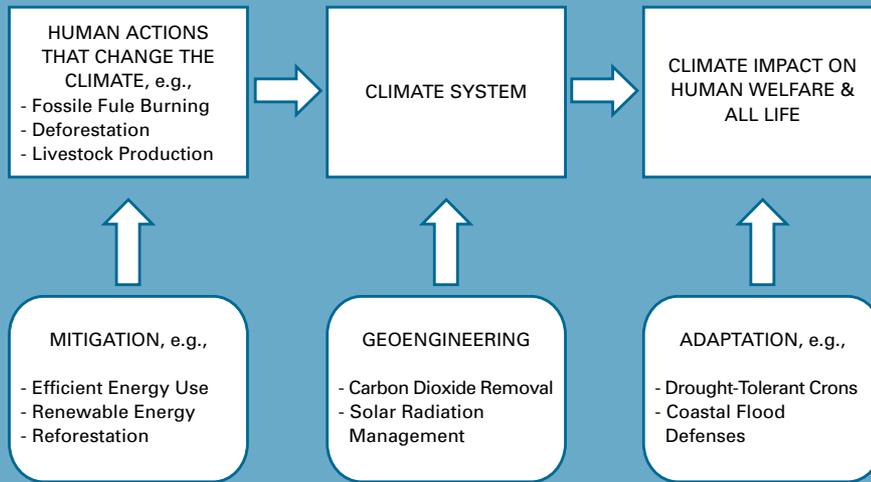
Geoengineering is typically defined as dealing only with climate change and approached as a straightforward, if difficult, engineering problem. Brad Allenby, a thought leader in the field of Earth Systems Engineering, argues that this definition results in a single-minded focus on technologies with just one function – reducing the impacts of climate change if cumulative GHG emissions become dangerously high. This narrow focus unnecessarily restricts the range of geoengineering strategies and technologies considered. What is needed is a broader definition of geoengineering as intentional, large-scale manipulation of Earth systems. Because these complex physical, biological and social systems are highly interconnected and co-evolving, focusing exclusively on one particular aspect – the climate system – will create unintended consequences and systemic risks, especially if policies focused on only this one aspect drive the approach to all the others.⁹

Understanding this leads to recognition that constructive approaches may appear laterally from many parts of the whole socio-technical environment, and that the best approaches will usually have beneficial effects across a wide range of problems and potential opportunities. For example, emerging methods to produce “cultured” or “in vitro” meat from stem cells in factories may have the potential to have large climatic impacts as well as being healthier, less polluting and more humane than conventional meat production methods. Fat content could easily be controlled. The incidence of food-borne disease could be dramatically reduced, thanks to strict quality control rules that are impossible to introduce in modern animal farms, slaughterhouses and meat packing plants. The use of hormones and antibiotics would be unnecessary. Methane releases from livestock – a major contributor to climate change – could be eliminated, along with pollution from confined animal-feeding operations and chemical use in growing feed crops. Demands for water, energy and other resources could be cut sharply. Large land areas could be freed to plant vegetation that is much more effective than food crops in capturing and storing carbon.⁹ This strategy would not be recognized as “geoengineering” as the word is usually defined today. But given its impact on methane emissions, carbon storage, land use, water cycles and other Earth systems, this is arguably a more comprehensive “geoengineering” strategy than any technologies listed in the traditional literature.

This particular example is drawn from the rapid progress occurring in biotechnology. But equally rapid progress is occurring in nanotechnology and materials science and in information and communication technology, as innovations move from each of these areas to the others (what some term “converging technologies”). New and currently unimagined potentials for dealing with the climate situation may emerge from this “next technological revolution” as it unfolds over the generation ahead, but we could miss them if we define the set of technologies for dealing with climate change too narrowly.

Allenby argues that a sophisticated agenda for future research on geoengineering should move toward this larger perspective. This report begins to move in this direction. It focuses on the field of geoengineering as it exists today but insists that geoengineering be viewed as only one part of a broader strategy of climate change management, and that both geoengineering and climate change should be addressed in the context of finding “simultaneous solutions” to other challenges, such as energy security, vulnerability to terrorism, water scarcity and food security, ocean health, economic competitiveness and job creation.

FIGURE 1
Climate Change Management



Adapted from a presentation by David Keith on Solar Band Climate Engineering to the Spring 2009 meeting of the American Physical Society held in Denver Colorado on May 4, 2009.

Climate Change Management

Geoengineering should always be treated as one of three approaches for responding to climate change that together can be said to constitute the tools of *climate change management*.

- *Mitigation* is the primary strategy. It addresses the underlying cause of climate change by reducing the human-produced greenhouse gases that are affecting the climate system.
- *Adaptation* is the secondary strategy. It involves adapting to climate changes that cannot be prevented in order to reduce their impact on human welfare and the environment.
- *Geoengineering* involves influencing the climate system itself to moderate global warming. Because many geoengineering actions involve significant risks for massive negative consequences, these actions should be considered as back-up options for use only if mitigation and adaptation appear unable to prevent serious climate disruption. Figure 1 illustrates the relationship of these three approaches.

Geoengineering Methods

All geoengineering methods to dampen the greenhouse effect work by one of two approaches: (1) by reflecting a small amount of solar radiation back into space (solar radiation management, or SRM); or (2) by removing carbon dioxide from the atmosphere and storing it in the ocean, plants, soil or geological formations (carbon dioxide removal, or CDR).¹⁰

The most powerful SRM methods, once deployed, would quickly have an effect on climate. For this reason, they might be useful when a rapid response is needed; for example, if a climate tipping point appears imminent. Major SRM methods include:

- Mimicking the effects of volcanic eruptions by injecting aerosol particles into the stratosphere to block and reflect away solar radiation;
- Making clouds over large areas of ocean brighter and more reflective by lofting fine particles of salt in sprays of sea water; and
- Increasing the surface reflectivity of the planet by painting human structures like roofs and

pavements white, planting lighter-colored crops or covering desert areas with reflective materials.

CDR methods, by contrast, would work slowly over many decades. They could, however, have significant impacts over time. Unlike SRM methods, CDR technologies deal with the underlying problem of growing concentrations of CO₂ in the atmosphere and generally pose fewer risks of unintended negative side effects. Major CDR methods include:

- Improving land-use management to protect or enhance the ability of soils and vegetation to store and hold carbon dioxide;
- Doing reforestation and afforestation to capture and hold carbon dioxide in plant matter; possibly genetically engineering trees to absorb more carbon;¹¹
- Sequestering biomass in the oceans and in the soil as biochar;
- Accelerating natural mineral weathering processes that remove CO₂ from the atmosphere;
- Engineering technologies that capture CO₂ from ambient air;
- Enhancing the ocean's uptake of CO₂ by fertilizing parts of the ocean with iron or other nutrients, or by increasing upwelling processes; and
- Using lasers, microwave beams and the Earth's magnetic field to eject CO₂ from the atmosphere into space.

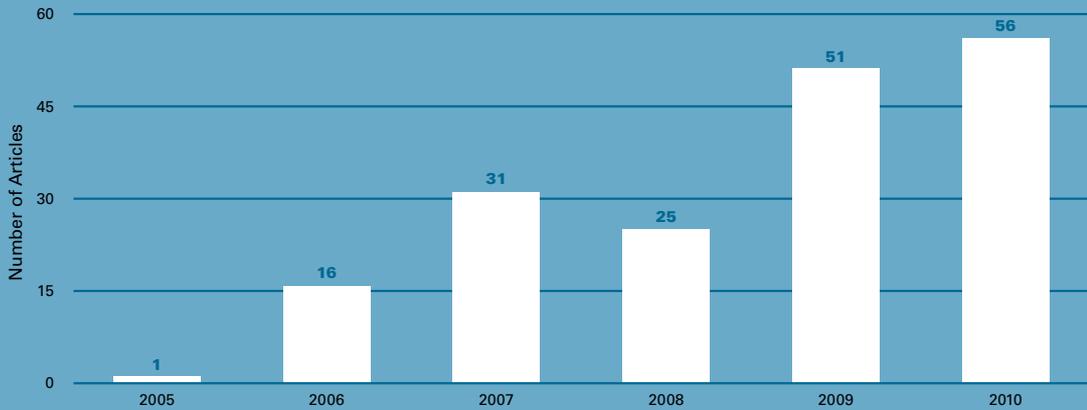
History of Geoengineering

Geoengineering is not a new idea. Speculation about it dates at least to 1908, when Swedish

scientist Svente Arrhenius suggested that the carbon dioxide released from burning fossil fuels might help prevent the next ice age.¹² The first serious proposals for using geoengineering to modify the climate were made in a 1965 report called *Restoring the Quality of Our Environment*, prepared for President Lyndon Johnson by the President's Science Advisory Committee.¹³ In retrospect, this was a landmark report, the first high-level acknowledgment of the reality of global climate disruption. The authors urged that "possibilities of deliberately bringing about countervailing climatic changes ... be thoroughly explored." In illustration, they suggested that the Earth's reflectivity could be increased by dispersing buoyant reflective particles over large areas of tropical ocean or by modifying high-altitude cirrus clouds. Interestingly, they did not even consider addressing the underlying cause of climate change by reducing the use of oil, coal and natural gas.

A few papers on geoengineering were published over the following three decades, notably by Freeman Dyson and by Edward Teller,¹⁴ but on the whole the scientific community took a wary stance. Geoengineering proposals were relegated to the fringes of the growing field of climate science. Few peer-reviewed journals would publish them. No governments would fund feasibility studies.

Climate scientist David Keith recalls that when he became interested in geoengineering as a graduate student 20 years ago, the topic could hardly be discussed in polite scientific company and was totally verboten in environmental circles.¹⁵ This attitude clearly discouraged people from working in the field. In a 2009 article in *Foreign Affairs*, David Victor and his colleagues wrote that until recently, "nearly the entire community of geoengineering scientists could fit comfortably in a single university seminar room and the entire

FIGURE 2**U.S. Media Coverage of Geoengineering: 2005-2010**

scientific literature on the subject could be read during the course of a transatlantic flight.”¹⁶

This skeptical attitude became dominant for good reasons. Many scientists are worried that we know too little about the Earth’s geophysical, ecological and climate systems to be confident that we could engineer changes on a planetary scale without making an already bad situation even worse. Scientists are also concerned that if politicians come to believe that geoengineering provides a low-cost “tech fix” for climate change, it would give them the perfect excuse for backing off from efforts to shift away from fossil fuels.

Despite these and many other good reasons for caution, a number of leading members of the scientific community have recently begun to change their views and argue that geoengineering deserves a second look. A 2006 editorial essay in the journal *Climatic Change*¹⁷ recommending research on the concept of cooling the Earth by injecting reflective aerosol particles into the stratosphere played an especially important role in making geoengineering a more legitimate topic. What gave this essay special weight was the background

of its author, Dutch atmospheric chemist Paul Crutzen. It was largely thanks to Crutzen that we skirted a previous global atmospheric threat: the destruction of the stratospheric ozone layer. His research unraveling the chemistry of stratospheric ozone depletion led to the global banning of CFCs and other ozone-depleting chemicals and earned him the 1995 Nobel Prize in Chemistry. Crutzen’s call for taking geoengineering seriously was supported by an editorial in the same issue of *Climatic Change* by atmospheric scientist Ralph J. Cicerone, currently the President of the U.S. National Academy of Sciences.

With scientists of this stature willing to break the taboo on thinking about geoengineering, other scientists have felt freer to look into the field. Since 2005 there has been an explosion of articles on the subject in both scholarly journals and the popular press, reflecting the growing interest in geoengineering as a strategy of climate change management and an increasing concern for environmental impacts of geoengineering proposals. Figure 2 above illustrates the dramatic increase in U.S. mainstream media coverage of the topic since 2005.¹⁸

Political decision makers are certain to face choices regarding geoengineering over the years ahead that will be highly controversial as well as fateful for the welfare of the nation and the planet.

By 2009, it was clear that the taboo against discussing geoengineering was largely gone. In April of that year, President Obama's Science Advisor, physicist John Holdren, stated that he had raised the subject of geoengineering in administration discussions, saying, "It's got to be looked at. We don't have the luxury of taking any approach off the table."¹⁹ A month later, Secretary of Energy Steven Chu, addressing the St. James's Palace Nobel Laureate Symposium in London, recommended a global initiative to help contain global warming by giving roofs, roads and pavements brighter, more reflective colors.²⁰ In June 2009, the U.S. National Academies held a two-day workshop on "Geoengineering Options to Respond to Climate Change: Steps to Establish a Research Agenda,"²¹ and in July the Novim Group released a report entitled *Climate Engineering Responses to Climate Emergencies*,²² which set out a decade-long agenda for research to reduce uncertainty surrounding the benefits and risks associated with the geoengineering concept of stratospheric aerosol injection. In September 2009, the Royal Society – the U.K.'s most prestigious scientific organization

– published the most comprehensive study of geoengineering options to date, *Geoengineering the Climate: Science, Governance and Uncertainty*.²³ In early 2010, the Committee on Science and Technology of the U.S. House of Representatives held major hearings on geoengineering.²⁴

This growing willingness to give geoengineering a second look is provoking a strong counter-reaction from other scientists, environmentalists and civil society groups who remain strongly opposed to geoengineering.²⁵ Some observers have questioned whether scientists and engineers, as a group, can even begin to address the social and ethical dimensions of intervening in complex, large-scale systems. Bill Wulf, former head of the National Academy of Engineering, said recently that "the complexity of newly engineered systems, coupled with their potential impact on lives, the environment, etc., raises a set of ethical issues that engineers have not been thinking about."²⁶ As a result, political decision makers are certain to face choices regarding geoengineering over the years ahead that will be highly controversial as well as fateful for the welfare of the nation and the planet.

BOX 2. Recent Controversies

Over the past few years a controversy has raged in the media about errors in the work of the Intergovernmental Panel on Climate Change (IPCC) and the soundness of the whole enterprise of climate science. How serious are the issues involved?

Critics have pointed to two main errors in the IPCC's *Fourth Assessment Report: Climate Change 2007*. The first error involves Himalayan glaciers. In a regional chapter on Asia in Volume 2 of the report, *Impacts, Adaptation and Vulnerability*, authors from the region erroneously projected that 80 percent of Himalayan glacier area would very likely be gone by 2035. The figure was taken from a non-peer-reviewed local source. However, the primary volume of the assessment report, *The Physical Science Basis*, contains a 45-page chapter by several of the world's leading glacier experts in which the correct projections are used. It was one of these experts, Georg Kaser from Austria, who first noticed and corrected the Himalaya error in Volume 2.

The second error in the IPCC report involves sea level in the Netherlands. Volume 2 of the report states that "the Netherlands is an example of a country highly susceptible to both sea level rise and river flooding because 55% of its territory is below sea level." This figure was provided by the Dutch government's own Environmental Protection Agency, which later published a correction stating that the sentence should have read "55% of Netherlands is at risk of flooding; 26% of the country is below sea level; and 29% is susceptible to river flooding."

These errors reflect a lapse in the high standards to which the IPCC tries to hold itself. But they are small errors that have no impact whatsoever on the larger picture of climate change being put together by the world's scientific community.

The same is true of the so-called Climategate controversy around e-mails written by scientists at the University of East Anglia in the U.K. Critics charged that the e-mails showed that data was being manipulated to make climate change look worse than it is. Four separate investigations have now cleared the scientists involved of all charges of wrongdoing, but the controversy does raise issues that always need to be attended to within the scientific community – issues of full openness and transparency of research and of rigor in acknowledging and analyzing uncertainties. In retrospect, however, the controversy did not call into question any specific aspects of the picture of climate change emerging from the scientific community.

The most serious issue posed by these recent controversies is not failures of climate science but the opening of the Overton window, a concept in political theory that describes a window or boundary within which people involved in public discussions have to stay to have their ideas taken seriously. In most of Western Europe, people who dismissed the reality of climate change went "outside the window" of legitimate discussion several years ago and were dismissed by the media as cranks. It took several more years for this to happen in the U.S. But now these controversies have opened wide the window, at least in the U.S. and the U.K. The views of climate change deniers and critics have been getting more exposure in the media than have the recent findings from the scientific community.

Serious damage has already been done. Gallup's annual update on Americans' attitudes toward the environment shows a public that over the last two years has become less worried about the threat of global warming, less convinced that its effects are already happening, and more likely to believe that scientists themselves are uncertain about its occurrence. In response to one key question, 48% of Americans now believe that the seriousness of global warming is generally exaggerated, up from 41% in 2009 and 31% in 1997, when Gallup first asked the question.

1. Major Concerns About Geoengineering

While there is a growing willingness to give geoengineering a second look, it is still a highly controversial topic. Most of the controversy and criticism deals with shortcomings and potential side effects of SRM geoengineering schemes, which pose much higher risks than CDR methods. But some critics argue a broader case, questioning the wisdom of doing any kind of geoengineering, at least given the current state of knowledge, and the absence of a governance regime to make it more likely that decisions of global import are made fairly and wisely. Below are 10 of the major concerns about geoengineering that policy makers need to be aware of and give due consideration. There are countering arguments that address some of these concerns and make the case for the potential benefits of geoengineering, but the objective here is to give voice to the major concerns that have been expressed in the literature on geoengineering and in other forums.

Unintended Negative Consequences

Many scientists – ecologists in particular – remain skeptical of SRM geoengineering, arguing that there are too many gaps and uncertainties in our understanding of geophysical and ecological systems to safely engineer the climate on a global scale.²⁷ Greater understanding could reduce the risks, but the climate system may be inherently too complex – and therefore the possibility of unanticipated harmful side effects too large – for us to ever consider geoengineering very safe.²⁸ Because geoengineering interventions have to be deployed on a massive scale to affect the climate of the entire planet, any harmful unintended consequences are also likely to be massive.

Nearly every analysis to date has focused on potential negative side effects of single geoengineering methods. A realistic geoengineering

TABLE 1
Solar Radiation Management Technologies (SRM)

METHOD	DESCRIPTION	CONCERNS
Stratospheric Aerosols	Lofting large quantities of aerosol particles into the stratosphere using aircraft, artillery or balloons in order to reflect sunlight back into space. Sulfate aerosols have been discussed most frequently, but other types of engineered aerosols might be even more effective	<ul style="list-style-type: none"> • Possible degradation of the stratospheric ozone layer • Regional impacts on precipitation and river flow patterns • Impacts of acid deposition as particles eventually settle to Earth • Impacts on crops and natural vegetation of an overall reduction of direct photosynthetically active radiation • Reduced efficiency of solar energy systems that rely on direct sunlight • Potential psychological effects of whitening of the sky, loss of blue sky • Termination effect – if aerosol injection is stopped for any reason, the climate will change abruptly
Cloud Brightening	Brightening clouds to reflect sunlight back into space by increasing the number of condensation nuclei in clouds over parts of the ocean. This can be done by lofting fine particles of sea salt derived from ocean water using conventional ships, aircraft or specially designed, automated sea craft. Other approaches use potentially more effective hydrophilic powders.	<ul style="list-style-type: none"> • Enormous engineering challenge • Non-uniformity of effects – may change regional weather and ocean circulation patterns • Pollution by materials used, if not sea salt
Space-based Methods	Reducing the amount of sunlight reaching the Earth by putting sun shields in near-Earth orbit or at the L1 point a million miles from Earth, where the gravitational pull of the Earth and the sun are equal. Sun shield concepts range from reflectors made of lunar glass to a superfine aluminum mesh or swarms of trillions of thin metallic disks.	<ul style="list-style-type: none"> • Enormous logistical demands • Great uncertainties regarding effectiveness, cost and time required to implement • Effects on plants and solar energy systems of reduced direct solar radiation • Inability to “turn off” • A brighter night sky – in some configurations, the Milky Way might never again be visible • Large amounts of orbiting material could be a hazard to manned space flight
Increasing the Reflectivity of the Built Environment	Painting roofs, roadways and pavements brighter shades to reflect sunlight.	<ul style="list-style-type: none"> • High cost for low cooling impact
Increasing the Reflectivity of Vegetated Surfaces	Choosing lighter-colored species and varieties of crops and vegetation for grasslands, open shrub land and savannas to increase their reflectivity.	<ul style="list-style-type: none"> • Potential loss of biodiversity • Need to ensure no loss of important characteristics such as growth rates, disease resistance and drought tolerance
Increasing the Reflectivity of Desert Areas	Increasing the reflectivity of large areas of desert by covering them with a polyethylene-aluminum surface or another highly reflective material.	<ul style="list-style-type: none"> • Massive ecological impacts on covered areas • Potential to change large-scale patterns of atmospheric circulation, such as the East Asian monsoon that brings rain to sub-Saharan Africa • High cost
Increasing the Reflectivity of Ice	Retarding the melting of polar and glacial ice by covering them with floatable, removable blankets that are both reflective and insulating.	<ul style="list-style-type: none"> • Feasibility and expense

approach, however, is likely to be more complex. For example, methods like stratospheric aerosol injection or cloud brightening would affect global temperatures, but not other impacts of the growing CO₂ concentrations in the ocean and atmosphere, like acidification. Other active efforts would therefore be needed to counter ocean acidification and offset other ecological impacts.²⁹ Those efforts might have their own side effects, making it all the more difficult to do geoengineering safely.

Unintended negative impacts could be particularly severe in situations where there is no way to shut down the geoengineering system or stem its effects. Once aerosols are put into the stratosphere, there is no way to quickly remove them. In the event of excessive cooling from miscalculation or a large volcanic eruption, severe regional droughts, failures of monsoon rains in Asia or other serious negative impacts, we would have to wait a year or more for the aerosol particles to settle out. Even when a geoengineering action with negative impacts can be quickly halted, there is no assurance

that the climate and the Earth's ecosystems, once perturbed, would return to their original state.

Tables 1 and 2 contain descriptions of SRM and CDR, the major types of geoengineering methods, and the concerns that have been raised about each of them.³⁰ Many of these concerns may turn out to be unjustified, and others may be remediable; however, some could emerge as show-stoppers. All deserve serious attention.

Potential Ineffectiveness

An important paper by Tim Lenton and his student Naomi Vaughn of the Tyndall Centre for Climate Change Research and the University of East Anglia in the U.K.³¹ is the first attempt to assess the potential effectiveness of a broad range of geoengineering strategies and rank them in terms of performance – how much heat absorption different methods can prevent (see Table 3). Several geoengineering options did not fare well in this analysis; for example, increasing the reflectivity of the built environment emerged as a fairly weak

10 Concerns

1. Unintended Negative Consequences
2. Potential Ineffectiveness
3. Risk of Undermining Emissions- Mitigation Efforts
4. Risk of Sudden Catastrophic Warming
5. Equity Issues
6. Difficulty of Reaching Agreement
7. Potential for Weaponization
8. Reduced Efficiency of Solar Energy
9. Danger of Corporate Interests Overriding the Public Interest
10. Danger of Research Driving Inappropriate Deployment

TABLE 2
Carbon Dioxide Removal Technologies (CDR)

METHOD	DESCRIPTION	CONCERNS
Improved Ecosystem and Land- Use Management (this can also be viewed as an adaptation strategy)	Integrated local and regional land- use management that incorporates multiple ecosystem services, including carbon storage, water regulation and biodiversity conservation. Reforestation and reduced deforestation on a national/global scale	<ul style="list-style-type: none"> • Land-use conflicts between reforestation and agriculture • Carbon stored in vegetation can easily be released by fire, drought or deliberate deforestation
Bioenergy with Carbon Capture and Sequestration	Biomass used as fuel for electricity generation or hydrogen production, with capture and sequestration (CCS) of the resulting CO ₂ . [Bioenergy without CCS is, at best, carbon-neutral and does not remove CO ₂ from the atmosphere.]	<ul style="list-style-type: none"> • Fuel vs. food: incentive for biomass production can reduce the availability and increase the cost of food crops • Environmental impacts of intensive growing • Availability and safety of sequestration sites
Biochar	Sequestering in the soil agricultural and forestry wastes burned through pyrolysis to produce biochar (charcoal).	<ul style="list-style-type: none"> • Supply of biomass wastes • Long-term impacts of high biochar applications are not yet known (moderate applications can increase soil fertility)
Biomass Ocean Sequestration	Sequestering carbon by putting tree logs and other biomass residue into the deep ocean.	<ul style="list-style-type: none"> • Potential disruption of nutrient cycling and growth of marine ecosystems • Energy use and expense required for processing, transporting and burying
Terrestrial- Enhanced Weathering Methods	Methods to accelerate the natural removal of CO ₂ from the atmosphere by the weathering of carbonate and silicate rocks. Methods include spreading finely ground olivine on agricultural soils, reacting CO ₂ with carbonate rock in chemical plants and releasing the resulting bicarbonate into the sea, and enhanced reactions of CO ₂ with minerals such as basalts and olivine in situ.	<ul style="list-style-type: none"> • Requires mining, processing and transportation on the scale of current coal mining and cement production • Disposal (or use) of large amounts of solid waste material • Uncertainties about impacts on soil pH and vegetation • High energy use and cost
Ocean-based Enhanced Weathering Methods	Mining carbonate materials and putting them into the sea.	<ul style="list-style-type: none"> • Costs and impacts of large-scale mining • Potential effects on ocean chemistry and biology not fully understood, but increases in alkalinity from carbonate materials could act to counter ocean acidification
Air Capture (“artificial trees”)	Industrial processes to extract CO ₂ from ambient air for sequestration.	<ul style="list-style-type: none"> • Technically feasible, but not clear if cost-effective processes can be developed • Availability and safety of sequestration sites
Ocean Fertilization	Adding iron, nitrogen or phosphates to ocean water as nutrients to stimulate the growth of phytoplankton that absorb CO ₂ during photosynthesis. Some of this organic matter sinks into the deep ocean, sequestering the carbon it contains.	<ul style="list-style-type: none"> • Potential disruption of the ocean carbon system • May increase anoxic regions of the ocean (i.e., “dead zones”) • Not as effective as hoped for removing carbon
Ocean Upwelling, Downwelling	Ocean fertilization by using vertical pipes to pump nutrient-laden waters from several hundred meters depth to the surface and to promote downwelling of dense water in the subpolar oceans.	<ul style="list-style-type: none"> • Same concerns as ocean fertilization • Huge engineering undertaking and cost for modest impacts
Magnetic Ejection of CO₂ Into Space	Using Earth’s magnetic field, given a helping hand by lasers and microwave beams, as a conveyor belt that vents CO ₂ molecules into space.	<ul style="list-style-type: none"> • Workability • Safety • Energy requirements • Atmospheric impacts

Adapted from T.N. Lenton & M.E. Vaughn, “The radiative forcing potential of different climate engineering options,” Atmospheric Chemistry and Physics, 9, 5539-5561, 2009.

The belief that an easy technological fix for global warming is available could undermine our political and social resolve to deal with the underlying cause of the problem by reducing greenhouse gas emissions.

strategy. Ocean fertilization produces useful results only if sustained on a millennial timescale. Enhancing ocean upwelling or downwelling has trivial effects on any meaningful timescale.

Risk of Undermining Emissions-Mitigation Efforts

The belief that SRM could be an easy technological fix for global warming could undermine our political and social resolve to deal with the underlying cause of the problem by reducing greenhouse gas emissions. Reducing emissions involves politically difficult actions, such as mandating energy-efficiency standards, increasing the cost of carbon by taxation or cap and trade schemes, going against the wishes of powerful fossil energy corporations and halting deforestation around the world. It requires an expensive and time-consuming effort to transform the entire energy infrastructure, improving the efficiency of all our energy-using technologies and building new energy sources on a massive scale. If politicians are led to believe that geoengineering can reduce or eliminate the need for these difficult actions, allow fossil fuel use to continue and accomplish all this quickly and at low cost, they will logically be inclined to back away from mitigation and adaptation efforts and to direct funding to geoengineering.

This is not just a theoretical concern; it is beginning to happen. The Copenhagen Consensus

on Climate Project, organized by Bjorn Lomborg, recently developed a prioritized list of the most – and least – effective ways of reining in global temperature increases. The Project’s panel of experts concluded that the most effective use of resources would be to invest in research on SRM technologies such as cloud brightening and stratospheric aerosols; the least effective approaches involve reducing emissions by increasing the cost of fossil fuels.³² In their popular recent book *SuperFreakonomics*, Steven D. Levitt and Stephen J. Dubner say that technologies like wind turbines and solar photovoltaic cells are more trouble than they are worth and characterize efforts to use less oil as “like wearing sackcloth.” Why bother doing these expensive and difficult things, they ask, when all we have to do to prevent climate change is inject some sulfate aerosols into the stratosphere? “For anyone who loves cheap and simple solutions,” they say, “things don’t get much better.”³³

Several of the U.S. think tanks that in the past have denied the existence of climate change or minimized its significance are now recommending geoengineering to policy makers as an alternative to emissions reductions. The American

Geoengineering initiatives that allow large buildups of CO₂ to occur would need to have internationally sanctioned control that is ultra-reliable and proof against mechanical failures, human error, economic depressions and funding failures, wars, terrorism, natural disasters and simple apathy across many centuries.

TABLE 3
Ranking the Cooling Power of Geoengineering Options

MOST POWERFUL	LESS POWERFUL	WEAKER	VERY WEAK (Some by an Order of Magnitude)
Stratospheric Aerosols	Air Capture	Biochar	Ocean Fertilization
Space-based Methods	Increasing the Reflectivity of Large Desert Areas	Afforestation	Increasing the Reflectivity of the Built Environment
Cloud Whitening		Increasing the Reflectivity of Vegetated Surfaces	Ocean Upwelling, Downwelling

Adapted from T.N. Lenton & M.E. Vaughn, "The radiative forcing potential of different climate engineering options," *Atmospheric Chemistry and Physics*, 9, 5539-5561, 2009.

Enterprise Institute has a large geoengineering project and has been an active participant in Lomborg's Copenhagen Consensus on Climate Project. A recent Hudson Institute paper argues that "successful geoengineering would permit Earth's population to make far smaller reductions in carbon use and still achieve the same retarding effect on global warming at lower cost." David Schnare at the Heartland Institute advocates geoengineering as "much less expensive than seeking to stem temperature rise solely through the reduction of greenhouse gas emissions" and as "delivering results in a matter of weeks rather than the decades or centuries required for greenhouse gas reductions to take full effect."³⁴

Risk of Sudden Catastrophic Warming

This concern stems directly from the possibility that of the prospect of successful SRM geoengineering would make emissions reductions seem less urgent and take the heat off politicians.

Then, as the editors of *Scientific American* recently wrote, carbon dioxide would continue to build up in the atmosphere, "breaching the level of 450 parts per million by volume (ppmv) that many climatologists now recommend as the upper limit, then passing the 550 ppmv mark that is the goal of many current policy initiatives, and eventually reaching ... a level not seen on Earth since the days of the dinosaurs." The danger then becomes that if the geoengineering effort should ever falter, "a century's worth of warming would hit us."³⁵ It would hit with a speed unprecedented in the Earth's history, making adaptation nearly impossible for large numbers of plant and animal species, and perhaps for human society.

Unchecked carbon dioxide emissions would build up in the ocean as well as the atmosphere. Carbon dioxide has a lifetime in the atmosphere of about a hundred years, but large amounts of CO₂ stored in the ocean would outgas for a much longer time, keeping the atmosphere laden with CO₂. This means that any geoengineering initiatives that allow such build-ups to occur

would need to have internationally sanctioned control that is ultra-reliable and proof against mechanical failures, human error, economic depressions and funding failures, wars, terrorism, natural disasters and simple apathy across many centuries. It may be, therefore, that the social and institutional requirements for some forms of geoengineering are much more daunting than the engineering requirements.³⁶

The extreme danger described here results from the improper use of SRM geoengineering as a substitute for emissions reduction so that CO₂ concentrations in the atmosphere and ocean continue to rise. A short-term use of geoengineering to limit the extent of warming or avoid a climate “tipping point,” combined with strong and active efforts to increase energy efficiency and to transition to Carbon free energy sources, would pose much lower risks.

Equity Issues

Geoengineering efforts are likely to produce differential impacts in different parts of the world: while some nations will benefit, others may experience worsening climate conditions. Evidence for this comes from past experience with volcanic eruptions, which inject material high into the atmosphere, producing a cooling effect in the same way as stratospheric aerosol injection, cloud brightening or a space shield would work – by blocking a fraction of sunlight from reaching the Earth’s surface. The 1991 eruption of Mount Pinatubo on the Philippine island of Luzon injected an estimated 20 megatons of sulfur dioxide into the stratosphere, producing a cooling that lasted several years. But cooling was not the only effect. Researchers at the National Center for Atmospheric Research showed in 2007 that the Pinatubo eruption

reduced precipitation, river flow and soil moisture in several regions, increasing the incidence of drought.³⁷ An analysis of 20th-century observations indicates that volcanic eruptions always caused detectable regional decreases in global land precipitation.³⁸ Studies looking further into the past find the same pattern. For example, the eight-month-long eruption of the Laki fissure in Iceland in 1783–1784 was followed by drought and famine in Africa, India and Japan.³⁹ The reason for these droughts is that with reduced incoming shortwave solar radiation and surface cooling, less energy is available for evaporation.

A recent study by two of the lead authors of the Intergovernmental Panel on Climate Change Fourth Assessment Report stresses the importance of differential regional impacts:

“The combination of a strong greenhouse effect with a reduction of incoming solar radiation could have substantial effects on regional precipitation, including reductions that would rival those of past major droughts. Geoengineered changes in the environment could thus lead not only to ‘winners and losers’ but even to conflicts over water resources and the potential for migration and instability, making shortwave climate engineering [“shortwave” = SRM] internationally very controversial.”⁴⁰

There are other studies, however, where models predict that, for most regions of the planet, SRM will reduce the stresses due to temperature and precipitation compared to a world with no SRM. So we face a situation where the use of SRM is certain to produce an inequality of results in different parts of the world, but where there are large uncertainties about the extent and impact of those inequalities.⁴¹

Difficulty of Reaching Agreement

The crux of the challenge of reducing GHG emissions is reaching political agreement within our nation and internationally. The science related to emissions reduction is well established, most of the needed technologies already exist and public support for renewable energy and more energy-efficient products is fairly high. The negative impacts of these technologies are very small compared with those of the technologies in current use, their costs can be spread over the natural capital-replacement cycle and the changes needed to reduce emissions have enormous co-benefits in terms of energy security, national security, a healthier environment, competitiveness and job creation. But the politics is still extremely difficult.

The crux of the challenge of geoengineering is also likely to be reaching political agreement, and it may well be even more difficult to reach agreement on geoengineering than on emissions reductions. The science related to geoengineering and its potential impacts is not well established, few of the potential technologies have actually been developed and public awareness of this entire area of technology is still low. The negative impacts of some geoengineering technologies may be large, all of the more powerful SRM technologies are controversial and liability for harmful impacts could be a legal nightmare. No international institutions or arrangements exist to authorize field tests or deployments or to make decisions about “where the thermostat should be set.” The results of geoengineering initiatives could be geographically uneven, producing angry losers as well as winners. The north-south divisions so evident at the Copenhagen Summit would almost certainly be intense around geoengineering. Finally, some people believe for religious or philosophical reasons that it is wrong for humans to interfere so fundamentally with the Earth’s natural processes.

Potential for Weaponization

Several countries have a long history of efforts to modify weather for military purposes. In the U.S., the leading example is the Central Intelligence Agency’s top-secret Project Popeye rain-making campaign that ran from 1966 to 1972 in an effort to swamp North Vietnamese supply lines along the Ho Chi Minh trail, drown out North Vietnam’s rice crops and disrupt anti-war protests by Buddhist monks.⁴² Many of the world’s military powers remain interested in weather control. The UN’s World Meteorological Association reported that at the turn of the century at least 26 governments were routinely conducting weather-altering experiments, although it could not distinguish between military and non-military efforts. The U.S. military continues to pursue work in this area. A 2001 Air Force study, *Weather as a Force Multiplier: Owning the Weather in 2025*, concludes that weather control “can provide battle space dominance to a degree never before imagined” by allowing U.S. forces to generate rainfall and enhance storms to disrupt enemy operations, deny precipitation to reduce freshwater supplies and induce drought, disrupt communications and radar, and remove fog and cloud cover to view enemy activities.⁴²

The United States and 84 other countries have signed the UN Convention on the Prohibition of Military or Any Other Hostile Use of Environmental Modification Techniques.⁴³ But if geoengineering research should lead to major advances in knowledge and techniques relevant for weather control, it is hard to imagine that knowledge not being put to use. In this respect, geoengineering is no different from other powerful technologies, from rocketry and atomic energy to computers and genetic engineering that have been put to military as well as peaceful uses.

Reduced Efficiency of Solar Energy

Scientists estimate that the warming caused by a doubling of carbon dioxide in the atmosphere from the pre-industrial level can be compensated by a 1.8 percent reduction in solar radiation reaching the Earth's surface – a level of reduction achievable by SRM technologies.⁴⁴ Unfortunately, one of the side effects of this reduction would be to significantly lower the amount of electricity generated by solar power.

The response of solar energy systems to total available sunlight is not linear and it varies depending on the kind of solar energy system. Solar technologies that use “concentrators” to focus sunlight work best with direct sunlight because diffuse sunlight that arrives from many directions is difficult to concentrate. These systems would be most affected by geoengineering methods to reduce solar radiation. Research at the National Oceanic and Atmospheric Administration in Boulder, Colorado, shows that for every 1 percent reduction in solar radiation, the average output of solar systems that rely on direct sunlight drops by 4 to 5 percent.⁴⁵ Efficiency reductions of this size might affect the economics of solar thermal electric systems and other solar technologies that use concentrators, slowing the shift away from fossil fuels. Solar technologies that do not use concentrators would be affected much less.

If geoengineering research should lead to major advances in knowledge and techniques relevant for weather control, it is hard to imagine that knowledge not being put to use.

Danger of Corporate Interests Overriding the Public Interest

Dozens of patent applications have already been filed for different geoengineering technologies, raising important questions about the future of geoengineering. Could patents on proprietary technologies allow the private sector to gain too much influence over research and development decisions? Could the drive for shareholder profits override the public interest and lead to inappropriate deployments? Would companies undermine mitigation efforts by influencing governments to allow geoengineering technologies to qualify for carbon credits or to meet emissions-reduction targets? Questions like these have not yet received the attention they deserve.

Danger of Research Driving Inappropriate Deployment

Researching geoengineering technologies can lead to inappropriately developing and deploying them. While this is certainly not inevitable, it is a pattern that has occurred in other technical areas. Dale Jamieson has studied this problem in the field of medical research, where over time many treatments and devices have come into use even though they ultimately were proved ineffective, damaging or ethically problematic.⁴⁶ Jamieson argues that while most historical cultures have had a bias toward caution, modern culture tends to view opposing the deployment of a new technology as holding back progress. More important, the social dynamics of the research community itself sometimes drives an unreflective shift from research to use.

“A research program often creates a community of researchers that functions as an interest group promoting the development of the

technology that they are investigating. Since the researchers are the experts and frequently hold out high hopes for a rosy future if their technology is developed, it can be very difficult for decision makers to resist their recommendations. In many cases the social and ethical issues created by the deployment of the technology are explored only after we are committed to it, but by then it is too late.”⁴⁷

A problem particular to geoengineering research is that real-world experimentation can slip into development and actual deployment. Research will naturally move from laboratory and computational work to small-scale field tests. If results of such tests are positive, they may seem to justify larger-scale tests to see how effective the technology can be. If small-scale tests produce inconclusive results, there will be pressure to move to more “real-world” large-scale tests.

This dynamic has already played out in the case of ocean fertilization. Despite a series of small-scale field experiments with inconclusive or negative results, some researchers continue to argue that much larger-scale tests are needed to fully assess the efficacy of the technology.⁴⁸

★ ★ ★

Taken together, these concerns suggest that the best future would be one in which geoengineering is not needed. The idea that SRM geoengineering is an easy technological fix that can replace efforts to reduce greenhouse gas emissions should be rejected. But questions remain. Can we reduce global GHG emissions fast enough to prevent dangerous climate change? Might geoengineering be needed despite all its difficulties and dangers?

2. Can We Reduce Greenhouse Gas Emissions Fast Enough?

The question of whether we can reasonably expect to reduce GHG emissions fast enough to prevent dangerous climate change is central to formulating policy toward geoengineering. Unfortunately, there is no way to answer this question with a high degree of certainty. There is no objective way to assess how rapidly the U.S. and global energy infrastructure could be “decarbonized” if we decide this is a high priority, and it is far from clear what circumstances might trigger strong action to shift away from fossil fuels.

There are also scientific uncertainties in important areas such as how clouds are affecting climate change and the influence of aerosols and other climatically active ingredients that industry, farming and land clearance add to the atmosphere. The computer models developed to forecast climate change are the most complex and sophisticated models developed in any area of science, but their accuracy depends on the assumptions and data fed into them, and there are areas where the data are still sparse. A small number of serious scientists, stressing these uncertainties, depart from the mainstream of scientific opinion on climate

change. They do not dispute that carbon dioxide and other greenhouse gases are being added to the atmosphere or that some amount of warming is occurring, but argue that these greenhouse gases will not cause as much warming as is generally assumed and that much of the warming of recent decades can be explained by natural fluctuations that are larger in scale and longer in duration than current climate science recognizes.⁴⁹ All serious scientists doing good, objective work – including dissenters from mainstream work on climate change – deserve to be respected.

Despite this tiny number of serious, knowledgeable dissenters, and the much larger numbers of ideological dissenters who simply do not want to believe in climate change, a high degree of consensus has developed within the climate science community about climate trends. It is a “moving consensus,” evolving over time as new research findings emerge. This consensus is summarized, at least roughly, by the periodic assessment reports of the IPCC.

A large body of new research published since the last IPCC assessment report in 2007 is

presenting an increasingly alarming view of the scale of the climate challenge and the urgency of dealing with it.

Climate Trends

During 2010, a record-shattering heat wave in Russia sparked wildfires that drove residents from Moscow and devastated the country's wheat crop. Another heat wave lingered in Mexico and the East Coast of the United States. A fifth of Pakistan went under water and millions were deluged by floods in places ranging from Australia to California. Prodigious snowstorms broke seasonal records in the United States and Europe. A huge chunk of ice broke off a glacier in Greenland, the most significant climate event there in 50 years. No single event or small set of events can "prove" that climate change is real – although climate change deniers were quick to celebrate the large snowfall in Washington, D.C., in the winter of 2009 as evidence against climate change. But beyond such specific, local events, more fundamental, long-term, measurable global trends have been underway.

Carbon dioxide emissions are "worse than worst case." The IPCC's third assessment report, published in 2001, included a wide range of climate change scenarios. The worst-case scenario with the highest estimates of warming assumed rapid economic growth, slow progress in improving energy efficiency and only weak efforts to reduce dependency on fossil fuels. But within just a few years it became clear that rapid growth in China, India, Brazil and other fast-developing countries was putting global emissions on a path that was higher than that worst-case scenario. The global growth rate of carbon dioxide emissions from fossil fuel burning accelerated from 1 percent per year during the 1990s to 3.4 percent between 2000 and 2008.⁵⁰ The global recession that

arrived in 2008 temporarily slowed this rise, but continuing rapid growth in emerging nations may mean that this "worse-than-worst-case scenario" should now be regarded as the most likely one in the absence of determined intervention.⁵¹

Global temperatures are rising. Over the past 30 years, the average global temperature has increased by an average of 0.19 degree C per decade (about 0.36 degree F).⁵² Some climate skeptics argue that now we are actually experiencing a global cooling. But the latest surface temperature figures released by the National Aeronautics and Space Administration (NASA) and the National Oceanic and Atmospheric Administration (NOAA) show that 2010 tied 2005 as the hottest year since 1880, when modern temperature records began.⁵³ The other hottest recorded years have all occurred since 1998.⁵⁴

Data from the Hadley Centre for Climate Change in the U.K. do, however, suggest that there has been a pause in the trend to higher global temperatures. This is not unexpected. Both temperature records and climate models show that there is a great deal of short-term natural variability in global temperatures caused by the Pacific decadal oscillation of ocean temperature, cycles of solar activity, El Niño/La Niña changes in wind currents, changes in the amount of water vapor in the stratosphere, volcanic aerosols and other factors. A graph of global temperatures over the past century looks much like a graph of the Dow Jones Industrial Average in a bull market: there are variations up and down, and it is possible to confuse a temporary pause or downward tic with a reversal of global warming, even though the overall trend is sharply up.⁵⁵ Most scientists expect the current pause to end soon, and the resumption of warming will come as a jolt as the temperature catches up with the greenhouse gases added during the pause.⁵⁶

Arctic sea ice is melting more quickly than anticipated. Most climate models have underestimated the rate of Arctic sea ice loss over the past three decades by a factor of three.⁵⁷ The extent of Arctic sea ice at its summertime minimum has shrunk by 34 percent just since 1979.⁵⁸ Recent studies project that the Arctic could be ice-free during the summer by as soon as 2030.⁵⁹

Both the Greenland and Antarctic ice sheets are losing mass at an accelerating rate. Melting along the edges of the Greenland ice sheet has been clearly documented since 1990. Independent measurements from different satellites indicate that Greenland entered a period of accelerated melting starting in the summer of 2004.⁶⁰ This increased melting around the edges substantially exceeds annual snowfall in the interior regions, which means that Greenland's ice is losing mass and contributing to sea level rise.⁶¹ The West Antarctic ice sheet is also exhibiting accelerated melting. Ten major ice shelf collapses have occurred there in the past decade, most recently in April 2009.⁶² Until late 2009, East Antarctica was thought to be too cold and stable to lose ice, but the latest satellite measurements show ice loss there as well.⁶³ In both Greenland and Antarctica, ice shelves along the edges of the land mass act to prevent the movement of land-based ice into the ocean. As these barriers melt and collapse, the glaciers behind them begin to flow more rapidly to the sea, lubricated by meltwater that sinks to the base of the glaciers.

Sea level rise may reach 1 to 2 meters by the end of the century. The IPCC's 2007 assessment report projected a global sea level rise of 0.18 to 0.59 meter (0.59 to 1.94 feet) by the end of the 21st century. That estimate was deliberately conservative, based primarily on the thermal expansion of the oceans as they warm, because there was no consensus on how much land-based ice might

melt and enter the oceans. Recent studies focused on capturing the ice contribution to sea level rise project increases that range from 0.5 to 2.0 meters (1.64 to 6.56 feet) by 2100.⁶⁴ Beyond 2100, a sea level rise of several meters must be expected over the next few centuries, even if efforts to reduce GHG emissions are successful.⁶⁵

Ocean acidification is increasing rapidly.

Ocean acidification is "the other CO₂ problem" that deserves much more attention. In an attempt to generate that attention, 150 leading marine scientists from 26 countries came together in 2009 to call for immediate action by policy makers to sharply reduce CO₂ emissions in order to avoid widespread and severe damage to marine ecosystems from ocean acidification.⁶⁶ As increasing amounts of carbon dioxide are absorbed by the world's oceans, the dissolved gas forms carbonic acid, making ocean water more acidic. This reduces the amount of carbonate in the oceans, which makes it harder for corals and shell-forming organisms of all kinds to grow. A new model designed to assess the rate at which the oceans are acidifying suggests that changes in the carbonate chemistry of the deep ocean may exceed anything seen in the past 65 million years. The model also predicts much higher rates of environmental change at the ocean's surface in the future than have occurred in the past, potentially exceeding the rate at which plankton can adapt.⁶⁷ Another recent modeling study concluded that if atmospheric concentrations of CO₂ double from the pre-industrial level to 550 ppmv, ocean ecosystems would be severely disrupted and "all coral reefs will cease to grow and start to dissolve."⁶⁸

The seriousness of these climate trends is underscored by the reaction they are provoking in the insurance industry. *Climate Change: Adapt or Bust*, a report by Lloyd's of London, summarizes scientific evidence that global temperatures, sea

levels and extreme weather events are increasing faster than previously thought and argues that for the insurance industry to survive it must adapt its responses to these trends sooner rather than later.⁶⁹ An analysis by Swiss Re reviews the impacts that accelerating climate change could have on property, casualty, life and health insurance and concludes that these trends could create major vulnerabilities affecting the company's reserves, its ratings and its very solvency.⁷⁰ Munich Re recently announced a strategic re-direction to address climate change, which it describes as "one of the greatest risks facing mankind." Its annual review of natural catastrophe experience cites the assertion in the Stern Review of the Economics of Climate Change that unchecked, human-caused global climate disruption will cause trillions of dollars of damages in our lifetimes, with impacts comparable to those of a world war.⁷¹

Dangrous Climate Change

When do rising global temperatures become truly dangerous? There is no exact and certain answer to this critical question. In the absence of full agreement delineating dangerous from acceptable climate change, limiting global warming to 2 degrees C (3.6 degrees F) has emerged as the principal focus of international and national policy.⁷²

In the absence of full agreement delineating dangerous from acceptable climate change, limiting global warming to 2 degrees C (3.6 degrees F) has emerged as the principal focus of international and national policy

Policy makers often approach climate goal setting by positing targets such as "an 80 percent reduction in emissions by 2050." However this approach can be misleading because a goal like this can be achieved by a wide variety of trajectories with large differences in *cumulative emissions* which are what really count in affecting the climate. Cumulative emissions are best stated in terms of CO_{2e} or carbon dioxide equivalent, the unit of measurement used to indicate the global warming potential of each of six major greenhouse gases. It serves as a simultaneous measure of the concentration of carbon dioxide and other greenhouse gases.

A few years ago, most climate scientists assumed that if the cumulative build-up of atmospheric CO_{2e} could be held to or returned to 550 ppmv by 2100, it would be sufficient to prevent warming from exceeding 2 degrees C. Climate policy in most nations still reflects that 550 ppmv goal. However, most climate scientists have revised their estimate of what is needed to stay below the 2 degree C threshold to 450 ppmv. Some scientists, like NASA's James Hansen, argue that the goal of limiting warming to 2 degrees C is "a recipe for disaster," and that we should strive to stop warming at 1.5 degrees C by returning to 350 ppmv CO_{2e} as quickly as possible from the current level of 390 ppmv.⁷³ This view is the basis for the 350.org global grassroots campaign. 350 ppmv was also the goal advocated at the Copenhagen Summit by island nations whose existence is threatened by sea level rise.

According to a much-cited recent synthesis of results from a wide variety of climate models by Malte Meinshausen and his colleagues, limiting cumulative emissions to 550 ppmv CO_{2e} would result in an 82 percent mid-value probability of exceeding 2 degrees C. Limiting cumulative emissions to 450 ppmv would give roughly a 50/50 chance of staying below 2 degrees C. To provide a 93 percent mid-value probability of not

exceeding 2 degrees C, GHG emissions would need to be stabilized at or below 350 ppmv.⁷⁴

Regardless of whether cumulative GHG emissions can be stabilized at 350 ppmv in this century, it seems reasonable that CO_{2e} will eventually need to come down to this level, and the sooner the better. At the current level of 390 ppmv, the world is already experiencing a loss of glaciers and the freshwater supplies they provide, a rapid loss of Arctic summer ice, increasing melting along the edges of the Greenland and Antarctic ice sheets, sea level rise, expansion of the subtropics, increasingly extreme forest fires and floods, serious ocean acidification and a worldwide loss of biodiversity.

Tipping Points

The greatest danger of allowing cumulative emissions to rise into what appears to be a danger zone above 450 ppmv (and possibly lower) is that we could pass “tipping points” of significant irreversible change.

The most critical of these tipping points is triggering the release of greenhouse gases from the biosphere itself on a scale that dwarfs the effects of human fossil fuel burning. This would overwhelm any efforts we could make to cut back carbon emissions. We would be powerless to stop an abrupt change to a new, hotter climatic state that could undermine agriculture in many parts of the world and have extreme impacts on global society.

Since 2003, scientific papers have explored several of these potential climate tipping points. There is still significant uncertainty about how close we are to each of them, but the basic mechanisms by which they would operate are well understood.

Melting Arctic Sea Ice. Light-colored ice and snow reflect sunlight back into space, while darker

water absorbs more radiation, heats, and subsequently emits long wave radiation that is trapped by GHGs and increases the Earth’s temperature. As melting Arctic ice shrinks the size of the polar ice cap, it exposes more dark ocean surface, which absorbs more heat, which melts more ice, exposing more dark water, and so on and on in a self-amplifying process. This so-called ice-albedo positive feedback largely accounts for the faster-than-expected melting of Arctic sea ice. By one estimate, the extra heat that would be added to the Earth by the complete melting of the Arctic ice cap would be roughly equivalent to the amount of warming produced by all the GHG emissions we have put into the atmosphere to date.⁷⁵

Water Vapor in the Lower Atmosphere. Warming driven by carbon dioxide and other greenhouse gases allows the air to hold more moisture. Increasing amounts of water vapor in the lower atmosphere trap heat, and increasing temperatures allow the air to hold even more moisture, creating a positive feedback loop.⁷⁶

Thawing Arctic Permafrost. Another self-amplifying process is the thawing of Arctic permafrost, which releases methane, a far more potent greenhouse gas than carbon dioxide, which accelerates melting and further methane release. Researchers studying the permafrost in northern Siberia report that methane emissions there increased by 58 percent between 1974 and 2000.⁷⁷ Recently a team of British scientists recorded a massive spike in the amount of methane seeping from Arctic permafrost, a rise by almost one-third over the past five years.⁷⁸ The Arctic is still a comparatively small source of atmospheric methane, but this accelerating release is troubling because if the Arctic permafrost continues to melt it could ultimately boost current levels of atmospheric methane ten-fold.

TIPPING POINTS

Melting Arctic Sea Ice

Water Vapor in the Lower Atmosphere

Thawing Arctic Permafrost

Thawing Arctic Sea Floor Permafrost

Tropical Forest Dieback

Shut-off of the Atlantic Thermohaline Circulation

Thawing Arctic Seafloor Permafrost. Much larger quantities of methane are trapped within icy lattices of hydrogen bonds, known as hydrates or clathrates, that lie within the pores of sediments under the seafloor. These hydrates are covered by a lid of solid permafrost that keeps the methane from escaping. In 2007, a team of researchers from Russia and other nations measured growing concentrations of dissolved methane in Arctic sea water and observed methane plumes bubbling to the surface in shallow waters along the Siberian Shelf. However, we do not know the normal background level of methane activity in this area, and it has not yet been definitely shown that the methane scientists have found comes from methane hydrates.⁷⁹ If it can be proved that seafloor hydrates are releasing growing quantities of methane into the atmosphere, it will be a truly alarming development. The Siberian Shelf alone is estimated to contain 1,400 billion tons of methane in gas hydrates, which is equivalent to nearly twice as much carbon as is contained in all the trees, grasses and flowers currently growing on the Earth. If just 1 percent of this methane escaped into the atmosphere over a few decades, it would be enough to trigger abrupt climate change.⁸⁰

Tropical Forest Dieback. Large amounts of carbon are locked up within the plant material of the world's forests. When forests are taken down, that carbon goes into the atmosphere. Deforestation in the tropics today accounts for nearly 20 percent of all carbon emissions due to human activities.⁸¹ Large tropical forest areas like the Amazon in effect create their own climate by recycling precipitation – holding rainwater that evaporates and falls again as rain. Climate models project that under conditions of a 3-to-4 degree C global warming a more persistent El Niño state would lead to drying over much of the Amazon Basin.⁸² Continued deforestation and drying would reduce the rainforest's ability to hold water, creating a downward spiral where forest dieback increases global warming, which further increases forest dieback, releasing more and more carbon into the atmosphere.

Shut-off of the Atlantic Thermohaline Circulation. The Gulf Stream that keeps much of Europe and the east coast of North America much warmer than these areas would otherwise be is driven by a process called thermohaline circulation. It is like a gigantic conveyor belt of warm surface water that

streams northward from the tropical Atlantic Ocean until, in the far North Atlantic, it becomes so cold and salty – and therefore so dense – that it plunges downward and moves south, continuing the circulation pattern. If climate change causes water in the North Atlantic to become too warm, or melting ice makes the water sufficiently less salty, this density-driven circulation could halt. Research suggests that this circulation has fluctuated and even stopped numerous times in the Earth’s distant past, and that these changes have happened not in geologic spans of thousands of years, but rather in decades. It is possible, therefore, that global warming could actually lead to a form of abrupt climate change that involves extreme cooling in some parts of the world.⁸³

Several other potential tipping points have been identified, including Greenland and West Antarctic ice sheet instability, boreal forest dieback and disruption of monsoon circulation in the Indian subcontinent, the Sahara/Sahel and West Africa.

The common characteristic of all these tipping points is that they could produce sudden climate change.

An extremely important implication of the tipping point concept is that “overshooting strategies” pose serious dangers. These strategies aim to stabilize the atmospheric concentration of GHGs at 450 ppmv or lower between 2100 and 2150, but overshoot that target by a very sizable amount during the century ahead. This is the de facto strategy of the Obama administration, China and virtually all other nations today. However, faith in the ability to do a large overshoot and then return to a safer climate may be misplaced if the overshoot passes irreversible tipping points or triggers self-amplifying climate change.

Preventing Dangerous Climate Change

What level of action appears necessary to significantly reduce the risk of dangerous climate

change by limiting warming to 2 degrees C or less? Several recent studies frame the answer in different ways.

- Computer modeling at the Met Office’s Hadley Centre for Climate Prediction and Research in the U.K. suggests that a “business as usual” approach of continued sluggish efforts to deal with climate change would cause almost unthinkable damage to human society and the natural world. With emissions increasing by more than 100 percent by 2050, the end-of-century rise in global average temperature could go as high as 7.1 degrees C (12.7 degrees F).⁸⁴ The Hadley Centre climate model illustrates the costs of delaying the peak and downturn of global emissions. Each 10 years of delay adds another 0.5 degree C to the likeliest end-of-century figure.
- A report from the UN Environmental Program timed to influence the Copenhagen Summit estimates that climate change will move well into the danger zone by the end of the century even if the world’s leaders fulfill all of their most ambitious pledges for reducing GHG emissions. The authors took the upper-range targets of nearly 200 nations’ climate policies – including U.S. cuts that would reduce domestic emissions 73 percent from 2005 levels by 2050, along with the European Union’s pledge to reduce its emissions 80 percent from 1990 levels by 2050 – and found that even if all those targets were reached the average global temperature is still likely to rise by 3.5 degrees C (6.3 degrees F).⁸⁵ Another analysis done shortly after the Copenhagen Summit concluded that the total current commitments of the world’s nations would lead to approximately 3.9 degrees C (7.0 degrees F) warming by 2100.⁸⁶

- A recent paper by Kevin Anderson and Alice Bows at the Tyndall Centre for Climate Change in the U.K. updates the computer modeling that formed the basis for the IPCC's 2007 assessment report, putting in more pessimistic assumptions about the rate of emissions, the biosphere's ability to absorb carbon emissions over time and other factors. At the same time, the authors make a series of fairly optimistic assumptions, such as global emissions peaking in 2020, overall emissions falling by 3 percent per year after 2020 with energy and process emissions falling by 3.5 percent, a rapid end to deforestation and a halving of emissions from global food production. The result of this scenario is that cumulative emissions stabilize at 650 ppmv CO_{2e} with an associated warming of roughly 4 degrees C.⁸⁷ In Anderson and Bows' modeling, stabilization at 450 ppmv CO_{2e} requires that emissions peak by 2015 followed by annual reductions of 4 percent in CO_{2e} and of 6.5 percent in energy and process emissions.
- In NASA climatologist James Hansen's 350 ppmv pathway, carbon emissions need to be limited to about 750 gigatons* between 2000 and 2050. Approximately 330 gigatons were emitted between 2000 and 2009, so we have already consumed nearly half of the 50-year 350 ppmv budget. To keep to the budget, emissions need to peak by 2011, then drop rapidly, soon reaching a rate of 10 percent per year. If

emissions peak just four years later, in 2015, a 20 percent annual rate of decline is needed. Hansen's pathway demands an immediate worldwide halt in the construction of coal-fired power plants without carbon capture and sequestration. It also assumes "negative emissions" of 150 gigatons based on carbon dioxide removal geoengineering efforts such as reforestation, biochar and biomass energy with carbon sequestration.⁸⁸

- Robert Socolow at Princeton University calculates that stabilization at 2 degrees C requires annual global CO_{2e} emissions to fall to an average of two tons per capita by mid-century and one ton by 2100. The world average annual emission level today is 5 tons per capita and the U.S. average is 20 tons per capita.⁸⁹

There are significant uncertainties in all these analyses, and new research constantly provides new information, some of which makes the picture look darker and some brighter. Despite the uncertainties, the overall picture of our situation seems reasonably clear. Atmospheric stabilization of carbon dioxide and other greenhouse gases below the level that risks dangerous climate change will require a societal mobilization and technological transformation at a speed and scale that has few if any peacetime precedents. If a mobilization on this scale cannot be achieved, we may find ourselves in a situation where the only alternative to dangerous climate change is geoengineering.

* Measured and stored at standard atmospheric pressure, one ton of CO₂ occupies a cube the size of a three-story building: (27ft x 27ft x 27ft). This is the amount of CO₂ the average person in an industrialized country emits each month. A gigaton of CO₂ is a billion times that much.

3. Geoengineering Scenarios

As concerns about climate change grow and the possibility that we may have to resort to geoengineering to avert a climate catastrophe begins to be taken more seriously, several different viewpoints are emerging about how geoengineering should or could be developed and used. Most of this range of opinion can be described in terms of five scenarios of how events could unfold:

- No Geoengineering
- Safe CDR Only
- Technology Transformation
- Insurance Policy
- Needed Soon

Scenarios

No Geoengineering

Under this scenario, little geoengineering research and development is done, and we depend

completely upon mitigation and adaptation to deal with climate change. This state of affairs could come about in different ways, from the inertia of business-as-usual to the emergence of strong opposition to geoengineering.

Safe CDR Only

Increasingly urgent efforts to respond to the climate challenge include the use of CDR technologies to complement emissions reduction through improvements in energy efficiency and renewable energy development. While research is conducted on SRM technologies, their use continues to be rejected as involving too many uncertainties and dangers.

Technological Transformation

Large increases in government spending for energy R&D combine with a burst of private sector innovation and entrepreneurship similar to what occurred in the 1980s and 1990s with information technology. The result is a portfolio of breakthrough solar, wind, battery and nuclear technologies that are so clean, climate-friendly and inexpensive that businesses and consumers

flock to them, leaving coal and oil behind. Like cell phone technology, the new low-cost energy systems are adopted rapidly in countries that still lack a well-developed energy infrastructure. CDR technologies are seldom used because the new energy technologies are more cost-effective. R&D is pursued on SRM methods, but the hope is that rapid transformation of the energy system can make SRM geoengineering unnecessary.⁹⁰

Insurance Policy

This scenario assumes that there has been only modest progress in reducing CO₂ emissions, creating growing risks as CO₂ keeps increasing. While emissions reduction through energy efficiency and renewable energy remains the primary strategy for dealing with climate change, growing concern that this primary strategy could fail leads to increasingly urgent efforts to develop geoengineering technologies as an insurance policy against a climate catastrophe. The main emphasis is on developing the capability to do “fast geoengineering” using stratospheric aerosols and cloud-brightening technologies that can be deployed and have large impacts quickly if we find ourselves passing a climate tipping point.⁹¹ Several CDR technologies are also developed and put into place.

Needed Soon

Rapidly rising Arctic temperatures and increasing methane emissions from melting permafrost convince scientists that SRM geoengineering needs to be used as soon as possible for preventing dangerous climate change. Stratospheric aerosols and cloud brightening technologies are developed on a high-priority basis. The goal is to deploy SRM as rapidly as possible to halt and reverse Arctic melting but to use it for as short a period of time as possible. However, scientists continue to press for greater effort

on emissions reduction, insisting that the capability to do geoengineering should not be used to justify inadequate climate policies and should never be treated as a substitute for emissions reduction.

Do It All

In this scenario all the bases are covered. There is major international effort to cut carbon emissions by shifting away from fossil fuels, improving energy efficiency, and expanding the use of low/no carbon energy sources. There is substantial R&D funding for CDR, with the objective of quickly using any CDR technologies that prove effective, safe and economic. There is also substantial funding for research on SRM to use as a backup if necessary if energy system transformation and CDR are not enough.

Each of these scenarios is distinct with respect to decisions made by society, costs to society, risks to society, and benefits to society. *No Geoengineering* is the only scenario in which little or no geoengineering R&D is done. It avoids the costs and risks of geoengineering, but could increase the costs and risks of climate change. *Safe CDR* is probably only possible if there is a high value put on carbon emissions (\$200–300/ton), and requires substantial expenditures on CDR technology development. *Technology Transformation* is the ideal outcome if achievable, so it is a desirable benchmark. It is distinguished from all other scenarios because energy-related advances are so large that it doesn't require geoengineering. *Insurance Policy* probably comes closest to the way major governments are acting today. It can lead to high risks because progress in reducing CO₂ emissions is so modest. *Needed Soon* focuses investment on “quick fix” SRM approaches, especially stratospheric aerosols. *Do It All* requires a level of investment hard to achieve in an era of budget cutting, but it arguably minimizes climate risks.

Failure Modes

It is important to understand how geoengineering could go wrong so we can consciously avoid those possibilities. Six plausible failure modes are outlined below.

Mitigation Undermined

The knowledge that climate engineering is possible makes climate change seem less fearful. This weakens commitments to cutting GHG emissions, and the world fails to head off dangerous climate change.

Geoengineering Goes Wrong

Geoengineering technologies are deployed in a climate emergency without adequate advance R&D to rule out the use of dangerous options and refine the best options. Unanticipated side effects make the situation worse and undermine the legitimacy of geoengineering.

Going Rogue

A country suffering particularly severe climate impacts decides to act unilaterally without waiting for the approval of dithering international institutions. The rogue actor could also be a corporation or even an individual multi-billionaire. It is within the realm of possibility that some future “Warren Gates Branson III” would decide that “all my money counts for nothing if the world’s gone to hell” and set out on his own geoengineering effort to save the planet.⁹² The resulting policy and legal conflicts create a crisis of international governance.

Ocean Systems Collapse

SRM geoengineering is emphasized over reducing GHG emissions because it is easier, cheaper and faster. The geoengineering efforts succeed in

stopping and even rolling back global temperature increases. However CO₂ levels continue to build up in the atmosphere and the ocean, and within a few decades ocean acidification causes a massive collapse of marine ecosystems.

Sword of Damocles

SRM geoengineering is adopted as the primary strategy for dealing with climate change. Rather than aiming at avoiding geoengineering or using it for as short a time as possible, policy makers decide to employ it freely as a partial or complete alternative to reducing the use of fossil fuels. As a result, large concentrations of carbon dioxide build up in the atmosphere and ocean, and over the entire millennium ahead people live with the threat of sudden, catastrophic climate change if they should ever fail to maintain the geoengineering enterprise.⁹³

Catastrophe

SRM geoengineering is substituted for emissions reduction in order to allow the fuller exploitation of fossil fuel resources. Very high CO₂ concentrations build up over the century ahead. The geoengineering efforts that need to be sustained to keep this CO₂ from abruptly changing the climate are disrupted by war and depression. The climate changes so violently and quickly that most life on Earth cannot adapt in time. The human population dies back sharply.

Over the generation ahead the six images set out here – No Geoengineering, Safe CDR Only, Technological Transformation, Insurance Policy, Needed Soon and Do It All – will compete, interact and take new forms in the arena of politics. Controversy is inevitable, and the stakes – the well-being of human civilization and life on Earth — will be very high.

If SRM geoengineering is rejected but efforts to reduce GHG emissions are not successful enough because we started too late, set our goals too low or could not achieve our goals, we would risk a climate catastrophe. If geoengineering is pursued, it risks politically undermining emissions-mitigation efforts. If it is deployed without adequate research to understand and minimize dangerous side effects, it could make a bad situation worse and destroy its own credibility. If it is deployed unilaterally, it could provoke a crisis of international governance. If politicians are

tempted by the idea that cheap and fast geoengineering can allow them to avoid the economic and political costs of reducing CO₂ emissions, it risks a collapse of ocean ecosystems and requires that geoengineering efforts be reliably sustained over many centuries through depressions, wars and potential disturbances of every kind.

Threading our way safely through these possibilities will require wise decision making. The nature of the governance processes used for making those decisions will be a major factor shaping how the future unfolds.

4. Geoengineering Governance

Should R&D on Geoengineering Be Supported?

Concerns about the potential negative consequences of geoengineering are justified, particularly for SRM technologies. Even early-stage research on geoengineering raises valid concerns, such as the possibility that it could create a community of researchers that functions as a self-interested lobby promoting the use of the technology.

Nonetheless, there are strong arguments for supporting R&D on geoengineering. In fact, a new analysis by the U.S. General Accounting Office (GAO) shows that funding for geoengineering R&D is already underway and growing in Europe. In the U.S., however, R&D has barely begun. It is dominated by a single set of grants from a private foundation with an insignificant amount of money from NSF.⁹⁴ The principal rationale for pursuing R&D is that nations around the world may not be able to reduce GHG emissions quickly enough to prevent dangerous climate change. Recent climate research presents mounting evidence that dangerous climate change

could emerge rapidly and portrays the challenge of reducing emissions as more daunting than was believed only a few years ago. Nothing remotely like the required scale of effort is on the table politically in the U.S. or other nations.

Given this situation, the moral argument for doing R&D on geoengineering now is that if there is even a modest chance we will fail to prevent dangerous climate change through emission reductions, then a resilient, farsighted approach must include preparing to deal with that failure before it occurs.

If it comes to a situation where geoengineering is the only recourse to a global climate catastrophe, decision makers will almost certainly choose to do geoengineering. They should not be put in the position of either letting dangerous climate change occur or deploying untested technologies at full scale.

Another rationale for doing research now is that it can reduce the danger of a “going rogue” scenario, where geoengineering is done unilaterally. A rogue deployment of an untested geoengineering technology could have highly damaging

impacts. But if research indicates that deploying that technology could be expected to have dreadful side effects, it is less likely to be used by a rogue actor. We need to know what approaches to avoid even if we are desperate.

The Importance of Upstream Governance

If R&D on geoengineering is pursued, even on a small scale, then governance immediately emerges as an important issue. The central problem of geoengineering governance is the so-called Collingridge dilemma,⁹⁵ an analysis of how efforts to control a technology's development face a double bind. On the one hand, a technology's negative impacts cannot be easily predicted and often become clear only after the technology is fully developed and widely used. On the other hand, after a technology has been fully developed and deployed it is extremely difficult to control and change. Put another way: the negative impacts of an emerging technology can be most effectively reduced or designed out when it is still in the early, upstream stages of the R&D process and its unintended impacts are not yet very clear.

The Collingridge dilemma cannot be fully resolved, but upstream governance is the most effective approach for dealing with it. Upstream governance involves iterative efforts, beginning at the very start of the R&D process, to understand potential environmental impacts and ethical, legal and social implications of an emerging technology. That evolving understanding, while imperfect, can make possible wiser choices about rejecting a technology or pursuing it and steering its development to minimize negative impacts.

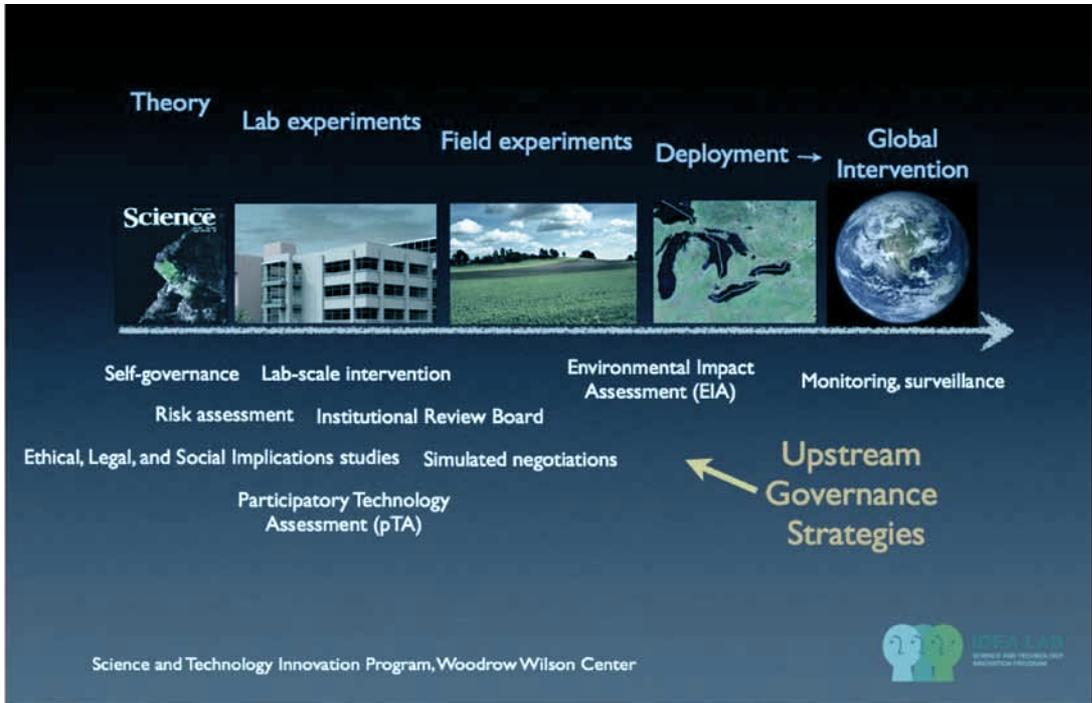
The concept of upstream governance strategies that can provide an early warning of risks, influence technology development and inform more formal downstream oversight efforts has

been missing from nearly all geoengineering governance discussions to date. It is sometimes assumed that governance concerns become important only at the stage of large-scale testing and deployment and, at that time, will involve complex, binding, multilateral agreements. That view needs to be rejected. Governance issues arise at every stage, beginning even with theoretical studies, modeling and laboratory experiments.

The word *governance*, as used here, is the sum of many ways that individuals and institutions, public and private, manage their common affairs. It includes the actions of government agencies, nation states and international institutions, but it also includes formal and informal efforts by scientific organizations, non-governmental organizations and many other non-state actors and networks carrying out purposive acts of steering. From this perspective, geoengineering governance includes a broader array of potential actors and strategies than has usually been considered.

Figure 3 is a summary of the upstream strategies that have been used in other areas of technological development. Integrating strategies of this kind into a cohesive framework for the upstream governance of geoengineering is just as important as developing a downstream governance framework for international decision making about the actual use of geoengineering.

These upstream governance strategies are particularly important for R&D on SRM technologies, which pose greater risks than CDR strategies. CDR also requires governance, but it is very heterogeneous. Ocean fertilization, for example, should be regulated because of its potential impact on ocean ecosystems. Other forms, like air capture, pose no risks beyond those of normal industrial operations and do not need to be subjected to close scrutiny and control. But effective upstream governance is critical for all SRM technologies, particularly stratospheric aerosols and cloud brightening.

FIGURE 3 Upstream Governance Strategies

Self-governance: Self-governance efforts by the scientific community have historically been an important upstream governance option. The most famous example is the Asilomar Conference organized by scientists in 1975 to examine the implications of recombinant DNA research, which had a substantial impact on subsequent research. However, this approach has inherent limitations. Voluntary self-regulation schemes face unique challenges when applied to emerging technologies, where little data exist, risk assessment models are uncertain, there are few or no best practices and the social contract between business and government is in flux. Also, scientists developing new technologies are often poor judges of the downstream impacts of their work. Recent survey research with university-based nanoscientists has indicated that researchers working

on new technologies tend to view their work as not producing any "new" or "substantial" risks, while those scientists downstream of development often feel the exact opposite.⁹⁶ As Princeton historian Edward Tenner once noted, "There is a tendency for advanced technologies to promote self-deception."

Ethical, Legal and Social Implications (ELSI) Studies:

As part of the Human Genome Project, the federal government set aside 5 percent of research funding to examine ELSI issues related to genome sequencing. Many other countries adopted the U.S. number. A similar set-aside could be mandated in any federal research grants for geoengineering; the approach could also be suggested for other sources of funding, such as foundations and private investors. As they did with the

Applying Clarke's First Law to Geoengineering

In 1962, scientist and science fiction writer Arthur Clarke published an essay entitled *The Hazards of Prophecy: The Failure of Imagination*, in which he posited three laws of prediction. The first law states, "When a distinguished but elderly scientist states that something is possible, he is almost certainly right. When he states that something is impossible, he is very probably wrong." Applied to geoengineering, this law implies that we need to pay attention not just to the significant unintended impacts that are projected to occur but also to those impacts that scientists and engineers assure us cannot happen. These should be treated as areas requiring additional research and should be monitored carefully over time.

Genome Project, other countries could adapt this set-aside strategy and apply it to any of their geoengineering research.

Lab-Scale Intervention: This involves embedding social scientists, ethicists and/or risk assessors directly in laboratories, a technique that has been used in the areas of biotechnology and nanotechnology. It is designed to enhance direct interaction between different social and natural science disciplines during the upstream research phase and could help ensure that social and ethical issues are addressed early in the development of geoengineering approaches.⁹⁷

Participatory Technology Assessment (PTA): PTA incorporates citizen participation methods to complement expert analysis and can be implemented at any scale, from local to global. The recent World Wide Views exercise to gather informed citizen input on climate change prior to the COP15 negotiations involved over 4,000 people from 38 countries.⁹⁸ This exercise demonstrates that public engagement efforts can be designed that are cost-effective, timely and scalable. A recent report recommended an institutional network model for participatory technology

assessment, called ECAST (Expert and Citizen Assessment of Science and Technology), which integrates the capacities of non-partisan policy research institutes with those of universities and science museums.⁹⁹

Institutional Review Boards (IRBs): IRBs have typically been used to review research projects that utilize humans in order to protect the rights and welfare of the research subjects. The concept could be expanded to require an institutional review of research for field experiments that use the Earth itself as a subject. IRB review requirements could be linked directly to research grants given for geoengineering, and a means would need to be created to provide reviews that transcend single institutions.

Risk Assessment: It should be possible to mobilize independent interdisciplinary efforts such as the International Risk Governance Council in Switzerland, which focuses on emerging systemic risks for which governance deficits exist and aims to provide recommendations for how policy makers can correct them, or groups like the Lighthill Risk Network in the U.K., which brings together scientists, engineers and the insurance and (re)

insurance industries to assess emerging risks.¹⁰⁰ The major challenge facing risk assessment efforts will be the lack of adequate data and models to even begin to frame the risks involved with some geoengineering scenarios.¹⁰¹ Research funding needs to be directed to developing applicable models.

Environmental Impact Assessments (EIAs):

Geoengineering field experiments supported by the federal government may require the submission of an EIA to the Environmental Protection Agency under Section 102 of the National Environmental Policy Act (NEPA). NEPA could be used as a proactive tool to require EIAs for any geoengineering experiments beyond a certain scale. The EIA requirement could be built into multi-lateral agreements covering large-scale geoengineering experiments.

Simulated Negotiations: As geoengineering ideas proceed toward deployment, scenarios for multi-party negotiations should become more apparent. At that time, these negotiations could be simulated using a variety of techniques—from on-line, multi-player games to conflict resolution models—to better understand what legal or informal oversight strategies might be workable, when and under what conditions. Simulations could also be incorporated into participatory technology assessment efforts.

For the most part, geoengineering today is in the earliest stage of theoretical studies, computer simulations and studies of “natural experiments” such as volcanic eruptions. This is the time for committing to norms of openness and transparency and for beginning to engage in several of these upstream governance strategies, including ELSI studies and self-governance initiatives to set out best practices for the least harmful and lowest-risk conduct of research and testing on proposed geoengineering methods. And it is not too soon to

begin giving rigorous and ongoing consideration to the question of what circumstances or trigger events might compel the use of geoengineering. Work on that question needs to be constantly reviewed in the light of evolving research findings on harmful effects of climate change and potential climate tipping points.

Research on some geoengineering methods has already moved from theory and modeling into laboratory experimentation. Lab-scale intervention that embeds social scientists, ethicists or risk analysts directly in laboratories can help assure that environmental and ELSI analyses continue to receive adequate attention.

Research on SRM methods like stratospheric aerosols and cloud brightening are already shading into lab-based development of technologies such as devices for injecting aerosols into the stratosphere or spraying sea water into clouds. At this point in the development process there is a possibility that corporate interests will try to steer the research, patent technologies and restrict access to research findings. Patents may be acceptable in most areas of CDR technology, but there are compelling reasons why all SRM research should be in the public domain. The inherently higher risks in the deployment of SRM compared with CDR methods in terms of causing sudden climate changes and other negative impacts justifies a more open-source approach to R&D on SRM technologies. An open-source approach to SRM R&D can speed progress, prevent private companies with proprietary technologies from gaining too much influence over R&D and minimize the risk that the drive for profits could lead to inappropriate testing and deployment.

It is also possible that governments will frame geoengineering research in terms of national security and attempt to classify some research findings.¹⁰² The scientific community should stand

BOX 3.**The Asilomar International Conference on Climate Intervention Technologies**

The Asilomar International Conference on Climate Intervention Technologies,¹⁰⁷ held in April 2010, brought together over 150 participants, including researchers working on geoengineering, scientists from a variety of fields, leaders of environmental groups, ethicists and specialists in economics, risk, governance, business and policy. Unlike its namesake, the 1975 Asilomar Conference on Recombinant DNA Research, which developed guidelines for work in the field, the 2010 conference was a free-form and sometimes chaotic event with speakers, panels and both formal and informal discussions. Nevertheless, there was considerable agreement among participants about many matters related to the governance of geoengineering,¹⁰⁸ including the importance of:

- Expanding efforts on mitigation and adaptation
- Never allowing geoengineering to be used as a substitute for mitigation
- Expanding research on climate science
- Expanding research on the efficacy of different geoengineering methods and on unintended impacts and risks associated with different methods
- Developing ethical principles or guidelines for guiding research
- Reaching agreements on the kind of field experiments that are needed and how they should be approved; defining the difference between sub-scale experiments with small, local, temporary impacts and large-scale experiments that require more thorough review and approval processes¹¹²
- Developing legitimate international governance arrangements for decision making about the deployment of SRM technologies
- Educating the public about climate change and geoengineering
- Addressing the challenge of inequalities inherent in geoengineering – how to deal fairly with situations in which some geographical areas suffer negative impacts while others benefit
- Preventing private sector involvement in geoengineering from leading to a geoengineering lobby; Granger Morgan, head of the Department of Engineering and Public Policy at Carnegie Mellon University, summed up the general view: “Lobbying is the *last* thing we need on this.”

firm in its commitment to openness, transparency and accessibility.

Field Experiments and Deployment

Field experiments designed to test the effectiveness of technologies and identify environmental risks are the next stage of geoengineering technology development. Several technologies are entering this stage. For example, a team of UK researchers is using a balloon to hoist one end of a 1-kilometer-long hose aloft to spray water in the atmosphere, testing a concept for pumping aerosols into the stratosphere. Armand Neukermans, a California-based engineer, is preparing to test a nozzle to spray seawater into clouds. Ken Caldeira at the Carnegie Institution for Science in Stanford, California has permission to add an alkali, sodium hydroxide, to an area of ocean to see if it can effectively counter ocean acidification.

Experiments with the CDR technique of ocean fertilization show both the difficulties and value of this kind of experimentation. Five ocean fertilization experiments were conducted in the Southern Ocean between 1973 and 2008. In response to widespread environmental concerns, the 191 parties to the United Nation's Convention on Biological Diversity agreed in 2008 on a moratorium on all ocean fertilization activities. Arguing that the moratorium did not apply to their particular experiment, in 2009 an Indo-European research consortium dumped 20 tons of iron sulfate in the Scotia Sea between Argentina and the Antarctic Peninsula, setting off a storm of controversy. Critics charged that this experiment was in flagrant disregard of international law and was large enough that it risked producing dangerous side effects. Its negative effects turned out to be negligible, but so were its intended effects. The fertilization did stimulate the

growth of CO₂-absorbing plankton, but this was negated by crustaceans known as amphipods that swarmed in to eat the plankton before they could die and sink below the ocean's surface layer, taking the carbon they absorbed with them. So the experiment proved valuable in demonstrating that ocean fertilization is not a highly effective carbon dioxide removal method.

This experiment also demonstrates how even small field tests can create tensions and risk creating a crisis of legitimacy that frustrates the ability to do further experimentation. To date, climate scientists have seldom thought of themselves as field scientists, and few have had to deal with field testing, which is a far more political activity than theoretical work or lab experiments. Climate scientists can make their lives easier and their work safer by welcoming the use of upstream approaches such as IRBs, formal EIAs and PTAs to help ensure that dangerous experiments are not undertaken.

In theory, field experimentation would proceed as David Keith has proposed, expanding "gradually to scales big enough to produce barely detectable climate effects and reveal unexpected problems, yet small enough to limit risks".¹⁰³ In practice, however, this kind of smooth expansion of the scale of experiments may sometimes prove unworkable because it may not be possible to reliably distinguish "barely detectable climate effects" caused by field experiments from the complex climate system's background variability. As a result, fairly large-scale experiments may be needed to get a clear "signal" of the geoengineering technology's impacts.

Eventually, large-scale or so-called climate impacts testing would be needed to confirm the effectiveness and safety of powerful SRM technologies like stratospheric aerosols and cloud brightening. The tests have to be large enough to have a clear impact on the climate and so are

BOX 4**UN Convention on Biological Diversity Moratorium on Geoengineering Experiments**

In a landmark consensus decision, the 193-member UN Framework Convention on Biological Diversity (CBD) closed its tenth biennial meeting in Nagoya, Japan, on October 29, 2010, by passing a resolution that would impose a de facto moratorium on geoengineering experiments.

The resolution, proposed by and lobbied for by the ETC Group, a Canadian environmental group, states that “no climate-related geoengineering activities that may affect biodiversity take place until there is an adequate scientific basis on which to justify such activities and appropriate consideration of the associated risks for the environment and biodiversity and associated social, economic and cultural impacts. ...” The resolution defines geoengineering as “any technologies that reduce solar insolation or increase carbon sequestration from the atmosphere on a large scale that may affect biodiversity,” a definition broad enough to encompass virtually every technical option. The resolution does exempt “small-scale scientific research studies that would be conducted in a controlled setting,” but only if they are “justified by the need to gather specific scientific data and are subject to a thorough prior assessment of the potential impacts on the environment.”

It is not clear what effect this action will have on geoengineering research. In the past, nations have not considered CBD decisions legally binding, although past decisions have had some influence, particularly in the area of genetically modified organisms. Moreover, the U.S. is not a party to the 1992 Convention.

The CBD moratorium’s language leaves many issues open. Who will judge whether an “adequate scientific basis” for experiments has been achieved? What constitutes a “controlled setting” for small-scale studies? How can the moratorium be enforced? Regardless of these unanswered questions, the action clearly brings the subject of geoengineering governance to the fore and claims a major role for the UN in future decision making. And whatever influence the moratorium has in the future, the resolution marks a coming of age for the field of geoengineering, which has now become a sufficiently serious option to arouse international efforts to control it.

essentially time-limited deployments. Upstream governance strategies are inadequate for dealing with large-scale field experiments.

Because large-scale testing is likely to have serious trans-boundary impacts, a legitimate international process needs to be developed for approval and oversight. There should be a moratorium on large-scale testing until such a process has been agreed upon.

An international mechanism for large-scale testing approval and oversight would need to be mandatory rather than voluntary. A possible basis for such a mechanism already exists in the approach taken by parties to the London Convention and London Protocol in regulating ocean fertilization experiments. David Santillo and Paul Johnson at the University of Exeter in the U.K. argue that “this approach explicitly allows for “legitimate scientific research ... supported by an assessment framework under which the legitimacy and scientific value of proposed research can be tested.” An assessment framework of ethics, responsibilities and standards to govern large-scale field experiments needs to include criteria such as scientific justification, thoroughness of risk assessment, prior international consultation, transparency and exclusion of projects with a commercial nature.¹⁰⁴

To be legitimate, an international process for large-scale testing approval and oversight will need mechanisms for drawing on the best science for assessing potential impacts and for providing ways for the public to be brought into the decision process. It will need to have the power to stop tests by any country or group if potential negative impacts are judged to be too serious. A major challenge will be defining the boundary that distinguishes large-scale tests from sub-scale field experiments.

The most difficult issues that arise with large-scale testing—issues that become even more difficult in the event of actual deployment—involve

responsibilities toward vulnerable populations. Populations living at the edge of subsistence—those with the least capacity to adapt to the impacts of climate change and almost no voice in international deliberations—are precisely the populations that will be most vulnerable to any negative side effects that geoengineering experiments may have. On the other hand, these are the populations most vulnerable to the climate change impacts that geoengineering might forestall. What responsibility, or even liability, do those conducting large-scale tests have for the harm they may cause to vulnerable populations? In medical experiments, doctors must secure informed consent from the patient. Do the populations most vulnerable to harm by geoengineering experiments deserve some opportunity for informed consent? And if so, how can this be done?¹⁰⁵

Ultimately, if geoengineering technologies are used, new international legal and institutional arrangements would be needed for decision making about deployment and ongoing global-scale intervention. Actual use of SRM technologies would require monitoring and surveillance of ongoing global impacts at a scale and level of sophistication that we are not yet ready to undertake. It would pose novel governance challenges, including the need for a rapid adjustment capability. International decision processes are typically consensus based and slow, but in the early stages of a global-scale intervention there would almost certainly be a need for rapid decisions about adjustments in some intervention variables.¹⁰⁶

Developing the needed international agreements would be easier to the extent that research is internationalized from an early stage, with the work of individual scientists and national programs integrated into an international framework. A coordinated, fully transparent international effort would be not only more efficient than independent efforts but also more

acceptable politically. Several proposals have already been made for organizing an international research effort through existing institutions or a new, dedicated international collaboration modeled along the lines of the European Organization for Nuclear Research (CERN) or the Human Genome Project.

Although the near-term priority is to develop upstream governance arrangements, it is not too soon to begin to cooperate in holding informal but focused international dialogues about the downstream governance arrangements needed to make decisions about large-scale testing and deployment. Decisions on these matters cannot be made by one or a few countries and imposed

on the international system, and the issues involved are so new and unfamiliar that it may be premature to start a full-scale UN treaty-making effort. The important need now is to organize informal international dialogues that do not require participants to take positions or votes but do allow them to learn, express their concerns and think creatively together about the design of geoengineering governance. Innovative upstream approaches like simulated negotiations might be used as part of these discussions.

If SRM geoengineering does eventually prove necessary, well-designed governance arrangements will be as important for its successful use as carefully developed and tested technologies.

5. Recommendations for Decision Makers

- Always consider geoengineering issues in a broader context of *climate change management*, which includes emissions reduction as the primary strategy and adaptation as the secondary strategy, with geoengineering as a third strategy to use only if clearly needed. An exclusive focus on geoengineering is likely to lead to an over-emphasis on this strategy.
- Address the climate problem and geoengineering in the context of related challenges, such as energy security, vulnerability to terrorism, water scarcity and food security, ocean health, economic competitiveness and job creation. Look for systemic approaches that provide simultaneous solutions to the climate problem and as many other related challenges as possible.
- Commit the U.S. fully to leadership in creating a 21st-century energy infrastructure that incorporates major improvements in energy efficiency and dramatic reductions in carbon dioxide emissions. This is the best way to achieve simultaneous solutions to the climate challenge, the energy challenge and other challenges facing our society.
- Support significantly greater funding for R&D on technologies that can drive down carbon emissions. This includes high-risk, high-reward energy efficiency and supply options that could be game changers if they prove feasible. The likelihood that SRM geoengineering will need to be used can be sharply reduced if we are able to make significant jumps of technological progress beyond current energy-supply technologies. There is a reasonable possibility that breakthroughs can be achieved in photovoltaics, algal biofuels, new approaches to nuclear fission, fuel cells, carbon capture and storage, electrical storage and other areas because so little investment has been made in innovative technological possibilities.
- Because the task of reducing global GHG emissions in time to avoid dangerous climate change is difficult, geoengineering should not

be taken off the table as an option for helping address the climate problem.

- Funding for geoengineering-related activity should never be allowed to reduce support for or divert funding from R&D on energy efficiency and carbon-free energy sources, climate science research or adaptation efforts.
- Do not allow geoengineering to be used as a source of carbon offsets, because this would divert effort from emissions reduction.
- Distinguish between the two different approaches to geoengineering, namely, CDR and SRM. CDR methods, such as engineered air capture, improved ecosystem management and some forms of enhanced weathering can remove CO₂ from the atmosphere without perturbing natural systems or requiring large land-use changes. If research shows that these methods can be made cost-effective and safe, then they can quickly play a valuable role, along with mitigation, in reducing CO₂ concentrations. Other CDR methods like biochar and bioenergy with carbon capture and sequestration, which have major land-use implications, can make a contribution at a small scale, but require extensive research to assess their sustainability if used on a large scale. Methods that perturb natural systems, like ocean fertilization, should be approached more cautiously.
- Never treat SRM methods – especially the more powerful ones such as stratospheric aerosols, cloud brightening and space-based approaches – as a substitute for emissions mitigation. If these SRM methods are ever used at all, it should be only as a time-limited emergency measure with a clear exit strategy to give more time for mitigation efforts to succeed. Their use as a substitute for emissions reduction would allow CO₂ to reach high concentrations in the atmosphere and ocean, posing a constant threat of sudden catastrophic climate change if the geoengineering effort should stop for any reason. If we fail to cut emissions, no amount of geoengineering will save us from catastrophe.
- Do not consider deployment of stratospheric aerosols, cloud brightening or space-based methods in the near term. These SRM methods have not been studied enough to understand their risks or to design them in a way that optimizes their safety and effectiveness.
- In R&D on SRM methods, give more attention to the idea of regional geoengineering or “geoadaptation,” which could have more localized, “where needed” effects and be especially important for use in polar areas to limit permafrost thawing, ice sheet melting, and sea level rise.
- All geoengineering methods have significant uncertainties about their likely costs, effectiveness and risks. Funding should be provided for rigorous and fully transparent research efforts to reduce these uncertainties. This kind of research can clarify priorities for further development and make potential rogue actors less trigger-happy by identifying the areas of SRM geoengineering that pose the greatest potential risks.
- Different geoengineering technologies pose different levels of risk, with air capture and some other forms of CDR posing the lowest risks and powerful SRM technologies like stratospheric aerosols posing the highest risks. To make wise choices about the development

of the higher risk geoengineering technologies it is important to learn as much as possible as soon as possible about their potential environmental impacts and ethical, legal and social implications. This requires the use of upstream governance approaches that begin at the earliest stage of theoretical and modeling studies and continue to be applied as research moves into laboratory and field experiments. Many strategies have been used in other areas of technological development, and some or all of them can be integrated into a framework for the upstream governance of higher risk geoengineering technologies.

- The research community can institute voluntary *self-governance* arrangements, developing a formal set of norms and best-practice guidelines for conducting research in an open and safe manner.
- The federal government can mandate that a percentage of all the research funding it provides be set aside to examine *ethical, legal and social implications*, as was done for research on the human genome.
- The kind of *lab-scale intervention* that has been used in some areas of research on nanotechnology and biotechnology can be applied, bringing social scientists, ethicists or trained risk assessors directly into laboratories to help ensure that risks and social and ethical issues are addressed early in the development of geoengineering approaches.
- *Participatory technology assessment* can incorporate citizen participation methods to complement expert analysis in studying geoengineering risks and benefits. These and other strategies reviewed in this report can be integrated into a cohesive upstream governance framework.
- The concept of *institutional review boards* can be expanded to require institutional review of field experiments that use the Earth itself as a subject.
- Independent, interdisciplinary *risk assessments* can be commissioned from bodies such as the International Risk Governance Council in Switzerland or the Lighthill Risk Network in the U.K.
- *Environmental impact assessments* can be required under the NEPA for any geoengineering experiments beyond a certain scale.
- *Simulated negotiations* could help clarify what approval and oversight strategies might be workable for dealing with large-scale field experiments.
- As research on SRM methods like stratospheric aerosols and cloud whitening shades into lab-based development and preliminary field testing of these technologies, commercial or government interests may try to restrict access to research findings. Therefore it is important for government and the scientific community to insist that all SRM research be in the public domain, and to stand firm in a commitment to openness, transparency and accessibility. Because SRM technologies like stratospheric aerosols are relatively inexpensive, fast acting, and likely to have different outcomes in different parts of the world, their development and use could lead to serious international tensions and conflicts. Openness and transparency are needed to reduce that risk.

- Large-scale field experiments that could have significant trans-boundary impacts will be legitimate only if they have international approval. Unapproved testing by national governments or other entities could provoke a crisis of legitimacy that severely constrains geoengineering development. Therefore a moratorium on large-scale or climate impact testing should be put in place until a legitimate international process for approval and oversight has been agreed upon. However field experiments without climate impacts or other significant risks should be allowed.
- A possible model for an international mechanism for approval and oversight of large-scale testing is provided by the approach taken by the London Convention and London Protocol for regulating ocean fertilization experiments. A review process using an assessment framework of ethics, responsibilities and standards would include criteria such as scientific justification, thoroughness of risk assessment, prior international consultation, transparency and exclusion of projects with a commercial nature.
- Developing the needed international agreements will be easier if related research is internationalized from an early stage. Therefore it is important to support the development of a coordinated, fully transparent effort where the work of individual scientists and national programs is integrated into an international framework.
- Downstream governance arrangements need to be developed for authorizing both large-scale testing and actual deployment. Decisions on these matters cannot be made by one country or a few countries and imposed on the international system, and the issues involved

are so new and unfamiliar that it may be premature to start a full-scale UN treaty-making effort. At this point, the important task is to organize informal but focused international dialogues about needed downstream governance arrangements. Informal dialogues where participants can learn, express their concerns and think creatively together without taking positions or votes can prepare the way for more formal negotiations.

The best future by far would be one in which geoengineering does not need to be done because greenhouse gas emissions are rapidly reduced by improvements in energy efficiency and new energy-supply technologies. But if the consensus among climate scientists is correct, the window of opportunity for reaching this future will not be open for long. If it closes, the next-best future may involve doing the same things, supplemented by the careful and time-limited use of geoengineering. Beyond these two possibilities, much worse futures loom.

The benefits of pursuing these best futures are far greater than we usually assume. A large-scale mobilization to decarbonize our energy system would not only avoid dangerous climate change; it would also end our addiction to oil, protect the environment from oil spills and other environmental impacts, defend our national security, promote innovation, create jobs and assure U.S. competitiveness as energy technology becomes the next great global industry.

Even if geoengineering proves necessary, doing it responsibly while rapidly cutting our greenhouse emissions would be a large first step toward becoming a mature technological society in responsible control of its impacts and willing and able to take on growing responsibility for the welfare of future generations and the future of life on the Earth.

Notes

1. Intergovernmental Panel on Climate Change, Fourth Assessment Report, *Climate Change 2007*, available online at: http://www.ipcc.ch/publications_and_data/publications_and_data.htm
2. Quotations from Gore's speech at the Bali conference are available online at: <http://www.greenpeace.org/international/news/sparks-fly-in-bali-141207>
3. *Policy Implications of Greenhouse Warming: Mitigation, Adaptation and the Science Base* (1992), NAS Committee on Science, Engineering and Public Policy.
4. For an authoritative overview of these and other environmental impacts, see James Gustav Speth, *The Bridge at the Edge of the World: Capitalism, the Environment and Moving from Crisis to Sustainability*. Yale University Press, 2009.
5. Paul Crutzen, "Albedo Enhancement by Stratospheric Sulfur Injections: A Contribution to Resolve a Policy Dilemma?" An editorial essay, *Climatic Change*, 2006, pp. 211-219.
6. Brad Allenby, 2007. "Earth Systems Engineering and Management: A Manifesto," *Environmental Science and Technology*, December 1.
7. Conversations with Walter Anderson. See his book *To Govern Evolution: Further Adventures of the Political Animal*. Houghton Mifflin Harcourt, 1987.
8. The ideas discussed here are primarily drawn from conversations with Brad Allenby, founding director of the Center for Earth Systems Engineering and Management at Arizona State University.
9. Clement Bezold and Robert L. Olson, *Food 2028: Key Forecasts*. Institute for Alternative Futures, June 2008.
10. SRM approaches are sometimes called by other names, such as "shortwave" or "albedo management" and CDR approaches are called by names like "long-wave" or "carbon management." But the terms SRM and CDR are used in the most important study of geoengineering to date and are likely to become the standard terms. See [Geoengineering the Climate: Science, Governance and Uncertainty](#). UK: The Royal Society, September 2009.
11. "Afforestation" refers to the planting of trees on areas that were not covered with forests. "Reforestation" refers to the replanting of trees on areas that were once covered with forests.
12. Arrhenius, D., *Worlds in the Making*. Harper & Row, New York, 1908.
13. James Fleming, "The Climate Engineers," *Wilson Quarterly*, spring 2007. Available online at: http://www.wilsoncenter.org/index.cfm?fuseaction=wq.essay&essay_id=231274
14. E.J. Dyson and G. Markland, "Technical fixes for the climatic effects of CO₂," workshop on the global effects of carbon dioxide from fossil fuels, *Rep. CONF-770385*, pp. 111-118, U.S. Department of Energy, Washington, DC, 1979; E. Teller, L. Wood and R. Hyde, "Global Warming and Ice Ages:

- Prospects for Physics-Based Modulation of Global Change," 15 August 1997.
15. Jonathan Gatehouse, "Plan B for Global Warming," *Macleans*, April 27, 2009, Vol. 122, Issue 15, pp. 40-43.
 16. David G. Victor, Granger Morgan, Jay Apt, John Steinbruner, Katherine Rich, "The Geoengineering Option," *Foreign Affairs*; March/April 2009, Vol. 88 Issue 2, pp. 64-76.
 17. Paul Crutzen, "Albedo Enhancement by Stratospheric Sulfur injections: A Contribution to Resolve a Policy Dilemma?" An Editorial Essay. *Climatic Change*, 2006, pp. 211-219.
 18. The estimates in figure 1 were made by running "Lexis-Nexus" and "EBSCO Academic Search Premier" queries for two separate terms: "geo-engineering" and "geoengineering." Search parameters were set to include only U.S. news sources. Searches were conducted for January 1 to December 31 of each year from 2005-2009. Recorded results were limited to those in the "newspaper" and "journals/magazines" headings. Foreign, industry-specific and non-mainstream sources were not counted. Less restrictive search criteria would have identified a significantly larger number of articles.
 19. Seth Borenstein, Associated Press, April 9, 2009. See "Obama looks at climate engineering," available online at <http://www.breitbart.com/print.php?id=D97ECHLG1>
 20. Steven Chu spoke at the St James Palace Nobel Laureate Symposium held in London May 26-28, 2008. News story available from the *Times Online* at <http://www.timesonline.co.uk/tol/news/environment/article6366639.ece>
 21. See www.americasclimatechoices.org/GeoEng%20Agenda%206-11-09.pdf
 22. Jason J. Blackstock, David S. Battisti, Ken Caldeira, Douglas M. Eardley, Jonathan I. Katz, David W. Keith, Aristes A. N. Patrinos, Daniel P. Shrag, Robert H. Socolow and Steven E. Koonin, *Climate Engineering Responses to Climate Emergencies*. (Novim, 2009), archived online at: <http://arxiv.org/pdf/0907.5140>
 23. The Royal Society, *Geoengineering the Climate: Science, Governance and Uncertainty* (September 2009), available online at <http://royalsociety.org/geoengineeringclimate/>
 24. See http://science.house.gov/publications/hearings_markup_details.aspx?NewsID=272
 25. 50 international civil society groups signed a letter criticizing a meeting on geoengineering held March 22-26, 2010 at the Asilomar Conference Center in California. The March 4, 2010, letter stated that "as civil society organizations and social movements working to find constructive solutions to climate change, we want to express our deep concerns with the upcoming privately organized meeting on geoengineering in Asilomar, California. Its stated aim, which is to «develop a set of voluntary guidelines, or best practices, for the least harmful and lowest risk conduct of research and testing of proposed climate intervention and geoengineering technologies,» is moving us down the wrong road too soon and without any speed limit."
 26. In: *Engineering Education*, October, pp. 459-464.
 27. Dean, Cordelia (2008). "Handle with Care," *The New York Times*, August 12. See: <http://www.nytimes.com/2008/08/12/science/12ethics.html?ref=technology&pagewanted=print>.
 28. In a symposium at the Ecological Society of America's 2009 Annual Meeting, ecologists discussing the viability of geoengineering reached a strong consensus that the risks currently outweigh the benefits. See "Geoengineering To Mitigate Global Warming May Cause Other Environmental Harm," *Science Daily*, August 7, 2009.
 29. The Novim Group, *Climate Engineering Responses to Climate Emergencies*,
 30. Douglas Fisher, "The Escape Route," *The Daily Climate*, 12 November 2009.
 31. Tables 1 and 2 were compiled from a variety of sources, the most important of which was the September 2009 report by The Royal Society, *Geoengineering the Climate: Science, Governance and Uncertainty*.
 32. T.M. Lenton and N.E. Vaughan, "The radiative forcing potential of different climate geoengineering options," *Atmospheric Chemistry and Physics*, 9, 2559-2608, 2009.
 33. The final report on this Copenhagen Consensus Center project is available online at <http://fixtheclimate.com/component-1/the-result-prioritization/>
 34. Steven D. Levitt and Stephen J. Dubner, *SuperFreakonomics: Global Cooling, Patriotic Prostitutes, and Why Suicide Bombers Should Buy Life Insurance*. William Morrow, 2009.

35. These and other views expressed by people at several think tanks are quoted in an article “Geoengineering and the New Climate Denialism,” 29 April 2009, posted on the Worldchanging web site at: <http://www.worldchanging.com/archives/009784.html>
36. Editors, *Scientific American*, November 2008, available online at: <http://www.nature.com/scientificamerican/journal/v299/n5/full/scientificamerican1108-38.html>
37. Climatologist Stephen Schneider stresses the “social limits of geoengineering” in many of his writings and speeches. See, for example, “The Bulletin Interview: Stephen Schneider,” *Bulletin of the Atomic Scientists*, July/August 2009, 5-13.
38. Kevin E. Trenberth and Aiguo Dai, “Effects of Mount Pinatubo Volcanic Eruption on the Hydrological Cycle as an Analog of Geoengineering,” *Geophysical Research Letters*, vol. 34, no. 16 (2007).
39. Gabriele C. Hergerl and Susan Solomon, “Risks of Climate Engineering,” *Science*, vol. 325, no. 5943, (6 August 2009).
40. Alan Robock, “20 Reasons Why Geoengineering May Be a Bad Idea,” *Bulletin of the Atomic Scientists*, Vol 64, No. 2, p. 14-18 (May/June 2008).
41. Juan B. Moreno-Cruz, Katharine L. Ricke, and David W. Keith. 2011. “A simple model to account for regional inequalities in the effectiveness of solar radiation management” forthcoming *Climatic Change* Available at: <http://works.bepress.com/morenocruz/2>
42. Hergerl and Solomon, “Risks of Climate Engineering,” op cit.
43. James R. Fleming writes eloquently about the militaristic history of climate modification schemes in “The Climate Engineers,” *Wilson Quarterly*, Spring 2007, pp. 46-60.
44. Available online at http://www.infowars.com/articles/science/weather_mod_own_weather_by_2025.htm
45. Available online at <http://www.un-documents.net/enmod.htm>
46. See Balan Govindasamy and Ken Caldeira, “Geoengineering Earth’s Radiation Balance to Mitigate CO₂-Induced Climate Change,” *Geophysical Research Letters*, vol. 27, pp. 2141-2144 (2000).
47. “Geoengineering Could Reduce Solar Power,” *New Scientist*, Vo. 202, Issue 2705, p. 17 (April 25, 2009).
48. Dale Jamieson, “The Artificial Heart: Reevaluating the Investment” in D. Mathieu (ed.), *Organ Substitution Technology: Ethical, Legal and Public Policy Issues*, Westview Press, Boulder, Colorado, 1988, pp. 277-293.
49. Dale Jamieson, “Ethics and Intentional Climate Change,” *Climatic Change*, 33, pp. 323-336, 1996.
50. ETC Group Special Report, *The Emperor’s New Climate: Geoengineering as 21st Century Fairytale*, 28 August 2009, available online at http://www.etcgroup.org/en/materials/publications.html?pub_id=762
51. See, for example Richard S. Lindzen and Yong-Sang Choi, “On the determination of climate feedbacks from ERBE data,” *Geophysical Research Letters*. Vol. 36, L16705, doi:10.1029/2009GL039628, 2009.
52. See *The Copenhagen Diagnosis: Updating the World on the Latest Climate Science*. I. Allison, N.L. Bindoff, R.A. Bindshadler, P.M. Cox, N. de Noblet, M.H. England, J.E. Francis, N.Gruber, A.M. Haywood, D.J. Karoly, G. Kaser, C. Le Quéré, T.M. Lenton, M.E. Mann, B.I. McNeil, A.J. Pitman, S. Rahmstorf, E. Rignot, H.J. Schellnhuber, S.H. Schneider, S.C. Sherwood, R.C.J. Somerville, K. Steffen, E.J. Steig, M. Visbeck, A.J. Weaver. December 2009. The University of New South Wales Climate Change Research Centre (CCRC), Sydney, Australia, 60 pp. Available online at: http://www.ccr.c.unsw.edu.au/Copenhagen/Copenhagen_Diagnosis_LOW.pdf. Also see “Global Carbon Emissions Speed Up, Beyond IPCC Projections” *Science Daily*, Sep. 28, 2008.
53. Clive Hamilton, “Is it too late to prevent catastrophic climate change?” Lecture to a meeting of the Royal Society of the Arts, Sydney, 21 October 2009. Available online at: http://www.clivehamilton.net.au/cms/media/documents/articles/rsa_lecture.pdf
54. Earth Trends environmental information on the web site of the World Resources Institute at <http://earth-trends.wri.org/updates/node/83>
55. Justin Gillis, “Figures on Global Climate Show 2010 Tied 2005 as the Hottest Year on Record,” *New York Times*, January 12, 2011.
56. John M. Broder, “Past Decade Warmest Ever, NASA Data Shows,” *New York Times* January 22, 2010 available online at: <http://news.google.com/news?hl=en&q=past+decade+warmest+ever,+NASA+Data+sh>

- ows&um=1&ie=UTF-8&ei=GjRfS8DxHI6N8Abe67WJDA&sa=X&oi=news_group&ct=title&resnum=1&ved=0CAwQsQQwAA
57. On the natural cyclical phenomena that affect global temperatures, see Paul Hudson, "What Happened to Global Warming?," BBC News, 9 October 2009 available online at: <http://news.bbc.co.uk/2/hi/science/nature/8299079.stm>
 58. Richard A. Kerr, "What Happened to Global Warming? Scientists Say Just Wait a Bit," *Science*, 2 October 2009, Vol. 36, pp. 28-29.
 59. J. Stoeve et al., "Arctic Sea Ice Decline: Faster the Forecast," *Geophysical Research Letters*, 2007, 34:9501.
 60. For details on the decline of sea ice, see the research summarized by the Pew Center on Global Climate Change available online at: <http://www.pewclimate.org/impacts/icecap>
 61. M. Wang and J.F. Overland, "A sea ice free summer Arctic within 30 years?" *Geophysical Research Letters*, 2009, 36:L07502.
 62. J. L. Chen, C. R. Wilson, and B. D. Tapley. 2006. Satellite gravity measurements confirm accelerated melting of Greenland ice sheet. *Science* 313:1958-1960.
 63. S. H. Mernild, G. E. Liston, C. A. Hiemstra, and K. Steffen. 2009. "Record 2007 Greenland Ice Sheet Surface Melt Extent and Runoff," *Eos, Transactions, American Geophysical Union* 90:13-14.
 64. See the report from the National Snow and Ice Data Center at: http://nsidc.org/news/press/20090408_Wilkins.html
 65. The latest data are summarized in "East Antarctica Is Now Losing Ice" on the *Skeptical Science* web page at: <http://www.skepticalscience.com/East-Antarctica-is-now-losing-ice.html>
 66. *Key Scientific Developments Since the IPCC Fourth Assessment Report*. Science Brief 2, June 2009, Pew Center on Global Climate Change. Available online at: <http://www.pewclimate.org/docUploads/Key-Scientific-Developments-Since-IPCC-4th-Assessment.pdf>
 67. *The Copenhagen Consensus*, op cit.
 68. "Global Scientists Draw Attention to Threat of Ocean Acidification," *Science Daily*, 5 February 2009. Available online at: <http://www.sciencedaily.com/releases/2009/02/090201124553.htm>
 69. Andy Ridgwell and Daniella Schmidt, "Past Constraints on the Vulnerability of Marine Calcifiers to Massive Carbon Dioxide Release," *Nature Geoscience*, 14 February 2010. Available online at <http://www.nature.com/ngeo/journal/vaop/ncurrent/abs/ngeo755.html>
 70. J.B. Silverman, B. Lazar, L. Cao, K. Caldeira, and J. Erez. 2009. "Coral reefs may start dissolving when atmospheric CO₂ doubles." *Geophysical Research Letters* 36:L05606.
 71. See the story "Lloyd's urges insurers to take climate change seriously or risk being swept away" on the Lloyd's web site at: http://www.lloyds.com/News_Centre/Features_from_Lloyds/Climate_change_adapt_or_bust.htm
 72. Presentation by Cosette R. Simon of Swiss Re to the Harvard University Center for Health and Global Environment available online at: <http://chge.med.harvard.edu/programs/policy/briefings/documents/simon.pdf>
 73. See the essay "Munich Re: Climate Change One of Mankind's Greatest Risks" on Doug Simpson's weblog of research on law, networks and disruptive technologies at: <http://www.dougsimpson.com/blog/archives/000636.html>
 74. Kevin Anderson and Alice Bows, "Reframing the Climate Challenge in Light of Post-2000 Emission Trends," *Philosophical Transactions of the Royal Society*. 2008, available online at <http://www.ncbi.nlm.nih.gov/pubmed/18757271>
 75. James Hansen, et al, "Target Atmospheric CO₂: Where Should Humanity Aim?" *Open Atmospheric Science Journal*, 2008) vol. 2, pp. 217-231, available online at: <http://arxiv.org/abs/0804.1126>
 76. Malte Meinshausen et al, "Greenhouse Gas Emission Targets for Limiting Global Warming to 2 Degrees C," *Nature*, 485, 20 April 2009, pp. 1158-1162. Available online at: <http://www.nature.com/nature/journal/v458/n7242/full/nature08017.html>
 77. James Lovelock, "The Vanishing Face of Gaia," lecture filmed for the Corporate Knights Video Presentation series, 2009, available online at: http://www.youtube.com/watch?v=Eg7Jt_Yz1o
 78. Research by atmospheric scientist Andrew Dressler and his colleagues at Texas A&M University, reported in *Discover Magazine*, May 2010, p. 16.

79. Katey Walter et al. *Nature*, 443, 2006, pp. 71-75; Katey Walter et al., *Philosophical Transactions of the Royal Society*, 2007, 365, pp. 1657-1676.
80. David Adam, "Arctic Permafrost Leaking Methane at Record Levels, Figures Show," *The Guardian*, 14 January 2010. Available online at: http://www.guardian.co.uk/environment/2010/jan/14/arctic-permafrost-methane?utm_source=feedburner&utm_medium=email
81. "A Sleeping Giant," *op cit*.
82. *Ibid*.
83. "Confirmed: Deforestation Plays Critical Climate Change Role," *Science Daily*, May 11, 2007. Available online at: <http://www.sciencedaily.com/releases/2007/05/070511100918.htm>
84. Timothy M. Lenton et al. Tipping Elements in the Earth's Climate System, *Proceeds of the National Academy of Sciences*, February 2008, available online at: <http://www.pnas.org/content/105/6/1786.full>
85. "A Current Controversy: Is Europe About to Freeze?" *Science Daily*, 22 February 2002. Available online at: <http://www.sciencedaily.com/releases/2002/02/020221072948.htm>
86. Reported by Michael McCarthy, environmental editor, *The Independent*, 9 March 2009. Available online at: <http://www.independent.co.uk/environment/climate-change/carbon-cuts-only-give-5050-chance-of-saving-planet-1640154.html>
87. The UNEP report is available online at: <http://www.unep.org/Documents.Multilingual/Default.asp?DocumentID=612&ArticleID=6472&cl=en>
88. The analysis was done by the Sustainability Institute, the MIT Sloan School of Management and Ventana Systems corporation using the C-ROADS climate policy simulation model. See <http://climateinteractive.org>
89. Anderson and Bows, *op cit*.
90. James Hansen et al., "Target Atmospheric CO₂: Where Should Humanity Aim?" *The Open Atmospheric Science Journal* 2, pp. 217-231. Available online at: http://www.columbia.edu/~jeh1/2008/TargetCO2_20080407.pdf See also Paul Baer et al., "A 350 ppm Emergency Pathway." Available online at: <http://www.sei-us.org/climate-and-energy/a-350-ppm-emergency-pathway-v2.pdf>
91. Robert Socolow, "Prospicience and Geoengineering." Presentation as part of a series of programs on ethics and climate change co-sponsored by the Princeton Environmental Institute and the University Center for Human Values, October 14, 2008.
92. Bill Gates recently made a strong public call for the development of new breakthrough energy technologies. See his speech "Innovating to Zero" (carbon emissions) at the 2010 TED conference: http://www.ted.com/talks/bill_gates.html For a comprehensive review of the status of technologies that can reduce carbon emissions, see Al Gore, *Our Choice*. Rodale Books, November 2009.
93. This view is reflected in a wide range of writing, from Paul Crutzen's editorial essay in 2006 that originally helped legitimize geoengineering to the Royal Society's recent report *Geoengineering the Climate: Science, Governance and Uncertainty*.
94. Jamais Cascio, *Hacking the Earth: Understanding the Consequences of Geoengineering*. 2009, available from Lulu online at: <http://www.lulu.com/content/6048806> See also David G. Victor et al., "The Geoengineering Option" in *Foreign Affairs*, *op cit*.
95. See Levitt and Dubner's book *SuperFreakonomics*, *op cit*. and the final report on this Copenhagen Consensus Center project on climate change available online at <http://fixthecclimate.com/component-1/the-result-prioritization/>
96. GAO, "Technology Assessment: Climate Engineering - Technical Status, Social Context, and Future Prospects", forthcoming. [Complete quote]
97. The dilemma was formulated by David Collingridge in the book *The Social Control of Technology*, Open University Press, 1981.
98. Powell, M.C. 2007. "New Risk of Old Risk, High Risk or No Risk? How Scientists' Standpoints Shape Their Nanotechnology Risk Frames," *Health, Risk & Society*, June, 9(2), pp. 173-190.
99. Schuurbiers, D. & Fisher, E, 2009. "Lab-scale Intervention," *European Molecular Biology Organization Report*, Volume 10, Number 5.
100. See: www.wvviews.org
101. Sclove, R. 2010. Reinventing Technology Assessment for the 21st Century, Washington, DC: Science and Technology Innovation Program, Woodrow Wilson Center.

102. See: <http://www.irgc.org/> and <http://www.lighthill-risknetwork.org/>
103. Kent, Adrian 2004. "A Critical Look at Risk Assessments for Global Catastrophes," *Risk Analysis*, Volume 24, Number 1.
104. Jason J. Blackstock and James C. S. Long, "The Politics of Geoengineering," *Science* Vol. 327, 29 January 2010, p. 527.
105. David W. Keith, E. Parson and M.G. Morgan, "Research on Global Sun Block Needed Now." *Nature* 463, 530-531.
106. David Santillo and Paul Johnson, "Governance of geoengineering research cannot be left to voluntary codes of conduct," *The Geoengineering Quarterly*, 20 March 2010.
107. Pablo Suarez, Jason Blackstock and Maarten van Aalst, "Towards a people-centered framework for geoengineering governance: a humanitarian perspective," *The Geoengineering Quarterly*, 20 March 2010.
108. *he NOVIM Report*, op cit.
109. See the conference description and invitation to participants at: <http://www.scribd.com/doc/25251727/The-Asilomar-International-Conference-On-Climate-Intervention-Geoengineering-Technologies-2010>
110. This summary of several areas of widespread agreement at the conference is based on the article "Jeff Goodell's Take on the Asilomar Geoengineering Conference" available online at <http://theenergycollective.com/TheEnergyCollective/62423> and the Statement from the Conference's Scientific Organizing Committee released at the end of the conference, available online at: http://www.climateactionfund.org/index.php?option=com_content&view=article&id=152&Itemid=89

Woodrow Wilson International Center for Scholars

Jane Harman

Director, President and CEO

BOARD OF TRUSTEES

Joseph B. Gildenhorn, Chair

Sander R. Gerber, Vice Chair

PUBLIC MEMBERS

Melody Barnes

designated appointee from
within the Federal Government

Hon. James H. Billington

Librarian of Congress

Hillary R. Clinton

Secretary, U.S. Department of State

G. Wayne Clough

Secretary, Smithsonian Institution

Arne Duncan

Secretary, U.S. Department of Education

David Ferriero

Archivist of the United States

James Leach

Chairman, National Endowment for the Humanities

Kathleen Sebelius

Secretary, U.S. Department of Health
and Human Services

PRIVATE CITIZEN MEMBERS

Timothy Broas

John Casteen

Charles Cobb, Jr.

Thelma Duggin

Carlos M. Gutierrez

Susan Hutchison

Barry S. Jackson

Mission

The Woodrow Wilson International Center for Scholars is the living, national memorial to President Wilson established by Congress in 1968 and headquartered in Washington, D.C. It is a nonpartisan institution, supported by public and private funds, engaged in the study of national and world affairs. The Wilson Center establishes and maintains a neutral forum for free, open, and informed dialogue.

The Center commemorates the ideals and concerns of Woodrow Wilson by: providing a link between the world of ideas and the world of policy; and fostering research, study, discussion, and collaboration among a full spectrum of individuals concerned with policy and scholarship in national and world affairs.



**Woodrow Wilson
International
Center
for Scholars**

**One Woodrow Wilson Plaza
1300 Pennsylvania Avenue, NW
Washington, DC 20004-3027
202 / 691 / 4000
www.wilsoncenter.org**