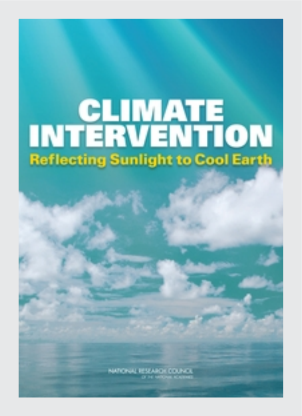

Climate Intervention: Reflecting Sunlight to Cool Earth

DETAILS

234 pages | 8.5 x 11 | PAPERBACK
ISBN 978-0-309-31482-4 | DOI 10.17226/18988

AUTHORS

Committee on Geoengineering Climate: Technical Evaluation and Discussion of Impacts; Board on Atmospheric Sciences and Climate; Ocean Studies Board; Division on Earth and Life Studies; National Research Council

CLIMATE INTERVENTION

Reflecting Sunlight to Cool Earth

Committee on Geoengineering Climate:
Technical Evaluation and Discussion of Impacts

Board on Atmospheric Sciences and Climate

Ocean Studies Board

Division on Earth and Life Studies

NATIONAL RESEARCH COUNCIL
OF THE NATIONAL ACADEMIES

THE NATIONAL ACADEMIES PRESS
Washington, D.C.
www.nap.edu

THE NATIONAL ACADEMIES PRESS • 500 Fifth Street, NW • Washington, DC 20001

NOTICE: The project that is the subject of this report was approved by the Governing Board of the National Research Council, whose members are drawn from the councils of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine. The members of the committee responsible for the report were chosen for their special competences and with regard for appropriate balance.

This study was supported by the U.S. Department of Energy under Contract Number DE-SC0011701, the National Aeronautics and Space Administration under Contract Number NNX13A041G, the National Oceanic and Atmospheric Administration under Contract Number WC133R-11-CQ-0048, the National Academy of Sciences' Arthur L. Day Fund, and the intelligence community. Any opinions, findings, and conclusions, or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the sponsoring agencies or any of their subagencies.

International Standard Book Number-13: 978-0-309-31482-4
International Standard Book Number-10: 0-309-31482-8
Library of Congress Control Number: 2015938939

Additional copies of this report are available for sale from the National Academies Press, 500 Fifth Street, NW, Keck 360, Washington, DC 20001; (800) 624-6242 or (202) 334-3313; http://www.nap.edu/.

Printed in the United States of America

Cover photo credits: Fotolia and National Oceanic and Atmospheric Administration

THE NATIONAL ACADEMIES

Advisers to the Nation on Science, Engineering, and Medicine

The **National Academy of Sciences** is a private, nonprofit, self-perpetuating society of distinguished scholars engaged in scientific and engineering research, dedicated to the furtherance of science and technology and to their use for the general welfare. Upon the authority of the charter granted to it by the Congress in 1863, the Academy has a mandate that requires it to advise the federal government on scientific and technical matters. Dr. Ralph J. Cicerone is president of the National Academy of Sciences.

The **National Academy of Engineering** was established in 1964, under the charter of the National Academy of Sciences, as a parallel organization of outstanding engineers. It is autonomous in its administration and in the selection of its members, sharing with the National Academy of Sciences the responsibility for advising the federal government. The National Academy of Engineering also sponsors engineering programs aimed at meeting national needs, encourages education and research, and recognizes the superior achievements of engineers. Dr. C. D. Mote, Jr., is president of the National Academy of Engineering.

The **Institute of Medicine** was established in 1970 by the National Academy of Sciences to secure the services of eminent members of appropriate professions in the examination of policy matters pertaining to the health of the public. The Institute acts under the responsibility given to the National Academy of Sciences by its congressional charter to be an adviser to the federal government and, upon its own initiative, to identify issues of medical care, research, and education. Dr. Victor J. Dzau is president of the Institute of Medicine.

The **National Research Council** was organized by the National Academy of Sciences in 1916 to associate the broad community of science and technology with the Academy's purposes of furthering knowledge and advising the federal government. Functioning in accordance with general policies determined by the Academy, the Council has become the principal operating agency of both the National Academy of Sciences and the National Academy of Engineering in providing services to the government, the public, and the scientific and engineering communities. The Council is administered jointly by both Academies and the Institute of Medicine. Dr. Ralph J. Cicerone and Dr. C. D. Mote, Jr., are chair and vice chair, respectively, of the National Research Council.

www.national-academies.org

Copyright National Academy of Sciences. All rights reserved.

COMMITTEE ON GEOENGINEERING CLIMATE: TECHNICAL EVALUATION AND DISCUSSION OF IMPACTS

MARCIA K. MCNUTT (Chair), *Science*, Washington, DC
WALEED ABDALATI, University of Colorado, Boulder
KEN CALDEIRA, Carnegie Institution for Science, Stanford, California
SCOTT C. DONEY, Woods Hole Oceanographic Institution, Massachusetts
PAUL G. FALKOWSKI, Rutgers, The State University of New Jersey, New Brunswick
STEVE FETTER, University of Maryland, College Park
JAMES R. FLEMING, Colby College, Waterville, Maine
STEVEN P. HAMBURG, Environmental Defense Fund, Boston, Massachusetts
M. GRANGER MORGAN, Carnegie Mellon University, Pittsburgh, Pennsylvania
JOYCE E. PENNER, University of Michigan, Ann Arbor
RAYMOND T. PIERREHUMBERT, University of Chicago, Illinois
PHILIP J. RASCH, Pacific Northwest National Laboratory, Richland, Washington
LYNN M. RUSSELL, Scripps Institution of Oceanography, La Jolla, California
JOHN T. SNOW, University of Oklahoma, Norman
DAVID W. TITLEY, Pennsylvania State University, University Park
JENNIFER WILCOX, Stanford University, California

NRC Staff

EDWARD DUNLEA, Senior Program Officer
CLAUDIA MENGELT, Senior Program Officer
KATHERINE THOMAS, Program Officer
AMANDA PURCELL, Research Associate
SHELLY FREELAND, Senior Program Assistant
ROB GREENWAY, Program Associate

BOARD ON ATMOSPHERIC SCIENCES AND CLIMATE

A.R. RAVISHANKARA (*Chair*), Colorado State University, Fort Collins
GERALD A. MEEHL (*Vice Chair*), National Center for Atmospheric Research, Boulder, Colorado
LANCE F. BOSART, State University of New York, Albany
MARK A. CANE, Columbia University, Palisades, New York
SHUYI S. CHEN, University of Miami, Florida
HEIDI CULLEN, Climate Central, Princeton, New Jersey
PAMELA EMCH, Northrup Grumman Aerospace Systems, Redondo Beach, California
ARLENE FIORE, Columbia University, Palisades, New York
WILLIAM B. GAIL, Global Weather Corporation, Boulder, Colorado
LISA GODDARD, Columbia University, Palisades, New York
MAURA HAGAN, National Center for Atmospheric Research, Boulder, Colorado
TERRI S. HOGUE, Colorado School of Mines, Golden
ANTHONY JANETOS, Joint Global Change Research Institute, College Park, Maryland
EVERETTE JOSEPH, SUNY University at Albany, New York
RONALD "NICK" KEENER, JR., Duke Energy Corporation, Charlotte, North Carolina
JOHN R. NORDGREN, The Kresge Foundation, Troy, Michigan
JONATHAN OVERPECK, University of Arizona, Tucson
STEPHEN W. PACALA, Princeton University, New Jersey
ARISTIDES A.N. PATRINOS, New York University, Brooklyn
S.T. RAO, North Carolina State University, Raleigh
DAVID A. ROBINSON, Rutgers, The State University of New Jersey, Piscataway
CLAUDIA TEBALDI, Climate Central, Princeton, New Jersey

Ocean Studies Board Liaison

DAVID HALPERN, Jet Propulsion Laboratory, Pasadena, California

Polar Research Board Liaison

JENNIFER FRANCIS, Rutgers, The State University of New Jersey, Marion, Massachusetts

NRC Staff

AMANDA STAUDT, Director
EDWARD DUNLEA, Senior Program Officer
LAURIE GELLER, Senior Program Officer
KATHERINE THOMAS, Program Officer
LAUREN EVERETT, Associate Program Officer
AMANDA PURCELL, Research and Financial Associate
RITA GASKINS, Administrative Coordinator
SHELLY FREELAND, Administrative and Financial Assistant
ROB GREENWAY, Program Associate

OCEAN STUDIES BOARD

ROBERT A. DUCE (*Chair*), Texas A&M University, College Station
E. VIRGINIA ARMBRUST, University of Washington, Seattle
KEVIN R. ARRIGO, Stanford University, California
CLAUDIA BENETIZ-NELSON, University of South Carolina, Columbia
EDWARD A. BOYLE, Massachusetts Institute of Technology, Cambridge
RITA R. COLWELL, University of Maryland, College Park
SARAH W. COOKSEY, State of Delaware, Dover
CORTIS K. COOPER, Chevron Corporation, San Ramon, California
ROBERT HALLBERG, NOAA/GFDL and Princeton University, New Jersey
DAVID HALPERN, Jet Propulsion Laboratory, Pasadena, California
SUSAN E. HUMPHRIS, Woods Hole Oceanographic Institution, Massachusetts
BONNIE J. MCCAY, Rutgers University, New Brunswick, New Jersey
STEVEN A. MURAWSKI, University of South Florida, St. Petersburg
JOHN A. ORCUTT, Scripps Institution of Oceanography, La Jolla, California
H. TUBA ÖZKAN-HALLER, Oregon State University, Corvallis
STEVEN E. RAMBERG, Penn State Applied Research Lab, Washington, DC
MARTIN D. SMITH, Duke University, Durham, North Carolina
MARGARET SPRING, Monterey Bay Aquarium, Monterey, California
DON WALSH, International Maritime Incorporated, Myrtle Point, Oregon
DOUGLAS WARTZOK, Florida International University, Miami
LISA D. WHITE, University of California, Berkeley, and San Francisco State University

Ex-Officio

MARY (MISSY) H. FEELEY, ExxonMobil Exploration Company *(retired),* Houston, Texas

NRC Staff

SUSAN ROBERTS, Board Director
DEBORAH GLICKSON, Senior Program Officer
CLAUDIA MENGELT, Senior Program Officer
STACEE KARRAS, Research Associate
PAMELA LEWIS, Administrative Coordinator
SHUBHA BANSKOTA, Financial Associate
PAYTON KULINA, Senior Program Assistant

Copyright National Academy of Sciences. All rights reserved.

Preface

The signs of a warming planet are all around us—rising seas, melting ice sheets, record-setting temperatures—with impacts cascading to ecosystems, humans, and our economy. At the root of the problem, anthropogenic greenhouse gas (GHG) emissions to the atmosphere continue to increase, a substantial fraction of which diffuse into the ocean, causing ocean acidification and threatening marine ecosystems. Global climate is changing faster than at any time since the rise of human civilization, challenging society to adapt to those changes. If the current dependence on fossil fuel use continues, evidence from previous periods of high atmospheric GHG concentrations indicates that our release of fossil fuel carbon into Earth's atmosphere in the form of CO_2 will be recorded in the rock record as a major planet-wide event, marked by transgressions of shorelines, extinctions of biota, and perturbations of major biogeochemical cycles.

The specific topic of this report, "climate geoengineering," was often framed in terms of a last-ditch response option to climate change if climate change damage should produce extreme hardship. Such deliberate intervention in the climate system was often considered a taboo subject. Although the likelihood of eventually considering last-ditch efforts to address damage from climate change grows with every year of inaction on emissions control, there remains a lack of information on these ways of potentially intervening in the climate system. In 2012 the U.S. government, including several of the science agencies, asked the National Academy of Sciences to provide advice on this subject. The National Research Council (NRC) committee assembled in response to this request realized that carbon dioxide removal and albedo modification (i.e., modification of the fraction of short-wavelength solar radiation reflected from Earth back into space) have traditionally been lumped together under the term "geoengineering" but are sufficiently different that they deserved to be discussed in separate volumes.

Carbon dioxide removal strategies, discussed in the first volume, are generally of lower risk and of almost certain benefit given what is currently known of likely global emissions trajectories and the climate change future. Currently, cost and lack of technical maturity are factors limiting the deployment of carbon dioxide removal strategies for helping to reduce atmospheric CO_2 levels. In the future, such strategies could, however, contribute as part of a portfolio of responses for mitigating climate warming and ocean acidification. In the meantime, natural air CO_2 removal processes (sinks) consume the equivalent of over half of our emissions, a feature that might be safely and cost-effectively enhanced or augmented as explored in the first volume.

In contrast, albedo modification approaches show some evidence of being effective at temporarily cooling the planet, but at a currently unknown environmental price. The committee is concerned that understanding of the ethical, political, and environmental consequences of an albedo modification action is relatively less advanced than the technical capacity to execute it. In fact, one serious concern is that such an action could be unilaterally undertaken by a nation or smaller entity for their own benefit without international sanction and regardless of international consequences. A research basis is currently lacking to understand more about the potential results and impacts of albedo modification to help inform such decisions. These approaches are discussed in the second volume.

The committee's very different posture concerning the currently known risks of carbon dioxide removal as compared with albedo modification was a primary motivation for separating these climate engineering topics into two separate volumes.

Terminology is very important in discussing these topics. "Geoengineering" is associated with a broad range of activities beyond climate (e.g., geological engineering), and even "climate engineering" implies a greater level of precision and control than might be possible. The committee concluded that "climate intervention," with its connotation of "an action intended to improve a situation," most accurately describes the strategies covered in these two volumes. Furthermore, the committee chose to avoid the commonly used term of "solar radiation management" in favor of the more physically descriptive term "albedo modification" to describe a subset of such techniques that seek to enhance the reflectivity of the planet to cool the global temperature. Other related methods that modify the emission of infrared energy to space to cool the planet are also discussed in the second volume.

Transparency in discussing this subject is critical. In that spirit of transparency, this study was based on peer-reviewed literature and the judgments of the committee members involved; no new research was done as part of this study and all data and information used in this study are from entirely open sources. Moving forward, the committee hopes that these two new reports will help foster an ethos in which all research in this area is conducted openly, responsibly, and with transparent goals and results.

It is the committee's sincere hope that these topics will receive the attention and investment commensurate with their importance to addressing the coming potential climate crises. By helping to bring light to this topic area, carbon dioxide removal technologies could become one more viable strategy for addressing climate change, and leaders will be far more knowledgeable about the consequences of albedo modification approaches before they face a decision whether or not to use them.

In closing, I would like to thank my fellow committee members for all of their hard work to summarize the existing, fragmented science and to work toward consensus on extremely complex issues. As well, we greatly appreciate all of the time and effort volunteered by our colleagues who generously gave their time and talent to review these reports, speak at our committee meetings, and communicate with us during the study process. We would also like to thank the NRC staff for their superb efforts to assemble and make sense of the many moving parts of two separate reports.

Marcia McNutt, *Chair*
Committee on Geoengineering Climate:
Technical Evaluation and Discussion of Impacts

Acknowledgments

This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the National Research Council's (NRC's) Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the institution in making its published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. The committee wishes to thank the following individuals for their review of this report:

DAVID VICTOR, University of California, San Diego
CLAIRE PARKINSON, NASA Goddard Space Flight Center, Greenbelt, Maryland
ALAN ROBOCK, Rutgers University, New Brunswick, New Jersey
CLIVE HAMILTON, Centre for Applied Philosophy and Public Ethics, Canberra, Australia
ROBERT WOOD, University of Washington, Seattle
TRUDE STORELVMO, Yale University, New Haven, Connecticut
EDWARD PARSON, University of California, Los Angeles
DAVID KEITH, Harvard University, Cambridge, Massachusetts
MICHAEL HANEMANN, University of California, Berkeley
JAMES ANDERSON, Harvard University, Cambridge, Massachusetts

Although the reviewers listed above have provided constructive comments and suggestions, they were not asked to endorse the views of the committee, nor did they see the final draft of the report before its release. The review of this report was overseen by **Warren M. Washington,** National Center for Atmospheric Research, Boulder, Colorado, and **James W. C. White,** University of Colorado, Boulder; appointed by the NRC, they were responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring panel and the institution.

Contents

Appendixes

Summary

Our planet has entered a period in which its climate is changing more rapidly than ever experienced in recorded human history, primarily caused by the rapid buildup of carbon dioxide (CO_2) in the atmosphere from the burning of fossil fuels. Scientists have identified a number of risks from changing climate, including rising sea level, drought, heat waves, more severe storms, increasing precipitation intensity, and associated disruption of terrestrial and aquatic ecosystems. Additionally, elevated atmospheric CO_2 is diffusing into the ocean, measurably acidifying surface waters and affecting marine ecosystems. Natural processes currently remove about half of our emissions from the atmosphere each year. Once emissions cease, it will take thousands of years before those processes eventually return Earth to something like preindustrial levels of atmospheric CO_2.

The two main options for responding to the risks of climate change involve mitigation—reducing and eventually eliminating human-caused emissions of CO_2 and other greenhouse gases (GHGs)—and adaptation—reducing the vulnerability of human and natural systems to changes in climate. A third potentially viable option, currently under development but not yet widely deployed, is carbon dioxide removal (CDR) from the atmosphere accompanied by reliable sequestration. A fourth, more speculative family of approaches called albedo modification seeks to offset climate warming by greenhouse gases by increasing the amount of sunlight reflected back to space.[1] Albedo modification techniques mask the effects of greenhouse warming; they do not reduce greenhouse gas concentrations (see Box S.1 for definitions of key terms).

The Committee on Geoengineering Climate: Technical Evaluation and Discussion of Impacts was charged with conducting a technical evaluation of a limited number of "geoengineering" (also known as "climate engineering") techniques that have been proposed so far and commenting generally on the potential impacts of deploying these technologies, including possible environmental, economic, and national security concerns. The committee prefers the term "climate intervention" because "geoengineering" has other meanings in the context of geological engineering. Furthermore, the term "engineering" implies a more precisely tailored and controllable process than might be the case for these climate interventions.

---

[1] Another speculative approach that seeks to make cirrus clouds thinner to increase the infrared thermal energy returned to space is considered alongside albedo modification approaches.

BOX S.1 DEFINITIONS OF KEY TERMS USED IN THE REPORTS

Climate Intervention—purposeful actions intended to produce a targeted change in some aspect of the climate (e.g., global mean or regional temperature); includes actions designed to remove carbon dioxide or other greenhouse gases from the atmosphere or to change Earth's radiation balance (referred to as "albedo modification"), but not efforts to limit emissions of greenhouse gases (i.e., climate mitigation).

Carbon Dioxide Removal—intentional efforts to remove carbon dioxide from the atmosphere, including land management strategies, accelerated weathering, ocean iron fertilization, bioenergy with carbon capture and sequestration, and direct air capture and sequestration. CDR techniques complement carbon capture and sequestration methods that primarily focus on reducing CO_2 emissions from point sources such as fossil fuel power plants.

Albedo Modification—intentional efforts to increase the amount of sunlight that is scattered or reflected back to space, thereby reducing the amount of sunlight absorbed by Earth, including injecting aerosols into the stratosphere, marine cloud brightening, and efforts to enhance surface reflectivity.

This study was supported by the National Academy of Sciences, the U.S. intelligence community, the National Oceanic and Atmospheric Administration, the National Aeronautics and Space Administration, and the Department of Energy (the statement of task for the committee can be found in Appendix A). This summary presents overarching conclusions from a pair of reports the committee authored in response to its charge. These reports are intended to provide a thoughtful, clear scientific foundation that informs ethical, legal, and political discussions surrounding these potentially controversial topics.

CARBON DIOXIDE REMOVAL AND ALBEDO MODIFICATION WITHIN A PORTFOLIO OF CLIMATE RESPONSES

There is no substitute for dramatic reductions in the emissions of CO_2 and other greenhouse gases to mitigate the negative consequences of climate change and, concurrently, to reduce ocean acidification. Mitigation, although technologically feasible, has been difficult to achieve for political, economic, and social reasons that may persist well into the future. Whatever we do as a society, some adaptation will be necessary, but the degree to which it is needed depends on the amount of climate change and the degree to which future emissions of CO_2 and other GHGs (henceforth in this context the committee often mentions only CO_2 as it has the largest climate impact) are reduced. Although there are ongoing efforts at climate adaptation in many communities, both humans and ecosystems face substantial challenges in adapting to the varied impacts of climate change over the coming century. For that reason, it may be prudent to examine additional options for limiting the risks from climate change (namely CDR and albedo modification), which could contribute to a broader portfolio of responses, even as mitigation and adaptation remain the primary emphasis. The committee evaluated CDR and albedo modification within this broader portfolio of climate response.

The deployment of any climate response strategy requires consideration of many factors: How effective is the strategy at achieving predictable and desirable outcomes? How much does the strategy cost to implement at a scale that matters? What are the risks for unintended consequences and opportunities for co-benefits? What governance mechanisms are in place or are needed to ensure that safety, equity, and other ethical aspects are considered (e.g., intergenerational implications)?

As the committee analyzed these factors for specific CDR and albedo modification strategies, it became apparent that there are vast differences in the inherent characteristics of the two approaches. CDR seeks to mitigate the primary *causes* of present climate change by reducing the amount of CO_2 in the atmosphere. Albedo modification seeks to offset some of the climatic *effects* of high greenhouse gas concentrations but does not address the greenhouse gas concentrations themselves. The research needs, environmental risks, and political ramifications associated with albedo modification are dramatically different from those associated with carbon dioxide removal (see Table S.1).

Recommendation 1: Efforts to address climate change should continue to focus most heavily on mitigating greenhouse gas emissions in combination with adapting to the impacts of climate change because these approaches do not present poorly defined and poorly quantified risks and are at a greater state of technological readiness.

CARBON DIOXIDE REMOVAL READY FOR INCREASED RESEARCH AND DEVELOPMENT

Some CDR strategies seek to sequester carbon in the terrestrial biosphere or the ocean by accelerating processes that are already occurring as part of the natural carbon cycle and which already remove significant quantities of CO_2 from the atmosphere. These approaches have challenges and risks that need to be assessed, including verifying and monitoring the amount of carbon removed, incomplete understanding

TABLE S.1 Overview of General Differences between Carbon Dioxide Removal Proposals and Albedo Modification Proposals

Carbon dioxide removal proposals…	**Albedo modification proposals…**
… address the cause of human-induced climate change (high atmospheric GHG concentrations).	… do not address cause of human-induced climate change (high atmospheric GHG concentrations).
… do not introduce novel global risks.	… introduce novel global risks.
… are currently expensive (or comparable to the cost of emission reduction).	… are inexpensive to deploy (relative to cost of emissions reduction).
… may produce only modest climate effects within decades.	… can produce substantial climate effects within years.
… raise fewer and less difficult issues with respect to global governance.	… raise difficult issues with respect to global governance.
… will be judged largely on questions related to cost.	… will be judged largely on questions related to risk.
… may be implemented incrementally with limited effects as society becomes more serious about reducing GHG concentrations or slowing their growth.	… could be implemented suddenly, with large-scale impacts before enough research is available to understand the risks relative to inaction.
… require cooperation by major carbon emitters to have a significant effect.	… could be done unilaterally.
… for likely future emissions scenarios, if abruptly terminated would have limited consequences	… for likely future emissions scenarios, if abruptly terminated would produce significant consequences.

NOTE: GHG stands for greenhouse gases released by human activities and natural processes and includes carbon dioxide, methane, nitrous oxide, chlorofluorocarbons, and others. The committee intends to limit discussion to proposals that raise the fewest problematic issues, thus excluding ocean iron fertilization from the CDR list. Each statement may not be true of some proposals within each category.

of how long carbon may be sequestered before possible rerelease to the atmosphere, unintended effects such as the release of other greenhouse gases that can partially offset or even cancel out the climate benefits from carbon sequestration, and expanded competition for resources such as land and freshwater. In general, published estimates show that land management and reforestation can remove significant amounts of CO_2 from the atmosphere and can often generate substantial co-benefits. On the other hand, previous studies nearly all agree that deploying ocean iron fertilization at climatically relevant levels poses risks that outweigh potential benefits. However, there may be other methods to enhance uptake of CO_2 through accelerated weathering cycles on land and in the ocean that are more environmentally benign and thus worth pursuing.

Other CDR approaches involve capturing CO_2 from the atmosphere and disposing of it by pumping it underground at high pressure. These include bioenergy with carbon capture and sequestration (BECCS), which uses plants to remove the CO_2 from the air, and direct air capture and sequestration (DACS), which includes various techniques to scrub CO_2 directly from ambient air. Proposals to capture CO_2 from the atmosphere have challenges and uncertainties including cost and maximum scale of feasible deployment. Removing CO_2 from ambient air is more difficult than removing CO_2 from the stack gas of power plants that burn conventional fuel or biomass because of its much lower concentration in ambient air; thus, it will involve higher costs in most circumstances. CDR approaches such as DACS and BECCS require reliable long-term disposal or sequestration of carbon to prevent its return to the atmosphere. Reliable disposal has challenges, environmental risks, and uncertainties, including cost, long-term monitoring, potential induced seismicity, and leakage.

The barriers to deployment of CDR approaches are largely related to slow implementation, limited capacity, policy considerations, and high costs of presently available technologies. Additional research and analysis will provide information to help address those challenges. For these reasons, if carbon removal technologies are to be widely deployed, it is critical to embark now on a research program to lower the technical barriers to efficacy and affordability. In the end, any actions to decrease the excess burden of atmospheric CO_2 serve to decrease, or at least slow the onset of, the risks posed by climate change. Environmental risks vary among CDR approaches but are generally much lower than the risks associated with albedo modification approaches. However, it is also less risky environmentally to avoid a given CO_2 emission to the atmosphere than to emit it with the expectation that it will be purposefully removed from the atmosphere at some later time. Developing the ability to capture and reliably and safely dispose of climatically important amounts of atmospheric CO_2 requires research into how to make the more promising options more effective, more environmentally friendly, and less costly. Such research investments would accelerate this development and could help avoid some of the greatest climate risks that the current carbon emission trajectory poses.

Recommendation 2: The committee recommends research and development investment to improve methods of carbon dioxide removal and disposal at scales that would have a global impact on reducing greenhouse warming, in particular to minimize energy and materials consumption, identify and quantify risks, lower costs, and develop reliable sequestration and monitoring.

- It is increasingly likely that, as a society, we will need to deploy some forms of CDR to avoid the worst impacts of climate change, but without research investment now such attempts at climate mitigation are likely to fall well short of needed targets.
- Many CDR strategies provide viable and reasonably low-risk approaches to reducing atmospheric concentrations of CO_2. Because the rate of CO_2 removal is inherently slow, CDR must be sustained at large scales over very long periods of time to have a significant effect on CO_2 concentrations and the associated risks of climate change.
- Absent some new technological innovation, large-scale CDR techniques have costs comparable to or exceeding those of avoiding carbon dioxide emissions by replacing fossil fuels with low-carbon energy sources. Widespread CDR deployment would likely occur in a policy environment in which there are limits or a price is imposed on emissions of carbon dioxide, and in that case CDR will compete directly with mitigation on a cost basis (i.e., cost per ton of CO_2 removed versus cost per ton of CO_2 emission avoided).
- Decisions regarding deployment of CDR will be largely based on cost and scalability. Carbon dioxide removal strategies might entail some local or even regional environmental risk, but in some cases, CDR strategies may have also substantial co-benefits.
- Several federal agencies should have a role in defining and supporting CDR research and development. The committee recommends a coordinated approach that draws upon the historical strength of the various agencies involved and uses existing coordination mechanisms, such as the U.S. Global Change Research Program, to the extent possible.

ALBEDO MODIFICATION PRESENTS POORLY UNDERSTOOD RISKS

Proposed albedo modification approaches introduce environmental, ethical, social, political, economic, and legal risks associated with intended and unintended consequences. However, there are both theoretical and observational reasons to believe that albedo modification has the potential to rapidly offset some of the consequences of global warming at an affordable cost. If less energy from the Sun is absorbed by the

Earth system, the surface of Earth will cool on average. This is clearly demonstrated by the history of past volcanic eruptions. For example, the eruption of Mount Pinatubo in the Philippines in June of 1991 injected 20 million tons of sulfur dioxide into the stratosphere, which increased Earth's reflectivity (albedo) and decreased the amount of sunlight absorbed, causing globally averaged surface air temperatures to cool an estimated 0.3°C for a period of 3 years. Such cooling can take place rapidly, within a year of the change in albedo, but only lasts for a few years unless additional material is injected. Increasing the reflectivity of low clouds is another strategy that might be able to cool the planet within a year or two from the onset of the intervention.

Modeling studies indicate that significant cooling, equivalent in amplitude to the warming produced by doubling the CO_2 concentration in the atmosphere, can be produced by the introduction of tens of millions of tons of aerosol-forming gases into the stratosphere. Although there are many reasons to be cautious in interpreting model results, climate simulations can extend scientific understanding of albedo modification to timescales beyond those observed with volcanic eruptions. Modeling results also suggest that the benefits and risks will not be uniformly distributed around the globe.

Feasibility studies (based on models, as yet untested in the field) suggest that it may be possible to introduce aerosols into the stratosphere that can produce significant reduction in incoming sunlight (1 W/m^2 or more) with few if any major technological innovations required. Direct costs of deployment of a stratospheric aerosol layer of sufficient magnitude to offset global mean radiative forcing of CO_2 have been estimated to be at least an order of magnitude less than the cost of decarbonizing the world's economy. Although these cost estimates do not include an appropriate monitoring system or indemnification for damages from albedo modification actions, they are small enough that decisions are likely to be based primarily on considerations of potential benefits and risks, and not primarily on the basis of direct cost.

Albedo modification presents a number of risks and expected repercussions. Observed effects from volcanic eruptions include stratospheric ozone loss, changes to precipitation (both amounts and patterns), and likely increased growth rates of forests caused by an increase in diffuse solar radiation. Large volcanic eruptions are by their nature uncontrolled and short lived, and have in rare cases led to widespread crop failure and famine (e.g., the Tambora eruption in 1815). However, effects of a sustained albedo modification by introduction of aerosol particles may differ substantially from effects of a brief volcanic eruption. Models also indicate that there would be consequences of concern, such as some ozone depletion or a reduction in global precipitation associated with sustained albedo modification. Furthermore, albedo modification does nothing to reduce the buildup of atmospheric CO_2, which is already changing the makeup of terrestrial ecosystems and causing ocean acidification and associated impacts on oceanic ecosystems.

Another risk is that the success of albedo modification could reduce the incentive to curb anthropogenic CO_2 emissions and that albedo modification would instead be deployed with ever increasing intensity. The committee considers it to be irrational and irresponsible to implement sustained albedo modification without also pursuing emissions mitigation, carbon dioxide removal, or both. Climate models indicate that the combination of large-scale albedo modification with large-scale CO_2 increases could lead to a climate with different characteristics than the current climate. Without reductions in CO_2 levels in the atmosphere, the amount of albedo modification required to offset the greenhouse warming would continue to escalate for millennia, generating greater risks of negative consequences if it is terminated for any reason (e.g., undesirable side effects, political unrest, and cost), because the effects of the forcing from the CO_2 concentrations present at the time of termination will be rapidly revealed.

It is not possible to quantify or even identify other environmental, social, political, legal, and economic risks at this time, given the current state of knowledge about this complex system. The uncertainties in modeling of both climate change and the consequences of albedo modification make it impossible today to provide reliable, quantitative statements about relative risks, consequences, and benefits of albedo modification to the Earth system as a whole, let alone benefits and risks to specific regions of the planet. To provide such statements, scientists would need to understand the influence of various possible activities on both clouds and aerosols, which are among the most difficult components of the climate system to model and monitor. Introducing albedo modification at scales capable of substantial reductions in climate impacts of future higher CO_2 concentrations would be introducing a novel situation into the Earth system, with consequences that are poorly constrained at present.

Gaps in our observational system also present a critical barrier to responsible deployment of albedo modification strategies. Currently, observational capabilities lack the capacity to monitor the evolution of an albedo modification deployment (e.g., the fate of the aerosols and secondary chemical reactions), its effect on albedo, or its environmental effects on climate or other important Earth systems. Finally, an international forum for cooperation and coordination on any sort of climate intervention discussion and planning is lacking.

Recommendation 3: Albedo modification at scales sufficient to alter climate should not be deployed at this time.

- Albedo modification strategies for offsetting climate impacts of high CO_2 concentrations carry risks that are poorly identified in their nature and unquantified.
- Deployment at climate-altering amplitudes should only be contemplated armed with a quantitative and accurate understanding of the processes that participate in albedo modification. This understanding should be demonstrated at smaller scales after intended and unintended impacts to the Earth system have been explicitly documented, both of which are lacking.
- There is significant potential for unanticipated, unmanageable, and regrettable consequences in multiple human dimensions from albedo modification at climate-altering scales, including political, social, legal, economic, and ethical dimensions.
- Current observing systems are insufficient to quantify the effects of any intervention. If albedo modification at climate-altering scales were ever to occur, it should be accompanied by an observing system that is appropriate for assessing the impacts of the deployment and informing subsequent actions.
- If research and development on albedo modification were to be done at climate-altering scales, it should be carried out only as part of coordinated national or international planning, proceeding from smaller, less risky to larger, more risky projects; more risky projects should be undertaken only as information is collected to quantify the risks at each stage.

THE NEED FOR MORE RESEARCH ON ALBEDO MODIFICATION

There are many research opportunities that would allow the scientific community to learn more about the risks and benefits of albedo modification, knowledge which could better inform societal decisions without imposing the risks associated with large-scale deployment. There are several hypothetical, but plausible, scenarios under which this information would be useful. For example:

- If, despite mitigation and adaptation, the impacts of climate change still become intolerable (e.g., massive crop failures throughout the tropics), society would face very tough choices regarding whether and how to deploy albedo modification until such time as mitigation, carbon dioxide removal, and adaptation actions could significantly reduce the impacts of climate change.
- The international community might consider a gradual phase-in of albedo modification to a level expected to create a detectable modification of Earth's

climate, as a large-scale field trial aimed at gaining experience with albedo modification in case it needs to be scaled up in response to a climate emergency. This might be considered as part of a portfolio of actions to reduce the risks of climate change.

- If an unsanctioned act of albedo modification were to occur, scientific research would be needed to understand how best to detect and quantify the act and its consequences and impacts.

In any of these scenarios, better understanding of the feasibility, verifiability, consequences (intended and unintended), and efficacy of proposed albedo modification strategies would be critical. Indeed, current implementation options are clearly crude and developing better methods in advance of any future development would provide less risky options for society and state actors to consider. There is a risk that research on albedo modification could distract from efforts to mitigate greenhouse gas emissions. This "moral hazard" risk may have kept more albedo modification research from being done up to now. The committee argues that, as a society, we have reached a point where the severity of the potential risks from climate change appears to outweigh the potential risks from the moral hazard associated with a suitably designed and governed research program. Hence, it is important to understand whether and to what extent albedo modification techniques are viable.

Much of the required research on albedo modification overlaps considerably with the basic scientific research that is needed to improve understanding of the climate system. Examples of such "multiple benefit research"—research that can contribute to a better understanding of the viability of albedo modification techniques and also a better understanding of basic climate science—include conducting research on clouds and aerosols, maintaining the continuity of measurement of the top-of-atmosphere radiation budget, and monitoring ocean-atmosphere energy exchange through programs such as the Argo float system. Of necessity, much of this multiple-benefit research would be part of a comprehensive climate research portfolio or research program aimed at other purposes (e.g., effect of volcanic eruptions on aerosols). In addition, the committee argues that research topics specific to albedo modification should also be identified and prioritized as part of a larger research effort and tasked to the relevant federal agencies for possible support within existing or expanded research programs.

Recommendation 4: The committee recommends an albedo modification research program be developed and implemented that emphasizes multiple-benefit research that also furthers basic understanding of the climate system and its human dimensions.

- If future decision makers reach a point that they are contemplating adopting albedo modification, or assessing such an adoption by others, they will need to assess a wide range of factors, both technical and social, to compare the potential benefits and risks of an albedo modification deployment. These factors would include an assessment of the expected climate with only emissions reductions and CDR (including risks from continued greenhouse gas emissions with no intervention), the expected effects from starting albedo modification, the expected effects from terminating albedo modification, ethical issues, and social responses.
- The goal of the research program should be to improve understanding of the range of climate and other environmental effects of albedo modification, as well as understanding of unintended impacts.
- U.S. research on albedo modification should be supported by a number of scientific research agencies in a coordinated manner. The U.S. Global Change Research Program could provide valuable oversight and coordination to ensure that the aspects of the research that are of benefit to both basic climate science and understanding of albedo modification are taken into account.
- Small-scale field experiments with controlled emissions may for some situations with some forms of intervention be helpful in reducing model uncertainties, validating theory, and verifying model simulations in different conditions. Experiments that involve release of gases or particles into the atmosphere (or other controlled perturbations) should be well-enough understood to be benign to the larger environment, should be conducted at the smallest practical scales, should be designed so as to pose no significant risk, and should be planned subject to the deliberative process outlined in Recommendation 6.

Recommendation 5: The committee recommends that the United States improve its capacity to detect and measure changes in radiative forcing and associated changes in climate.

- A new generation of short-wavelength (albedo) and long-wavelength (outgoing infrared) space-based instruments should be developed and deployed that can measure radiative forcing with an accuracy of better than 1 W/m^2, including hyperspectral instruments that could improve discrimination of the processes that cause changes in radiative forcing. Such instruments would significantly improve understanding of the effects of clouds and stratospheric aerosols on climate, improve the ability to predict the effects of albedo modification, and provide an ability to detect large-scale albedo modification by unilateral and uncoordinated actors.

- An observational capability should be developed to make better use of future major volcanic eruptions to improve understanding of the effects of stratospheric aerosols on climate. This would involve space-based sensors and rapidly deployable ground-based and airborne sensors for monitoring stratospheric aerosols.

GOVERNANCE CONSIDERATIONS

Some types of research into intentional albedo modification will likely have legal, ethical, social, political, economic, and other important ramifications. Albedo modification research must abide by existing laws, regulations, and policies that apply to research broadly and its impacts on worker safety, the environment, and human and animal welfare. However, such research is not specifically addressed by any federal laws or regulations.

Given the perceived and real risks associated with some types of albedo modification research, open conversations about the governance of such research, beyond the more general research governance requirements, could encourage civil society engagement in the process of deciding the appropriateness of any research efforts undertaken.

"Governance" is not a synonym for "regulation." Depending on the types and scale of the research undertaken, appropriate governance of albedo modification research could take a wide variety of forms ranging from the direct application of existing scientific research norms, to the development of new norms, to mechanisms that are highly structured and extensive. The most appropriate type of governance structures for albedo modification research will potentially depend on the nature and scale of that research. It is not the purview of the committee to make an assessment or recommendation of the appropriate structure. However, the committee does believe that governance considerations should be targeted at ensuring civil society involvement in decision making through a transparent and open process. It should focus on enabling safe and useful research on the viability and impacts of albedo modification strategies. Ultimately, the goal is to ensure that the benefits of the research are realized to inform civil society decision making, the associated challenges are well understood, and risks are kept small.

Recommendation 6: The committee recommends the initiation of a serious deliberative process to examine (a) what types of research governance, beyond those that already exist, may be needed for albedo modification research, and (b) the types of research that would require such governance, potentially based on the magnitude

of their expected impact on radiative forcing, their potential for detrimental direct and indirect effects, and other considerations.

- If a new governance structure is determined to be needed based on deliberations among governance experts and civil society representatives, the development of the governance structure should consider the importance of being transparent and having input from a broad set of stakeholders to ensure trust among the stakeholders and appropriate consideration of all dimensions.
- Such a governance structure should consider setting clear and quantitative guidelines for experimentation and be responsive to domestic and international laws and treaties.
- The deliberative process should consider focusing on research activities that involve injecting material into the atmosphere, for example aerosol-producing substances injected into the upper atmosphere or cloud-brightening substances injected near the surface.
- If a program of research in albedo modification includes controlled-emission experiments, it should provide for a sufficiently specific governance regime to at least define the scale of experiments at which oversight begins.
- The approach to governance should consider the need for increasing supervision as the scope and scale of the research and its potential implications increase, including the amount of material emitted, the area affected, and the length of time over which emission continues.
- The goal of the governance should be to maximize the benefits of research while minimizing risks.
- The United States should help lead the development of best practices or specific norms that could serve as a model for researchers and funding agencies in other countries and could lower the risks associated with albedo modification research.

CONCLUDING THOUGHTS

Addressing the challenges of climate change requires a portfolio of actions that carry varying degrees of risk and efficacy. CDR strategies and other technologies and approaches that reduce net emissions (e.g., carbon capture and sequestration, non-carbon-based energy, and energy efficiency improvements) offer the potential to slow the growth and reverse the increase of CO_2 concentrations in the atmosphere. The lowest-risk CDR strategies are currently limited by cost and at present cannot achieve the desired result of removing climatically important amounts of CO_2 beyond the significant removal already performed by natural processes. However, with declining costs and stronger regulatory commitment, atmospheric CO_2 removal could become a valuable component of the portfolio of long-term approaches to reducing CO_2 concentrations in the atmosphere and associated impacts. Overall, there is much to be gained and very low risk in pursuing multiple parts of a portfolio of CDR strategies that demonstrate practical solutions over the short term and develop more cost-effective, regional-scale and larger solutions for the long term.

In contrast, even the best albedo modification strategies are currently limited by unfamiliar and unquantifiable risks and governance issues rather than direct costs. The committee reiterates that it is opposed to climate-altering deployment of albedo modification techniques, but it does recommend further research, particularly multiple-benefit research that furthers the basic understanding of the climate system and seeks to quantify the potential costs, consequences (intended and unintended), and risks from these proposed albedo modification techniques.

Climate change is a global challenge that will require complex and comprehensive solutions, which in turn will require that people of many nations work together toward common objectives. For the outcome to be as successful as possible, any climate intervention research should be robust, open, likely to yield valuable scientific information, and international in nature. The impacts of any potential future climate interventions should be honestly acknowledged and fairly considered. The committee firmly believes that there is no substitute for dramatic reductions in CO_2 emissions to mitigate the negative consequences of climate change at the lowest probability of risk to humanity. However, if society ultimately decides to intervene in Earth's climate, the committee most strongly recommends any such actions be informed by a far more substantive body of scientific research than is available at present.

CHAPTER ONE

Introduction

For more than three decades, scientists have predicted that a doubling of carbon dioxide in Earth's atmosphere from preindustrial levels would warm Earth's surface by an average of between 1.5°C and 4.5°C (about 3°F to 8°F). The latest report from the Intergovernmental Panel on Climate Change (IPCC) confirms this finding, with greater confidence, and furthermore affirms that the primary cause of the observed increase in global-average temperature is anthropogenic greenhouse gas (GHG) emissions (IPCC, 2013b). The IPCC further concludes that, if current emissions trends continue, by the end of the century the planet will experience a warming of up to 5°C (Figure 1.1), sea level will rise by as much as 1 m (Figure 1.2), and the Arctic will be ice free in the summer by midcentury. As part of this change in climate, society will experience an increase in the frequency and severity of heat waves, droughts, and heavy precipitation events (also see NCA, 2014).

To date, scientists have observed a number of manifestations of the changing climate, all of which will likely be amplified in the future (IPCC, 2014b). Moreover, the ability to predict these changes carries considerable uncertainties that suggest that while the adverse effects of climate change may not be as severe as many predictions, it is also quite possible that they may in fact be considerably worse (NRC, 2013a). One very visible example is the reduction in Arctic perennial sea ice cover, which has diminished at a rate of 13 percent per decade (relative to the 1979-2012 mean; see Fetterer et al., 2012; Stroeve et al., 2012b). This reduction in ice cover far exceeded model predictions (Stroeve et al., 2012a) and serves as a stark indication that the challenges we may face with climate change may occur sooner rather than later. Such a circumstance underscores the potential mismatch between the timescales at which detrimental change may occur and the timescales at which meaningful mitigation strategies may be implemented.

Globally, greenhouse gas emissions have been increasing as the growing demand for energy has more than offset what progress there has been from improved efficiency and deployment of new energy sources with lower GHG emissions (Le Quéré et al., 2013). In May 2013 the CO_2 concentration measured at the Mauna Loa Observatory in Hawaii briefly exceeded 400 parts per million (ppm) for the first time in the modern era, before the spring bloom in the Northern Hemisphere temporarily drew down CO_2 levels (Figure 1.3). Concentrations of CO_2 in the atmosphere have been increasing from preindustrial levels of 280 ppm largely as the result of the combustion of

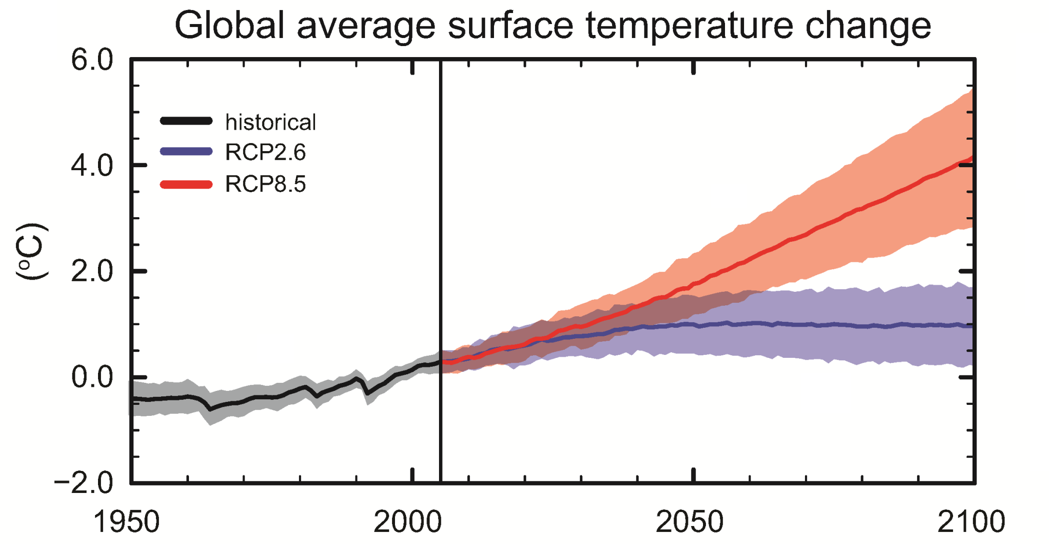

FIGURE 1.1 Temperature increase for various emission scenarios. A temperature rise of up to 5°C is possible by the end of the century if current emission trends continue. CMIP5 multimodel simulated time series from 1950 to 2100 for change in global annual mean surface temperature relative to 1986-2005. Time series of projections and a measure of uncertainty (shading) are shown for two representative concentration pathway (RCP) scenarios, RCP2.6 (blue) and RCP8.5 (red). The RCP scenarios represent a family of hypothetical future scenarios for emission of CO_2 and other greenhouse gases. They are labeled according to the peak radiative forcing from all gases up to the year 2100, so that higher-numbered RCP scenarios correspond to climate futures with greater emissions. The full set of scenarios consists of RCP2.6, RCP4.5, RCP6.0, and RCP8.5, and the middle two have been selected for the analysis in this section. The RCP2.6 trajectory involves very aggressive emission mitigation and also requires negative emissions (e.g., carbon dioxide removal) to help meet its target. SOURCE: IPCC, 2013b, Fig. SPM.7.

fossil fuels. Unlike many other air pollutants—such as nitrogen oxides and sulfur oxides, which are removed by natural physical and chemical processes in just hours to days after they are emitted—the GHGs most responsible for causing climate change remain in the atmosphere for decades to centuries.[1] In order to stabilize or reduce atmospheric concentrations, and thus avoid the worst impacts of warming, global emissions of GHGs must be reduced by at least an order of magnitude (NRC, 2011a).

---

[1] Excess carbon is absorbed by the land biosphere and ocean over decades and centuries, and it reacts with carbonate and silicate materials over thousands of years; nevertheless, most of the excess carbon emitted today will still be in the atmosphere, land biosphere, or ocean many tens of thousands of years later, until geologic processes can form rocks and deposits that would incorporate this carbon (Archer et al., 2009; Berner et al., 1983).

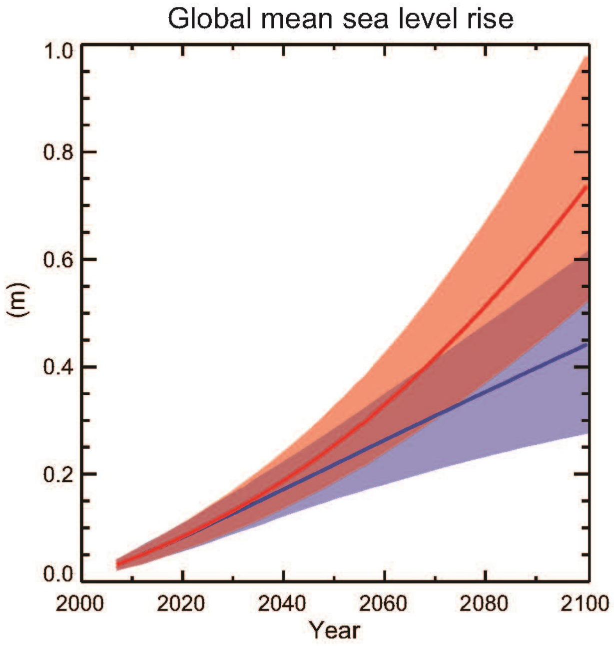

FIGURE 1.2 Sea level rise for emission scenarios RCP2.6 (blue) and RCP8.5 (red). A sea level rise of up to 1 m is possible by the end of the century if current emission trends continue. SOURCE: IPCC, 2013b, Fig. SPM.9.

To date, little progress has been made toward achieving such a major reduction (IPCC, 2011; NRC, 2010c).

Although many uncertainties remain in our understanding of climate science, it is clear that the planet is already experiencing significant climate change as a result of anthropogenic influences (IPCC, 2013b). To avoid greatly increased risk of damage from climate change, the international community has been called upon to embark on a major program to reduce emissions of carbon dioxide and other greenhouse gases (e.g., Hoffert et al., 1998; IPCC, 2013a, b, 2014a; NRC, 2011b). Because major actions to reduce emissions have been delayed, considerable additional climate change is inevitable (Cao et al., 2011). There is a portfolio of responses and proposed strategies for diminishing climate damage and risk (Figure 1.4). As outlined below in the section "Decarbonizing the Energy System," implementing an aggressive program of emissions abatement or *mitigation* presents major challenges to how we live and function as a society. These challenges have to date been a major barrier to the undertaking of substantive steps to reduce greenhouse gas emission, even though doing so is technologically well within our grasp and constitutes the lowest-risk and most efficacious

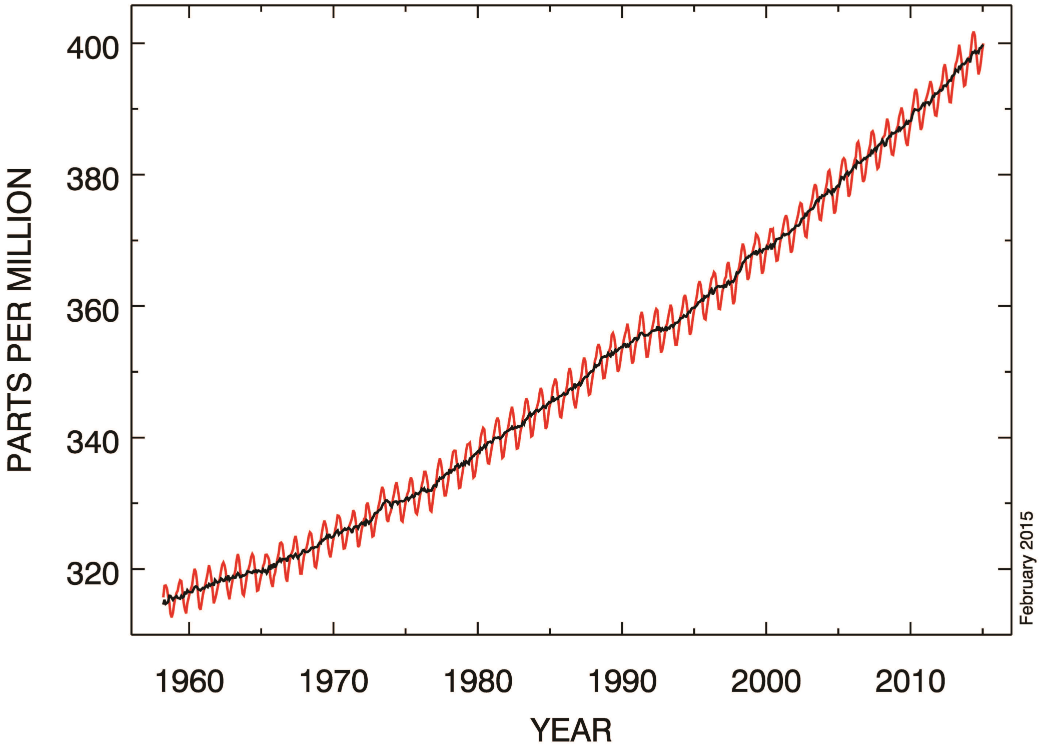

FIGURE 1.3 Record of the concentration of atmospheric carbon dioxide measured at the summit of Mauna Loa in Hawaii. The carbon dioxide data (red curve), measured as the mole fraction in dry air, on Mauna Loa constitute the longest record of direct measurements of CO_2 in the atmosphere; the black curve represents the seasonally corrected data. The collection of this record was begun in 1958 by Charles David Keeling of the Scripps Institution of Oceanography. Today, similar trends are observed in locations all around the planet (see http://www.esrl.noaa.gov/gmd/ccgg/carbontracker/). SOURCE: Scripps CO_2 Program.

path toward reducing the threats associated with anthropogenic climate change. Even if an aggressive global mitigation program is undertaken, substantial reductions in greenhouse gas levels would not be realized for several decades, and the halting or reversing of some of the detrimental effects already built into the climate system (e.g., ocean warming, ocean acidification, polar ice melting, sea level rise) would not follow for many decades or even centuries beyond that. Although there is considerable opportunity to limit the future growth of climate change, the world cannot avoid major climate change. As a result *adaptation* will be required and is indeed already happening (discussed below in "Adapting to Climate Change"). Adaptation will become increasingly costly and disruptive as the magnitude of climate change increases.

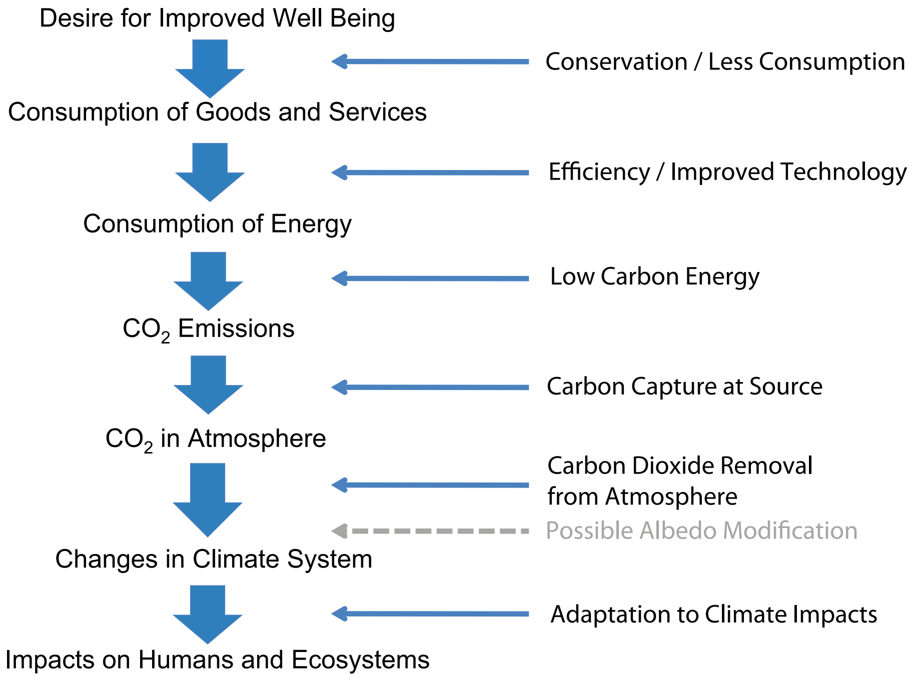

FIGURE 1.4 There is a portfolio of responses and proposed strategies for diminishing climate risk and damage at various steps in the causal chain of the human-climate system. Carbon dioxide removal approaches if proven effective could reduce the amount of CO_2 in the atmosphere. Albedo modification strategies have been proposed as a method to reduce the amount of warming that results from the accumulation of CO_2 in the atmosphere. SOURCE: Adapted from Caldeira et al., 2013.

This slow implementation of mitigation and the challenges of adaptation have led some people to consider whether strategies might exist to reduce the climate impacts of greenhouse gases after they have been emitted to the atmosphere. The committee refers to purposeful actions that are intended to produce a desired change in some aspect of the climate (e.g., global mean or regional temperature) as "climate intervention." Climate intervention includes actions designed to remove carbon dioxide or other greenhouse gases from the atmosphere or to mask some of the climate effects of these gases by changing Earth's radiation balance. This report examines approaches that actively increase the amount of short-wavelength radiation that is reflected to space, referred to as "albedo modification." The terms "climate engineering" and "geoengineering" have been used to refer to highly heterogeneous and poorly defined collections of activities. The committee believes that these overarching terms do little to advance the discussion of the set of activities under consideration here. Therefore, the committee refers instead to carbon dioxide removal (CDR) and albedo modification strategies independently. These two classes of strategies have very different characteristics (see Box 1.1).

The committee recognizes that altering Earth's albedo is an extreme measure, one that many already dismiss as unwise. However, the fact that the risks associated with climate change may themselves be unmanageable and irreversible through mitiga-

BOX 1.1 WHY THERE ARE TWO SEPARATE REPORTS

This committee was tasked with conducting a technical evaluation of examples of both carbon dioxide removal (CDR) techniques and albedo modification techniques (also known as "solar radiation management" or "sunlight reflection methods," both going by the initials SRM).[a]

Some carbon dioxide removal techniques such as reforestation have already been considered in the public policy process as a form of mitigation—the effort to reduce net greenhouse gas emissions resulting from human activity. Linking direct air capture of carbon with carbon sequestration (DACS) has the potential to lead to a net reduction of CO_2 from the atmosphere if and when fossil fuel use is significantly reduced. As such, CDR approaches such as reforestation and DACS have more in common with widely discussed climate change mitigation approaches than they do with, for example, stratospheric aerosol injection. Reforestation and bioenergy with carbon capture and sequestration figured prominently in the IPCC Working Group III chapter on Mitigation of Climate Change, where mitigation is defined as "a human intervention to reduce the sources or enhance the sinks of greenhouse gases" (IPCC, 2014b).

In contrast, even the lowest-risk albedo modification approaches entail unknown and potentially large international political and environmental challenges, and therefore more research is required to better understand consequences of a possible implementation. The political ramifications, environmental risks, and research needs associated with albedo modification differ dramatically from those associated with carbon dioxide removal. Table S.1 summarizes the many contrasts in cost, risk, impact, and scale between these two approaches.

Although both share the goal of reducing the climate consequences of high greenhouse gas concentrations, CDR methods have more affinity with solutions aimed at reducing net anthropogenic CO_2 emissions (e.g., transitions to near-zero-emission energy systems), whereas albedo modification approaches aim to provide symptomatic relief from only some of the consequences of high greenhouse gas concentrations. The committee sees little benefit in or rationale for closely associating these carbon dioxide removal approaches with only distantly related and highly controversial albedo modification approaches. Therefore, the committee has decided that it can most effectively carry out its charge by producing two separate volumes: one on carbon dioxide removal and another on albedo modification.

---

[a] Appendix A describes the charge to the committee for this study and Appendix B lists the committee membership.

tion efforts that are implemented too late makes examination of alternatives such as albedo modification a prudent action at this time, so that the limits and potential can at least be understood and weighed against the alternatives.

DECARBONIZING THE ENERGY SYSTEM

The most important human activity contributing to GHG emissions is the burning of fossil fuels (coal, oil, and natural gas) (IPCC, 2013b). Hence stabilizing or reducing atmospheric concentrations of carbon dioxide, and thus the climate, will require performing a massive transformation in the energy and transportation system (NRC, 2010b). Most knowledgeable observers understand that humanity should embark on an aggressive program to reduce emissions, although the scale of this challenge is underappreciated by some but not as daunting as it is made out to be by others.

According to the International Energy Agencyn (IEA), the total electricity consumption worldwide in 2011 was approximately 20,000 TWh (a rate of ~2,300 GW), and the United States accounted for just over 4,000 TWh (a rate of ~460 GW), or about 20%, of that amount (IEA, 2013). To gain some perspective on what will be involved in reducing fossil fuel dependence, a large power plant can produce about 1 GW of electrical power (EIA, 2013b; see also http://www.eia.gov/electricity/annual/), so the above numbers can be thought of as the amount of electricity produced by 2,300 large power plants globally or 460 large power plants for the United States alone. If society is to decarbonize the electricity system, it will be necessary to replace much of that infrastructure with carbon-free energy sources or to modify existing power plants to be carbon free. It took the United States more than five decades to create its existing electrical system infrastructure, and the lifetime for an existing coal-fired power plant is typically several decades (EIA, 2013a; Smil, 2010).

Further, global energy use is conservatively projected to rise between 15 percent and 30 percent by 2035 (from 2011 levels[2]), adding to the challenge of decarbonizing global energy. In addition to the electric power sector, the transportation, industrial and residential and commercial sectors currently account for the majority of energy use in the United States. As Figure 1.5 shows, energy input into electricity is only about 35 percent of U.S. total energy consumption. Most of the remainder involves the direct combustion of fossil fuels in transportation, heating and cooling of buildings, and industrial processes. In order to decarbonize the entire energy system, all of these

---

[2] 2011 total energy consumption = 8,918 Mtoe (million tons oil equivalent; 10,400 TWh); 2035 projections are between 10,390 and 11,750 Mtoe (12,100 and 13,700 TWh); http://www.iea.org/publications/freepublications/publication/KeyWorld2013. pdf; accessed October, 2014.

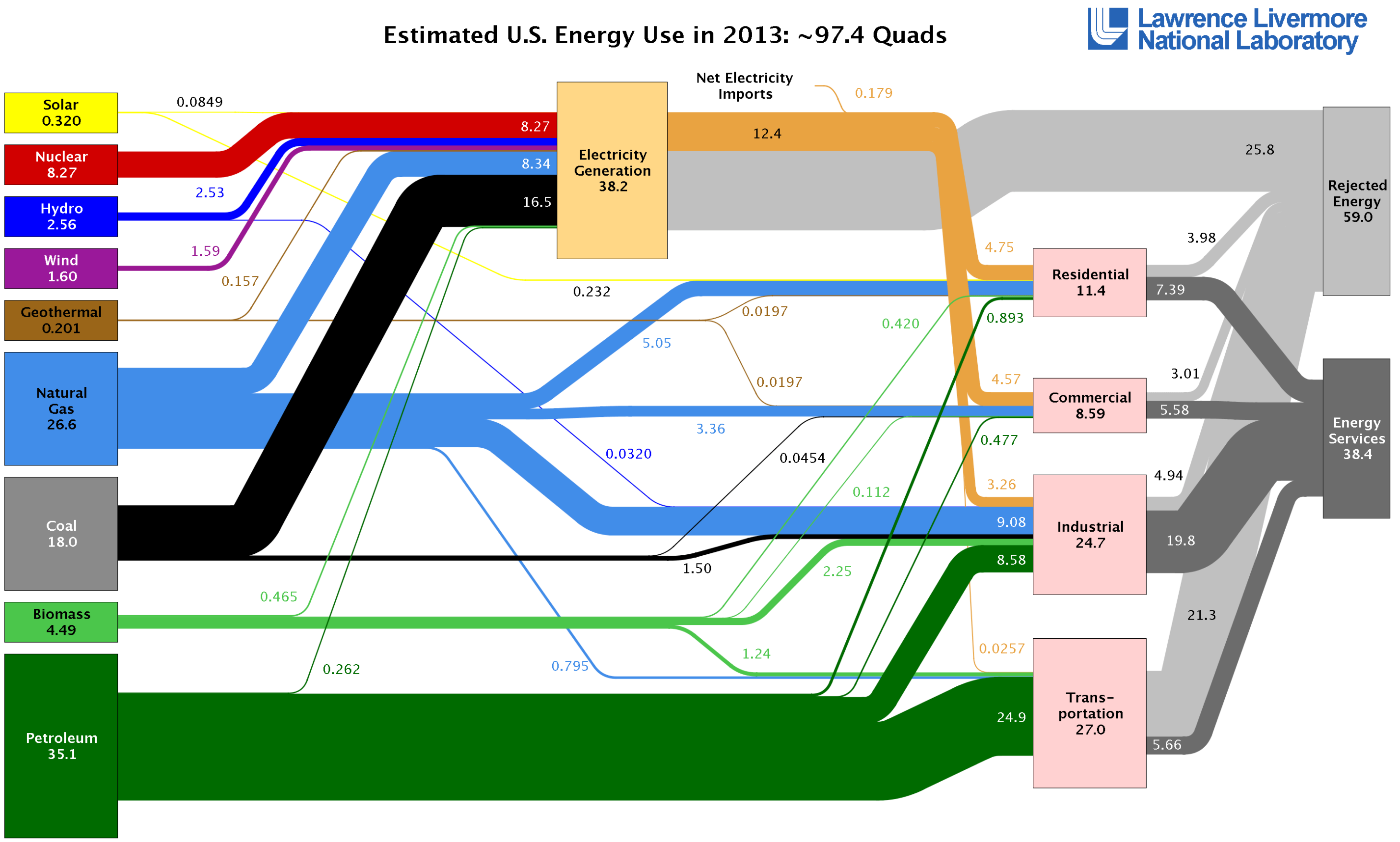

FIGURE 1.5 Flows of energy through the U.S. economy. The light gray bands on the right indicate energy that performs no useful service (i.e., waste). The dark gray bands on the right indicate energy that is used in the residential, commercial, industrial, and transportation sectors. Note that roughly 88 percent of the energy that presently enters the U.S. economy involves combustion of a fuel, which releases carbon dioxide to the atmosphere (1 quad is 10^{12} BTUs or 293 TWh). SOURCE: Lawrence Livermore National Laboratory, https://flowcharts.llnl.gov/.

applications will also need to be converted to systems that emit little or no carbon dioxide, in many cases by converting them to run on cleaner sources of electricity.

"Decarbonization" of the energy system could be facilitated by adopting the following strategies (IPCC, 2014b; NRC, 2010b):

1. Improve the efficiency with which the energy enters and is distributed within the system and increase the efficiency of all technologies that use energy.
2. Convert the electricity, residential, commercial, industrial, and transportation systems to sources of energy that release less carbon dioxide to the atmosphere. Examples of such sources could include nuclear energy; systems that capture and "sequester" carbon dioxide from power plants that use coal or natural gas; hydroelectricity, wind and solar power; some systems based on biomass (though not all bioenergy has low net carbon emissions); and geothermal energy.

A recent NRC report (2010b) assesses the feasibility of decarbonizing the energy system as follows:

> There are large uncertainties associated with these sorts of projections, but the variation among them illustrates that the United States has many plausible options for configuring its future energy system in a way that helps meet GHG emissions-reduction goals. Note, however, that all cases involve a greater diversity of energy sources than exist today, with a smaller role for freely emitting fossil fuels and a greater role for energy efficiency, renewable energy, fossil fuels with CCS, and nuclear power. The virtual elimination by 2050 of coal without CCS—presently the mainstay of U.S. electric power production—in all the scenarios is perhaps the most dramatic evidence of the magnitude of the changes required. (NRC, 2010b)

Because they produce varying and intermittent power, it is thought that wind and solar cannot currently be the sole replacement for conventional fossil fuel–fired power plants. A reliable and affordable supply of carbon-free electricity will require a broad mix of generation types and energy sequestration approaches. Figure 1.6 shows three examples of potential scenarios for the mix of future generation types.

Although such estimates of future deployment of carbon-free energy sources indicate that it may be possible to achieve a decarbonized energy system, great uncertainties remain regarding the implementation of such scenarios due to factors such as costs, technology evolution, public policies, and barriers to deployment of new technologies (NRC, 2010b). Furthermore, simply accounting for the emissions from existing fossil fuel energy facilities over their remaining lifetime commits the planet to an additional

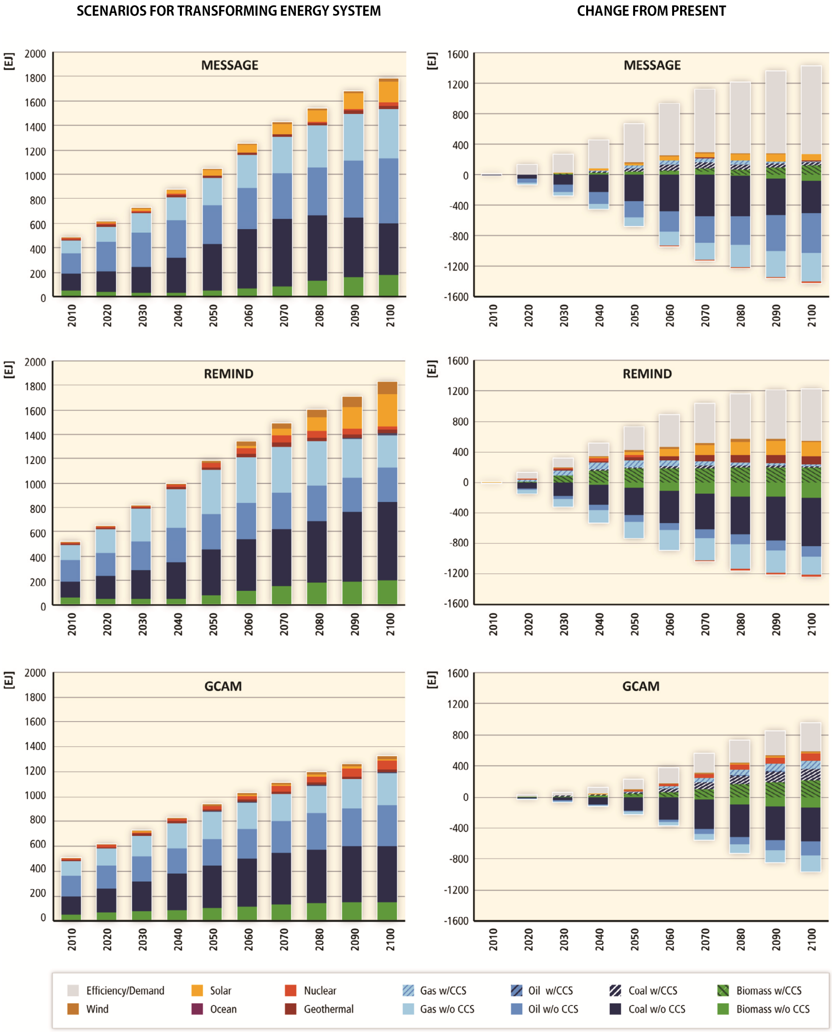

FIGURE 1.6 Three examples of alternative energy system transformation pathways are presented, where each pathway is consistent with limiting CO_2-equivalent (CO_2-eq) concentrations to about 480 ppm CO_2-eq by 2100. The scenarios from the three selected models (Model for Energy Supply Strategy Alternatives and their General Environmental Impact [MESSAGE], Regional Model of Investments and Development [ReMIND], and Global Change Assessment Model [GCAM]) show that there are different strategies for combining renewable and nonrenewable energy sources with increases in energy efficiency to meet the target. The left-hand panels show the energy supply for each scenario by year, which, in absence of new policies to reduce GHG emissions, would continue to be dominated by fossil fuels. Right-hand panels show alternative scenarios that limit GHG concentration to low levels through rapid and pervasive replacement of fossil fuels. Between 60 and 300 EJ of fossil fuels are replaced across the three scenarios over the next two decades (by 2030). By 2050 fossil energy use is 230-670 EJ lower than in non-climate-policy baseline scenarios. SOURCE: IPCC, 2014b.

300 billion tons of CO_2 (Davis and Socolow, 2014).[3] With whatever portfolio of technologies the transition is achieved, eliminating the carbon dioxide emissions from the global energy and transportation systems will pose an enormous technical, economic, and social challenge that will likely take decades of concerted effort to achieve.

ADAPTING TO CLIMATE CHANGE

The likely impacts of climate change have been described at length in reports of the IPCC (IPCC, 2013b; NRC, 2010a). Impacts likely to be experienced in the territories of the United States have been described in the U.S. National Climate Assessment (NCA, 2014) and the Arctic Assessment (ACIA, 2004; NRC, 2010a). These and similar studies conclude that, although it will be difficult and expensive, with a deliberate effort industrialized societies and economies can adapt to the climate change that may occur over the remainder of this century. There is much to do to build the capacity to adapt in the United States (NRC, 2010a, 2012a). The outlook is more pessimistic for the less industrialized societies and economies of the world, and grimmer still for many natural terrestrial, aquatic, and oceanic ecosystems (IPCC, 2013b).

The past 10,000 years have been a period of relative climatic stability that has allowed human civilization to flourish, agrarian sedentary communities to replace a nomadic lifestyle, and cities to emerge on mostly stable shorelines. This has been true despite notable exceptions, such as the Little Ice Age and episodes of volcanic-influenced weather that resulted in famine and widespread travail (Parker, 2013; Wood, 2014). What swings there have been in the global climate system have occurred within a relatively narrow range compared to those in the longer paleoclimate record. History suggests that some ancient civilizations have not adapted well to past climate changes. For example, it is believed that natural climate excursions, along with other factors, contributed to the end of the Anasazi and Mayan civilizations in the southwestern United States and Central America (Diamond, 2011; Tainter, 1988).

Globally, communities are already experiencing changing conditions directly linked to climate change—including rising seas that threaten low-lying island nations, loss of glaciers and sea ice and melting permafrost that expose Arctic communities to increased shoreline erosion, and consecutive record years of heat and drought stress (IPCC, 2013a,b, 2014a; NCA, 2014).

---

[3] Units of mass adopted in this report follow the convention of the IPCC and are generally those which have come into common usage; $GtCO_2$ = gigatonnes of carbon dioxide, where 3.67 $GtCO_2$ = 1 GtC.

As described above, the challenge of decarbonizing the energy system is indeed daunting, and adapting to climate change is also likely to present substantial challenges. For example, much of the current infrastructure essential for commerce of coastal cities such as New York, Boston, Miami, Long Beach, Manhattan, New Orleans, Los Angeles, San Diego, and parts of San Francisco today could end up below sea level as the ocean continues to rise and, thus, could be submerged in the absence of protective dikes or other adaptive measures (NRC, 2012b; Strauss et al., 2012, 2013; Tebaldi et al., 2012). With sufficient planning, the possibility of moving infrastructure to higher ground is a cost-effective mitigation strategy for many localities, but there is little history of abandoning commercial use of coastal land in anticipation of sea level rise and there are many social and societal factors involved in potentially relocating communities (NRC, 2010a). Anticipatory adaptation is made more difficult because disruption to human lives and property typically does not occur gradually (see, for example, NRC, 2013a) but rather as a result of major weather events, such as hurricanes and other large storms, that cause billions of dollars in damage.

Food production is also sensitive to climate change. Although the relationship is complex—some regions will experience longer growing seasons while others will suffer from more heat stress—global yields of wheat, barley, and maize have decreased with increasing global-average temperature (Lobell and Field, 2007). There are numerous adaptation strategies that are available to cope with various climate changes—including changes to temperatures, precipitation, and ambient CO_2 concentrations—but all require substantial effort and investment (see Table 3.3 in NRC, 2010a). But even with adaptation, climate change can still cause long-term loss (for example, long-term loss of land due to sea level rise).

Shifts in mean temperature, temperature variability, and precipitation patterns are already causing stress on a diversity of ecosystems (NRC, 2013a). Species' range shifts have already become evident (Chen et al., 2011; Parmesan, 2006; Parmesan and Yohe, 2003; Poloczanska et al., 2013; Root et al., 2003; Staudinger et al., 2012) and are expected to accelerate with increasing rates of climate change, as are changes in the timing of species migrations (Gill et al., 2013) and other important plant and animal life-cycle events. The world's surface ocean has already experienced a 30 percent rise in acidity since the industrial revolution, and as that acidity continues to rise, there could potentially be major consequences to marine life and to the economic activities that depend on a stable marine ecosystem (NRC, 2013b). These impacts, combined with increasing numbers of exotic species introductions and demands on ecosystems to provide goods and services to support human needs, mean that extinction rates are increasing (Pimm, 2009; Staudinger et al., 2012). With continued climate change, species will be increasingly forced to adapt to changing environmental conditions and/or migrate to new locations, or face increasing extinction pressures.

There are many climate adaptation and resilience efforts ongoing within the United States, often at the state or local levels (Boston Climate Preparedness Task Force, 2013; Miami-Dade County, 2010; PlaNYC, 2013; Stein et al., 2014; USGS, 2013; http://www.cakex.org/). Although this is a rapidly evolving field, there is still a great deal of research to be done in the field of climate adaptation and there may be insufficient capacity for adaptation (NRC, 2010a). Overall, both humans and ecosystems face substantial challenges in adapting to the varied impacts of climate change over the coming century.

CARBON DIOXIDE REMOVAL AND ALBEDO MODIFICATION

As discussed above, industrialized and industrializing societies have not collectively reduced the rate of growth of GHG emissions, let alone the absolute amount of emissions, and thus the world will experience significant and growing impacts from climate change even if rapid decarbonization of energy systems begins. Given the challenges associated with reducing GHG emissions and adapting to the impacts of climate change, some people have begun exploring whether there are climate intervention approaches that might provide additional mechanisms for facing the challenges of climate change.

In this volume, the committee considers strategies to increase the fraction of incoming solar radiation that is directly reflected back to space (i.e., increase the albedo), which have been discussed in various forms over the past several decades (Box 1.2). Chapter 2 gives an overview of the concept of albedo modification and discusses some issues that are common to multiple proposed albedo modification techniques. Chapter 3 discusses specific proposed albedo modification techniques in detail; in particular, the committee focuses on two strategies that have received the most attention and which may most feasibly have a substantial climate impact: stratospheric aerosol injection and marine cloud brightening. The committee also briefly discusses another strategy to modify the planet's radiative balance by allowing more infrared energy back to space through thinning cirrus clouds, as well as several approaches for modifying the albedo of the planet's surface. The prospect of large-scale albedo modification raises political and governance issues at national and global levels, as well as ethical concerns, and Chapter 4 discusses some of the social, political, legal, and ethical issues surrounding these proposed albedo modification techniques. Albedo modification strategies are limited primarily by considerations of risk, not by direct costs, and Chap-

BOX 1.2 HISTORY OF ALBEDO MODIFICATION CONCEPT

Reviews by the National Research Council (NRC, 2011b) and the IPCC (1991, 1997, 2003, 2007a, 2013b) concluded that the anthropogenic climate change has the potential to cause substantial harm to both humans and ecosystems. The idea of intentionally cooling the Earth by increasing reflectivity of the Earth as a way to reduce the amount of harm from climate change was suggested in official government reports since at least the 1965 report of the President's Science Advisory Committee (PSAC, 1965). For example, Budyko was the first to propose that Earth's climate could be cooled with the intentional release of aerosols into the stratosphere (Budyko, 1974, 1977). Some of these early suggestions would, if implemented, have obvious potential negative consequences (Fleming, 2010a). Other suggested methods for modifying Earth's reflectivity gained prominence in the early 1990s and into the 2000s through a series of papers by prominent scientists (Cicerone, 2006; Crutzen, 2006; Keith and Dowlatabadi, 1992). Approaches for albedo modification were broadly explored by The Royal Society (Shepherd et al., 2009), a group of more than 100 leading researchers and thinkers at the Asilomar Conference Center (ASOC, 2010), the House Science Committee of the U.S. Congress through a series of three hearings (U.S. Congress, 2010), the Government Accountability Office (GAO, 2010), and the Bipartisan Policy Center's Task Force on Climate Remediation Research (BPC, 2011), among numerous other publications.

ter 5 discusses the committee's views on further research to better understand and quantify those risks.

Human-induced climate change is a global issue, potentially addressed by both collective international actions and unilateral interventions. Because the committee was tasked to do a technical analysis of a limited number of proposed climate intervention approaches by the U.S. government, these two volumes deliberately focus on what the United States could do while bearing in mind the global context in which the United States acts. Appendix A describes the charge to the committee for this study and Appendix B lists the committee membership.

The companion volume to this report, *Climate Intervention: Carbon Dioxide Removal and Reliable Sequestration*, considers strategies to remove GHGs (largely CO_2) from the atmosphere and to provide reliable sequestration for it in perpetuity, which are termed CDR. The introductory material for both reports is the same (Chapter 1 in both reports). The concluding chapter of the companion volume summarizes the discussions in that volume; the concluding chapter of this volume (Chapter 5) summarizes the discussions in this volume as well as providing an overview of both volumes.

CHAPTER TWO

Climate Intervention by Modifying Earth's Albedo

INTRODUCTION

This report considers climate intervention strategies for deliberately modifying the energy budget of Earth to produce a cooling designed to compensate for some of the effects of warming associated with greenhouse gas increases. The physical principles for modifying the energy budget to cool the planet are discussed more thoroughly below, but they also appear to all of us in our everyday lives. For example, in the temperate and polar regions, winter temperatures are generally colder than summer temperatures, because those regions receive less sunlight in the winter. The energy principles controlling temperature on a hot day or cool night result from and influence weather on a day-to-day local scale and also operate on climate at seasonal through millennial timescales over the globe. For example, in 1784, Benjamin Franklin speculated that "a constant fog over Europe" arising from volcanic eruptions near Iceland diminished the heating effect of the rays of the sun, and that it was responsible for the abnormally cold winter of 1783-1784 in Europe (Franklin, 1789). Since that time, the connection between cooler temperatures and volcanic eruptions (which release particles into the atmosphere that scatter sunlight back to space) has been well established.

These principles operate everywhere in nature; as understanding of Earth's physical system has increased, some scientists have begun to consider deliberately making use of these physical principles to counter global warming. Budyko (1974) was the first to suggest that global warming might be countered by burning sulfur on airplane flights high in the atmosphere to make small particles (called aerosols) that, like volcanic emissions, would reflect sunlight. Since that time, a variety of suggestions have been made regarding ways to reduce the amount of sunlight absorbed at the planet's surface.

Climate intervention ideas have been explored in a variety of ways: (1) through basic theoretical considerations, (2) through the study of climate-relevant features that occur today and have occurred in the past that serve as approximate analogues relevant to the methods being suggested for engineering the climate, and (3) through computer models. Climate models, known to be only an approximation of the real world, suggest that it might be possible to intervene in the climate system to counter some of the effects of global warming, but they also point to negative consequences and new issues of concern from these proposed techniques. Models provide an incomplete and imperfect picture of the world, and one must be cautious in interpreting their results. Nevertheless, these results indicate to some scientists that it would be worthwhile to continue to do research to better evaluate and understand the possibility of deliberately modifying the climate. The need to carefully evaluate and understand these proposals is highlighted by the limited success of previous attempts to deliberately control weather and climate, discussed in Box 2.1.

In the remainder of this chapter we introduce the major themes that are explored at length in subsequent chapters. The principal terminology used throughout this report is summarized in Box 2.2, together with alternate terminology used at places in the existing literature to refer to similar concepts.

BOX 2.1 HISTORICAL CONTEXT FROM PREVIOUS ATTEMPTS TO CONTROL WEATHER

Humans have inadvertently affected regional and global weather in different ways. History has demonstrated the human capability to deploy technologies that affect climate at global scale. As agriculture spread across the continents, land use changes meant that in many areas dark forests were replaced by lighter colored croplands, and in high latitudes this caused a regional cooling (IPCC, 2013a). Sulfate aerosols, largely from coal-fired power plants with inadequate pollution controls, have a global cooling influence, but the effect is most pronounced over large parts of the Northern Hemisphere. Of course, our fossil fuel emissions are affecting climate the world over (IPCC, 2013b). At first, people were not aware that such activities would affect climate and thus unknowingly undertook climate modification. Although humans have never undertaken actions with the express intent of altering regional or global climate on a large scale for a sustained period of time, there have been efforts to affect local weather and proposals to alter regional or global climate (see below).

Visionary proposals for weather and climate control have a long history (see Byers, 1974; Fleming, 2010b, 2012; Huschke, 1963). The National Science Foundation produced a report, *Weather and Climate Modification*, in 1966 (NSF, 1966) and the National Research Council followed this up with an update in 1973, titled *Weather and Climate Modification: Problems and Progress* (NRC, 1973).

Many early weather modification proposals did not move beyond the discussion stage, and the ones that did mostly did not produce the desired effects on the physical environment. In many cases, these proposals gave rise to complicated political, social, and economic issues. As we look forward at proposals for intentionally modifying Earth's climate, society can learn important lessons from previous weather modification proposals.

BOX 2.1 CONTINUED

In 1841, James Espy, the first U.S. national meteorologist, proposed a massive rainmaking scheme based on the convective updrafts theory, the best science of his day. Inspired by volcano dynamics, he proposed burning woodlots each week along the Appalachian Mountains to enhance convection and provide regular rains to the east coast. Espy claimed this would keep the rivers navigable, break up cold snaps and heat waves, and also provide a health benefit by clearing the air of miasmas (Espy, 1841). The immediate result was public criticism, and even ridicule, for Espy (Fleming, 2010a). This is one example of a common theme through history: proposals to modify weather have tended to produce strong public opposition.

A century later, in 1946, Nobel Laureate Irving Langmuir believed he and his team at the General Electric Corporation had discovered a means of controlling the weather with cloud-seeding agents such as dry ice and silver iodide. The following year, in conjunction with the U.S. military, they sought to deflect a hurricane from its path, but planned publicity for the experiment went awry. After seeding, the hurricane veered suddenly, due to what were later determined to be natural steering currents (rather than the seeding), and smashed ashore on Savannah, Georgia (Fleming, 2010a). An important lesson is that those who conduct experiments that substantively alter weather—regardless of whether the interventions had any actual effect—can potentially be held legally liable for damage caused by the altered weather. (See further discussion in Appendix C, including descriptions of cloud-seeding activities that are ongoing today.)

Prospects for larger-scale, even planetary, intervention in the climate system arrived after World War II with the dawn of several transformative technologies. Proposed weather modification projects included ideas such as cloud-seeding techniques, weakening hurricanes with biodegradable oil slicks, and breaking up polar ice with nuclear weapons, often as part of the Cold War quest to militarize the atmosphere (Fleming, 2010b; Hoffman, 2002, 2004). These previous attempts highlight both societal and scientific difficulties in attempting to exert deliberate control over nature, in particular the challenge of demonstrating the efficacy of the modification against a background of natural variability.

A 2003 NRC study, *Critical Issues in Weather Modification Research* (NRC, 2003), concluded that there was "no convincing proof" that cloud seeding is effective at increasing precipitation. However, peer-reviewed studies have indicated some modest increases in precipitation resulting from cloud seeding in some cases (Breed et al., 2014; California Department of Water Resources, 2005; Morrison et al., 2009).

History teaches us that things change—often in surprising or unanticipated ways—and that a certain amount of clarity can be gained by looking backward as we inevitably rush forward. Although there have been proposals aimed at attempted control of weather and climate that have had some success, there have also been many that have fallen well short of their goals. The potential for public opposition, the potential liability for any negative consequences, and the complex nature of the weather-climate system all point to the need to approach any future proposals for modifying Earth's climate with caution. A further discussion of previous attempts at planned weather modification is found in Appendix C.

BOX 2.2 SUMMARY OF TERMINOLOGY USED IN THIS REPORT

Albedo modification: Intentional efforts to increase the amount of sunlight that is scattered or reflected back to space, thereby reducing the amount of sunlight absorbed by the Earth, including injecting aerosols into the stratosphere, marine cloud brightening, and other efforts to enhance surface reflectivity. This set of approaches is often referred to by the acronym SRM, standing most often for the term "solar radiation management" but sometimes also "sunlight reflection methods" (Caldeira et al., 2013; The Royal Society, 2009). The committee prefers the term "albedo modification" because it is a more straightforward and neutral description of the physical process involved, and it is free of the connotations of a precise, routine, and orderly process carried by the term "management."

Stratospheric aerosol injection: A proposed method of albedo modification that involves increasing the amount of small reflecting particles (aerosols) in the stratosphere. The stratosphere is a layer in the upper regions of the atmosphere (starting at approximately 18 km altitude in the tropics) above the more turbulent troposphere layer where rainfall and most conventional "weather" occurs. The aerosol increase is generally not accomplished by injecting aerosols themselves, but by injecting chemical precursors such as sulfur dioxide (SO_2), which transform into aerosols via subsequent processes.

Marine cloud brightening: A proposed method of albedo modification that involves injecting substances near the surface of Earth that increase the reflectivity of low cloud layers. The emphasis is generally on clouds over the ocean (which has a low albedo), because these present the best opportunities for increasing reflectivity.

SOME BASIC PHYSICS CONCERNING CLIMATE INTERVENTION BY ALBEDO MODIFICATION

It has been known since the work of Fourier in the early 1800s that the temperature of Earth is determined by the requirement that, in steady state, the rate at which energy is lost to space in the form of outgoing infrared radiation balances the rate at which energy in the form of incoming solar radiation is absorbed by Earth. A mismatch in this balance would cause Earth to warm or cool. The rate at which infrared radiation is emitted increases as the temperature of the surface and atmosphere increases, so the planet can come into equilibrium by warming up or cooling down until balance is achieved. Convection and other vertical mixing processes tightly couple most of the atmosphere to the surface temperature, and for that reason the surface temperature can largely be determined by the top-of-atmosphere energy balance without explicit reference to the details of how energy is transferred between the surface and the atmosphere (Pierrehumbert, 2010).

The climate system can be compared to a heating system with two knobs, either of which can be used to set the global mean temperature. The first knob is the concentration of greenhouse gases such as CO_2 in the atmosphere that affects the infrared side of the energy balance; increases in concentration of these gases reduce the rate at which infrared radiation is emitted to space for any given surface temperature (Figure 2.1). As more greenhouse gases are added to the atmosphere, the system (if otherwise undisturbed) will warm up until outgoing infrared radiation increases sufficiently to restore Earth's energy balance. The other knob is the reflectance of the planet, which controls the amount of sunlight that the Earth absorbs. Sunlight is reflected or scattered by clouds and particles in the atmosphere, and by the surface. One could instead attempt to restore the balance at the original temperature by increasing the proportion of sunlight that Earth's surface and atmosphere reflect back to space, reducing energy reaching Earth's surface (Figure 2.1). The technical term for this proportion of reflected incoming sunlight is "albedo," which comes from the Latin

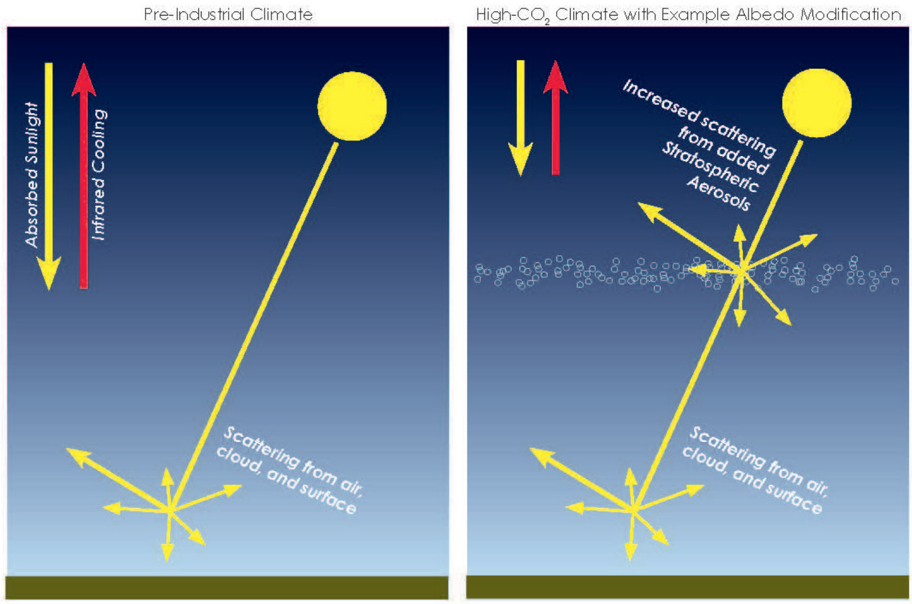

FIGURE 2.1 Schematic illustration of the energy balance of the preindustrial climate (left panel) and a modified high-CO_2 climate following a climate intervention by albedo modification (right panel). In the albedo-modified high-CO_2 climate, the infrared cooling to space (red arrow) is reduced relative to the preindustrial climate, but the effect on the energy budget is offset by a corresponding reduction in the amount of solar energy absorbed. The solar absorption is reduced by increasing the albedo so as to reflect more sunlight back to space.

root meaning "whiteness." For example, adding tiny particles to the upper atmosphere scatters light and brightens the sky, increasing the planet's albedo. However, these two knobs do more than affect global mean temperature. In differing ways, they also influence regional temperatures, the global hydrological cycle, land plants, and other components of the Earth system. So, turning up one knob and turning down the other might be able to restore Earth's global mean temperature but could nevertheless produce substantial changes to Earth's environment (see Chapter 3 for further discussions).

By way of analogy, consider a home heated in winter by passive solar heating, where sunlight entering the windows maintains a comfortable interior temperature. If insulation is added to the roof and walls, the rate at which heat is lost to the outside would decrease, and the temperature inside the house would increase until a balance is restored with the amount of solar energy streaming through the windows. As a result, the house could become uncomfortably hot. One could address this problem by pulling down the window shades a bit, reducing the amount of sunlight entering the house.

There are a number of means by which the amount of sunlight absorbed by Earth could be altered. Objects such as mirrors, lens arrays, or orbiting clouds of reflecting particles could be placed in outer space, diverting some sunlight before it can encounter Earth (Early, 1989). Small particles (aerosols) or substances that lead to their formation could be injected into the stratosphere and renewed as needed (Budyko, 1974). Substances can be injected near the surface of Earth that either directly reflect sunlight or cause low-level clouds to become more reflective (Latham, 1990). See Figure 2.2 for an illustration. Finally, the land surface reflectivity can be directly modified, for example, by adding white roofs and parking lots or by planting light-colored vegetation to cover or replace darker surfaces (Irvine et al., 2011). All of these ideas have been proposed as possible mechanisms to modify Earth's albedo on a large scale, and some of these proposed strategies are discussed in more detail in Chapter 3.

Climate change is driven by an imbalance in Earth's energy budget. The magnitude of this imbalance (after accounting for some adjustment processes) is radiative forcing (see Box 2.3), typically quoted in units of watts per square meter (W/m^2) of Earth's surface. The radiative forcing caused by doubling of the preindustrial CO_2 concentration is approximately 4 W/m^2. Sunlight is absorbed by Earth at a rate of about 240 W/m^2, so reflecting back to space approximately 2 percent of the currently absorbed sunlight would offset the top-of-atmosphere radiative imbalance caused by a doubling of atmospheric CO_2 content (Govindasamy and Caldeira, 2000; Kravitz et al., 2013a). Because aerosols are very effective reflectors of sunlight (see Chapter 3), the required

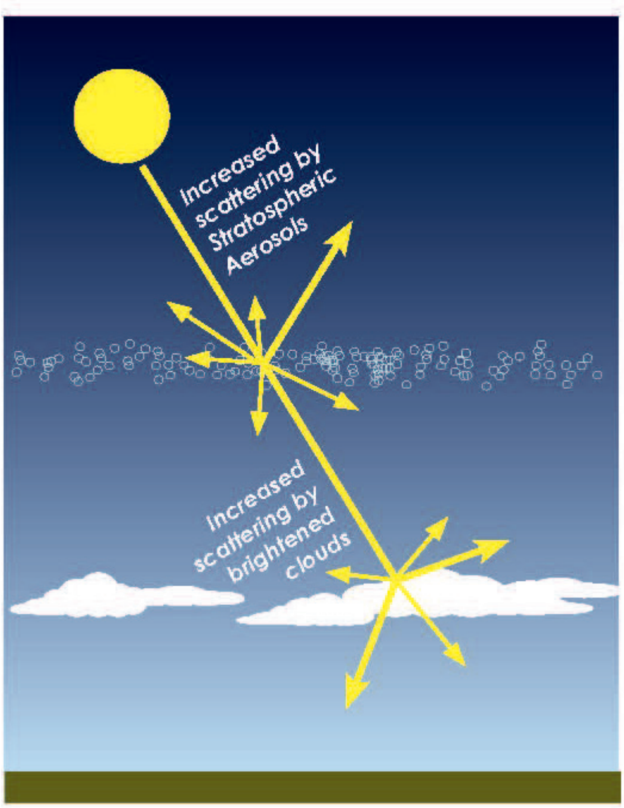

FIGURE 2.2 Illustration of the two proposed approaches for increasing albedo that are discussed in this report: increasing the concentration of reflecting particles in the upper atmosphere (specifically, the stratosphere) and increasing the reflectivity of low clouds.

change in albedo can in theory be accomplished by maintaining a small mass of aerosols in the atmosphere; this is the chief appeal of climate intervention by aerosol injections.

To put the required increase in albedo into perspective, the 1991 Pinatubo eruption, which is estimated to have been the largest eruption since Krakatau in 1883, led to a radiative forcing of approximately -3 W/m^2 within a month following the eruption, decreasing to nearly zero over the subsequent 2 years (IPCC, 2007b, Fig. 2.18) and causing the average surface air temperature to cool an estimated 0.3°C over a period of 3 years.

BOX 2.3 RADIATIVE FORCING AND ALBEDO

Radiative forcing provides a measure of the amount by which a change in some given characteristic of the Earth system (e.g., atmospheric CO_2 concentration) alters Earth's energy budget, all other things being held constant. The larger the radiative forcing, the more the surface and atmospheric temperature must change in order to restore balance. The forcing is referred to as "radiative" because essentially all energy enters or leaves the Earth system in the form of electromagnetic radiation—largely infrared or visible light. Radiative forcing is measured in units of watts per square meter (W/m^2), corresponding to the change in amount of energy per unit time per unit of Earth's surface area entering or leaving the top of the atmosphere. The change in energy is referenced to a baseline period, typically in recent preindustrial times.

Radiative forcing can be divided into long- and short-wavelength components. The long-wavelength component refers to changes in the amount of infrared radiation emitted by Earth to space and is controlled primarily by changes in the greenhouse gas content of the atmosphere. The short-wavelength component refers to changes in the amount of solar energy absorbed by Earth and is controlled primarily by the proportion of sunlight reflected back to space by the atmosphere and the surface. This proportion is known as the *albedo*. Albedo is commonly quoted as a percentage; an albedo of 100 percent would mean that all of the incident sunlight is reflected back to space and none is absorbed, whereas an albedo of 0 percent would mean that none of the incident sunlight is reflected and all of it is absorbed. The best current estimates of Earth's albedo put the value between 29 percent and 30 percent for the past decade (Stephens et al., 2012).

For a more precise technical definition of radiative forcing, see IPCC (2013a, Box 8.1).

MOTIVATION FOR RESEARCHING ALBEDO MODIFICATION

Reviews by the NRC (2011b) and the Intergovernmental Panel on Climate Change (IPCC, 1991, 1997, 2003, 2007a, 2013b) have concluded that the anthropogenic climate change has the potential to cause substantial harm. IPCC Working Group I projects that the RCP8.5 "business-as-usual" scenario will result in 4°C (7.2°F) warming by year 2100 (IPCC, 2013b). At this level of warming, IPCC Working Group II projects "severe and widespread impacts on unique and threatened systems, substantial species extinction, large risks to global and regional food security, and the combination of high temperature and humidity compromising normal human activities, including growing food or working outdoors in some areas for parts of the year." For example, under a business-as-usual scenario, climate models project that by the end of the twenty-first century most summers in the tropics will be hotter than the hottest summer experienced in the twentieth century, which could potentially threaten tropical crop productivity (Battisti and Naylor, 2009).

The IPCC (2013b) estimates anthropogenic releases of aerosols to the atmosphere are currently offsetting about 30 percent of the radiative forcing from anthropogenic greenhouse gases, primarily by affecting planetary albedo. The IPCC (2013b) further estimates that albedo change due to land use change offsets about 5 percent of the radiative forcing from anthropogenic greenhouse gases. Crutzen (2006) raised the question of whether humanity might want to develop the capability to intentionally modify Earth's albedo to a greater degree and offset a larger amount of forcing. Unfortunately, today's aerosols emissions create large health and environmental problems. Thus, it is important for society to know whether it is possible to alter Earth's albedo by much greater amounts while being sure that the effort will do a large amount of good and only a small amount of harm.

Should it ever become important for society to cool Earth rapidly, albedo modification approaches (in particular stratospheric aerosol injection and possibly marine cloud brightening) are the only ways that have been suggested by which humans could potentially cool Earth within years after deployment. Over the past 15 years, stratospheric aerosol injection and marine cloud-brightening ideas were tested in modern climate models, and results for an idealized set of scenarios across a broad spectrum of models (Kravitz et al., 2013a) yielded consistent results on the direct cooling effects of such approaches and some indirect processes. These models indicate that decreasing the amount of sunlight absorbed by Earth can offset most of the global mean warming caused by elevated greenhouse gas levels (Kravitz et al., 2013a). Changes in the hydrological cycle are more complex and harder to summarize; these are discussed in Chapter 3. Although these model results are consistent with one another, the remaining unknowns with respect to the overall effects of increasing Earth's albedo raise the risks if they are not well understood before embarking on any deployment.

Nonetheless, climate models, observations of volcanic effects, and basic physical theory indicate that it would be possible for humans to cool Earth within a few years after deployment by reflecting more sunlight to space. Some assessments have been made on the feasibility of deploying albedo modification methods (see Chapter 3 below). Engineering analysis suggests that at least some of the proposed methods to achieve substantial cooling may be within the realm of technological feasibility and would have relatively modest direct costs, not including, however, the costs of the necessary control and monitoring infrastructure. The accuracy with which a targeted degree of cooling can be achieved is unclear, and indirect costs of potential damages have not yet been quantified and could be substantial. For these reasons, there has been interest in learning more about albedo modification proposals.

There are a number of hypothetical but plausible scenarios in which deployment of albedo modification might be considered. One scenario is a response to sudden and severe climate change, which is sometimes referred to as a "climate emergency." If, for example, global warming resulted in massive crop failures throughout the tropics (e.g., Battisti and Naylor, 2009), there could be intense pressure to temporarily reduce temperatures to provide additional time for adaptation.[1] In such circumstances, there could be demands for immediate deployment of albedo modification, even in the absence of a rigorous assessment of the implications or an adequate monitoring system.

It has also been suggested that albedo modification with strictly limited magnitude might be initiated without waiting for a climate emergency to occur (Burns, 2011; Keith, 2013; Wigley, 2006). For example, the international community might agree to a gradual phase-in of albedo modification to a level that is expected to create a verifiable modification of Earth's climate (e.g., 1 W/m^2) as a large-scale field trial aimed at gaining experience with albedo modification in case it needs to be scaled up in response to a later climate emergency. A limited deployment of albedo modification might also be considered as part of a portfolio of actions to reduce the risks of climate change.

Finally, as a matter of physical and economic capability, a single nation, a large corporation, or a group of individuals with sufficient means could potentially deploy albedo modification in the absence of an international consensus or coordination (Bodansky, 2011; Victor et al., 2009). Such attempts might begin at small scales (e.g., a few small ships for modification of low clouds) or as an attempt to modify regional climate (e.g., an attempt to restore a failed Indian monsoon or to ameliorate a severe European heat wave). However, in practice, unilateral capability is likely to be limited to those states with significant political and economic power and world stature, such that it would be difficult or costly for others to make them stop an unsanctioned albedo modification program through the threat or act of military attacks against deployment devices and associated infrastructure (Parson and Ernst, 2013). There is also the possibility, however, that similar countermeasures could be used by a sufficiently powerful dissenter against a sanctioned deployment by other nations.

As described in the next section, such scenarios bring with them a wide range of concerns and a likelihood of unintended consequences (also see Robock, 2014). It is these risks and concerns that form the chasm between what may be technically feasible and what might constitute wise and prudent action. Substantial research would be required and understanding developed before this gap could be bridged, and such

---

[1] Albedo modification would not be an effective response to some types of climate emergencies, such as a rapid collapse of the West Antarctic ice sheet, which are not driven by surface air temperatures (Barrett et al., 2014).

research should be done before albedo modification is seriously considered. The unilateral and uncoordinated actor scenario raises questions of how we could detect albedo modification activities and attribute changes in climate to such activities. Arguments to oppose such unilateral action would be bolstered by better understanding of the underlying science of the albedo modification, its detection, and its unintended consequences. The state of knowledge on these techniques and future research directions are discussed in Chapter 3.

COMPARISON OF SOME BASIC RISKS ASSOCIATED WITH ALBEDO MODIFICATION

The increase in greenhouse gas concentrations from anthropogenic emissions introduces many risks to the planet. Deploying albedo modification could produce a generally cooler climate, but it would introduce risks of a different type. Compensation by albedo modification is only approximate, and some manifestations of high CO_2 concentrations are not addressed at all. This imprecise compensation implies that there could be regional disparities in the distribution of benefits and risks (Kravitz et al., 2014; Moreno-Cruz et al., 2012), and a means would need to be found to agree on the right mix of albedo modification in the portfolio of responses, if it were ever to be deployed (Ricke et al., 2013). Any of these decisions, however they are made, would benefit from a more informed understanding of the nature of the climate response. The bulk of this report is devoted to reviewing the extent to which the response is understood currently and the research agenda needed to address questions that remain open.

Poorly Understood and Regionally Heterogeneous Consequences for the Climate System

Earth's albedo is governed by cloud, water vapor, aerosols, land surface, and sea ice processes that link dynamically to all other aspects of the climate system, all of which are affected by both addition of anthropogenic greenhouse gases to the atmosphere and actions aimed at increasing the albedo. The uncertainties in modeling of both climate change and the consequences of albedo modification make it impossible today to provide reliable, quantitative statements about relative risks, consequences, and benefits of albedo modification to the Earth system as a whole, let alone benefits and risks to specific regions of the planet. To provide such statements, scientists would need to understand the influence of various possible activities on both clouds and aerosols, which are among the most difficult components of the climate system to model and monitor.

Albedo modification can in principle reduce the annually averaged global mean temperature to a given target level, but the resulting climate will be different in a number of important ways from the low-CO_2 climate with natural albedo. There is potential for substantial consequences to other aspects of the climate system, including precipitation; regional temperature; atmospheric and oceanic circulation patterns; stratospheric temperature, chemistry, and dynamics; and the amount and characteristics of sunlight reaching the surface (see sections in Chapter 3 on modeling and environmental consequences).

The geographical and seasonal distribution of radiative forcing due to albedo modification is substantially different from that arising from a decrease of CO_2. The atmosphere and ocean respond to radiative forcing by redistributing the heat in a way that alleviates the mismatch, but this requires changes in circulation patterns and also can leave regional climate anomalies uncompensated to one extent or another. Additionally, increasing albedo alters the surface energy budget by reflecting sunlight that would otherwise sustain evaporation (and hence precipitation); this can have effects on precipitation patterns. The ratio of change in precipitation to change in temperature is greater for a change in albedo than it is for a change in carbon dioxide content. Furthermore, albedo modification does not address the ocean acidification problem (Matthews et al., 2009), which, in the absence of ocean alkalinization (see Box 2.4), is an

BOX 2.4 OCEAN ACIDIFICATION

Albedo modification techniques could address some, but not all, of the consequences of rising atmospheric carbon dioxide that extend well beyond alterations in the radiative balance of the planet and climate change. Of particular importance, the ocean uptake of excess atmospheric carbon dioxide—the excess above preindustrial levels driven by human emissions—causes well-understood and substantial changes in seawater chemistry that can negatively affect many marine organisms and ecosystems (Doney et al., 2009; Gattuso and Hansson, 2011).

The additional carbon dioxide causes direct changes in seawater acid-base and inorganic carbon chemistry in a process often termed ocean acidification. Long-term ocean acidification trends are clearly evident over the past several decades in open-ocean time-series and hydrographic survey data, and the trends are consistent with the growth rate of atmospheric carbon dioxide (see Figure) (Doney, 2013; Doney et al., 2014; Dore et al., 2009).

The biological impacts of ocean acidification arise both directly—via effects of elevated carbon dioxide, lower pH, and lower carbonate ion concentrations on individual organisms—and indirectly—via changes to the ecosystems on which they depend for food and habitat (Doney et al., 2009, 2012). Ocean acidification leads to a decrease in the saturation levels of calcium carbonate ($CaCO_3$), a hard mineral used by many marine microbes, plants, and animals to form shells and skeletons. The potential biological consequences due to acidification are slowly becoming clearer at the level of individual species, but substantial uncertainties remain, particularly at the

BOX 2.4 CONTINUED

ecosystem level (Doney, 2013; Gattuso and Hansson, 2011). Ocean acidification acts as a stress on marine ecosystems and will likely also exacerbate other human perturbations such as climate change, overfishing, habitat destruction, pollution, excess nutrients, and invasive species.

The magnitude of ocean acidification and biological impacts is related to the concentration and growth rate of excess atmospheric carbon dioxide. Thus, approaches for mitigating future ocean acidification impacts require curbing human carbon dioxide emissions to the atmosphere and/or developing atmospheric carbon dioxide removal and sequestration methods. Proposed strategies for limiting the potential negative impacts of ocean acidification also include a combination of targeted adaptation strategies and evolving coastal management practices (Washington State Blue Ribbon Panel on Ocean Acidification, 2012).

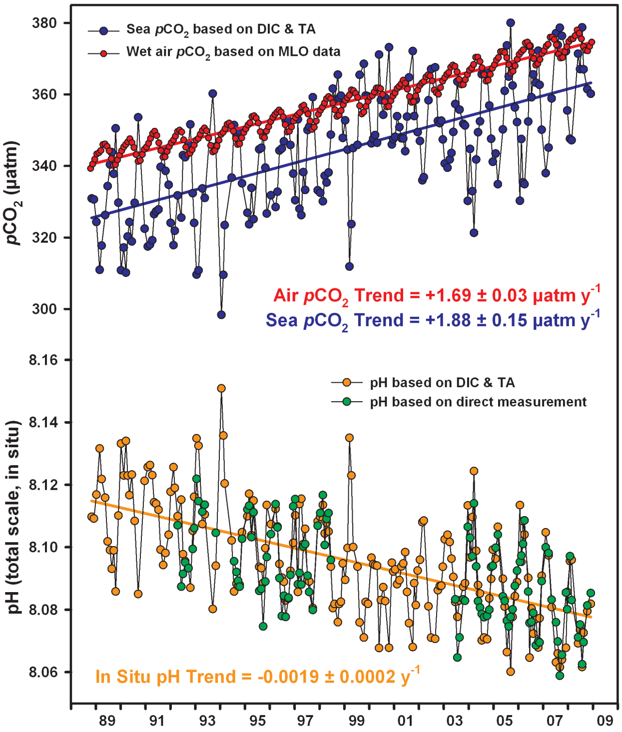

FIGURE Top: Time series showing the increase in dissolved CO_2 in the ocean and increasing ocean acidity (decreasing pH) over the past several decades. Partial pressure of CO_2 in seawater calculated from dissolved inorganic carbon (DIC) and total alkalinity (TA) (blue symbols) and in water-saturated air at in situ seawater temperature (red symbols). Bottom: Time series of mean carbonic acid system measurements within selected depth layers at Station ALOHA, 1988-2007. In situ pH, based on direct measurements (green symbols) or as calculated from DIC and TA (orange symbols), in the surface layer and within layers centered at 250 and 1000 m. SOURCE: Dore et al., 2009.

inevitable consequence of the uptake of CO_2 emissions by the oceans. (For the same reason, albedo modification does retain the benefits of CO_2 fertilization of land plants [Govindasamy et al., 2002].) These considerations apply to all albedo modification schemes and are discussed in detail in Chapter 3.

Additional considerations apply specifically to albedo modification techniques that involve stratospheric aerosols. Stratospheric aerosols heat the stratosphere at the same time they cool the surface, which can have important implications for the climate of both the stratosphere and the surface, as well as for stratospheric chemistry (see further discussion in Box 3.2 and stratospheric aerosol modeling sections in Chapter 3).

Intervening in the climate system through albedo modification therefore does not constitute an "undoing" of the effects of increased CO_2 but rather a potential means of damage reduction that entails novel and partly unknown risks and outcomes. Approaches that limit or reduce levels of CO_2 in the atmosphere address the major cause of human-induced climate change, whereas albedo modification attempts to counter some effects of high greenhouse gas concentrations without addressing the causes. This nonequivalence of climate states has a bearing on any decision that will ultimately be made regarding the proper place of albedo modification in the portfolio of responses to the problems caused by greenhouse gas emissions arising from human activities. Along the continuum of hypothetical climate futures—ranging from those with comparatively low CO_2 and little or no albedo modification (because greater reliance has been placed on mitigation and carbon dioxide removal [CDR]), extending to scenarios with unrestrained emissions and very high CO_2 and a correspondingly high degree of albedo modification—the risk increases as one moves toward higher CO_2 because the climate system is forced further outside the range in which it has known, historically established behavior. As one example of such a consequence, consider that if CDR were ramped up to very high levels to compensate very high levels of CO_2, one would expect the diurnal cycle of temperature to be reduced significantly with the potential for significant impacts on ecosystems.

The less CO_2 that humans release to the atmosphere, the lower the environmental risk from the associated climate change and the lower the risk from any albedo modification that might be deployed as part of the strategy for addressing climate change. It is widely recognized that the possibility of intervening in climate by albedo modification does not reduce the importance of efforts to reduce CO_2 emissions. Notably, an assessment by The Royal Society (Shepherd et al., 2009) concluded that "[g]eoengineering methods are not a substitute for climate change mitigation, and should only be considered as part of a wider package of options for addressing climate change." The findings of this committee, summarized in Chapter 5, support this conclusion.

Timescale Mismatch, Risks of Millennial Dependence, and Constraints on Strategies for Limiting the Duration of Reliance on Albedo Modification

Another important difference between an albedo-modified high-CO_2 state and the preindustrial state arises from the mismatch in timescales between the high rate of dissipation of substances introduced into the atmosphere, for the purposes of modifying albedo, and the very low rate of removal of CO_2 from the atmosphere by natural processes. Marine cloud brightening dissipates in a matter of days to weeks after the cessation of active climate intervention, and stratospheric aerosols dissipate within 1 to 2 years (as evidenced by the lifetime of volcanic forcing). In contrast, the climate forcing due to CO_2 persists for millennia even if emissions cease (Archer et al., 2009; NRC, 2011a; Solomon et al., 2009).

If CO_2 emissions into the atmosphere were not reduced and instead albedo modification was relied on as the primary means to avoid CO_2-induced warming, the amount of albedo modification required would continue to escalate as atmospheric CO_2 concentrations increased. This scenario of increasing reliance on albedo modification coupled with increasing atmospheric CO_2 concentrations is a scenario of profoundly increasing risk. As the albedo modification system was ramped up, negative consequences would likely amplify because at higher CO_2 levels imperfections and nonlinearities in the attempted climate change cancellation would become more pronounced (Bala et al., 2003). Furthermore, as the amount of CO_2 in the atmosphere and the scale of offsetting albedo modification effort increases, termination, whether it be gradual or sudden, becomes more problematic and risky. If albedo modification activities are ceased abruptly, rapid warming of potentially large magnitude will ensue (the magnitude rising with the level of CO_2 being dealt with).

The committee refers to the set of potential challenges that may confront such long-term maintenance of albedo modification in this class of deployments as the problem of millennial dependence risk. These issues are discussed at length in Chapter 3.

OVERVIEW OF THE ALBEDO MODIFICATION ASSESSMENT

Rather than discuss every potential means of modifying Earth's albedo that has been proposed, this report focuses on the two strategies that have received the most attention and which may most feasibly have a substantial climate impact: stratospheric aerosol injection and marine cloud brightening. The stratospheric aerosol and marine boundary layer cloud schemes are the ones that have been most extensively studied so far, and they are also the ones that are the closest to being deployable in the limited sense of technical ability to inject sufficient material into the atmosphere to cause a significant (if not necessarily well-controlled) modification to Earth's albedo. The physical basis of these techniques, their technical feasibility, the nature of the climates produced when they are used to partly offset the effects of high CO_2, and the physical risks involved are discussed in detail in Chapter 3.

Other proposed albedo modification techniques include placing large arrays of reflecting satellites in space or altering the reflectivity of the land or ocean surface. As described in the Chapter 3 section "Other Methods," these other proposed techniques are generally either prohibitively expensive or difficult to scale to the point where they could offset a substantial amount of CO_2 radiative forcing. Proposals to modify cirrus clouds, which are not formally an albedo modification method but use another means to modify the planet's energy balance, have received less attention thus far and are also discussed briefly in this section.

One of the charges of this committee is to assess the technical feasibility of albedo modification techniques. Although it might be possible to deploy albedo modification procedures rapidly and at modest expense (in comparison with the cost of rapidly decarbonizing the world economy), doing so would entail substantial risk and uncertainty. The risk of inadvertent and possibly harmful side effects is increased in the absence of adequate monitoring needed to determine what climate forcing was actually achieved by a given intervention. Some preliminary work based on control theory analysis (MacMartin et al., 2014) suggests that it may be possible to design intervention strategies that rely on temperature measurements alone, but it is unclear at present whether such strategies can actually be implemented by known ways of affecting albedo. The infrastructure needed to accurately monitor albedo and aerosols involves developing capabilities to model the albedo modification caused by a particular injection protocol, to observe the resulting change in aerosol content and albedo of the atmosphere to determine what modification was actually achieved, and to detect the response of climate to the modification. There is considerable uncertainty about whether it would be possible to create an observational infrastructure that would greatly reduce unnecessary risk. If it were possible, the amount of time and resources it would take to develop such an infrastructure is also at present unsettled. This is a crosscutting issue that applies to all albedo modification techniques, and therefore it forms a key part of our feasibility assessment in Chapter 3.

Sociopolitical issues raised by the prospect of climate intervention by albedo modification are taken up in Chapter 4, including a discussion of governance that might be required in order to regulate experiments on albedo modification that involve controlled emissions. Many of the risks associated with albedo modification are sociopolitical in nature. These are among the hardest risks to assess, and the expertise to perform such an assessment is for the most part beyond the capabilities of the committee. Though the chief recommended actions in this report are to move forward with research but not with deployment, expansion of research in albedo modification is not without risk, and most of the risks are sociopolitical in nature; on the other hand, ignorance (through failure to carry out research) of consequences of albedo modification deployment also entails considerable risk. In Chapter 5, the committee suggests a way forward toward appropriate research on albedo modification, synthesizing findings from the present report with insights derived from the committee's report on CDR technologies.

CHAPTER THREE

Technical Analysis of Possible Albedo Modification Techniques

This chapter reviews a number of proposed strategies for minimizing the damage and risks from climate change by modifying Earth's energy budget. The chapter begins with a discussion of idealized studies that provide insight into the general response of the climate system to albedo changes. Two more realistic strategies (stratospheric aerosol injection and marine cloud brightening) are then discussed in greater detail because studies suggest they have the potential to produce a significant cooling and/or they have been discussed more widely in the literature. Other methods that have received less attention or appear to be impractical are discussed briefly later in the chapter, followed by a discussion of observational problems concerning Earth's radiation budget and climate response to albedo modification that are common to all albedo modification techniques. This chapter concludes with a series of tables summarizing the committee's assessment of various aspects of these albedo modification strategies.

IDEALIZED SIMULATIONS OF THE EFFECTS OF ALBEDO MODIFICATION

Although simple energy balance principles, backed up by observations of volcanic cooling, are sufficient to establish that reducing the amount of solar radiation absorbed by Earth can reduce the global mean surface temperature, they do not constrain the geographic or seasonal pattern of temperature that would prevail in an albedo-modified world. These patterns are determined not only by the top-of-atmosphere fluxes, but also by the transport of heat and moisture by atmospheric circulations, the transport of heat by ocean circulations, and various complex regional feedbacks including changes in cloud properties. These processes are represented, with varying degrees of fidelity, in atmosphere-ocean general circulation models (GCMs). Representation of the complex chain of processes linking a specific climate intervention (e.g., injection of SO_2 gas into the stratosphere) to the resulting albedo change poses very considerable challenges. Idealized simulation studies bypass the modeling of this complex chain of events, instead directly imposing a reduction in absorbed solar radiation. Earth's near-surface environment is the product of a complex interacting system involving physics, chemistry, and biology of the land, ocean, and atmosphere. This real system has far greater complexity than does any model, and thus no model of this system can provide a quantitatively reliable detailed prediction of how Earth will respond to a novel occurrence. Nevertheless, model simulations and theory do suggest some basic properties of the response of the climate system to reductions in the amount of sunlight absorbed.

There is no known way to modify albedo to yield a pattern of top-of-atmosphere solar radiative forcing that is similar (seasonally and geographically) but of opposite sign and amplitude to the radiative forcing pattern due to an increase of CO_2 (see, for example, Figure 3 of Kravitz et al., 2013a). A change in albedo has little or no effect at night or in mid- to high-latitude winters, where there is little or no sunlight to reflect, but these areas are influenced by CO_2 radiative forcing. A spatially uniform decrease in sunlight also leads to more radiative forcing in the tropics than near the poles, because the annual mean incident solar radiation is greater in the tropics. Even if CO_2 and albedo changes could cause the same change in the top-of-atmosphere energy balance, they would cause different changes in the surface energy budget; hence, any albedo modification designed to cancel out the top-of-atmosphere CO_2 radiative forcing will cause changes in the surface energy budget, relative to the preindustrial state (Bala et al., 2008; Pierrehumbert, 2010, Chap. 6). The climate response may be geographically more similar than the forcing since the atmospheric and ocean circulation processes that redistribute energy are the same for CO_2 radiative forcing and albedo change (Govindasamy and Caldeira, 2000). Idealized simulations can shed light on how the climate system responds to these disparities in forcing. The idealized experiments do not, however, address the question of how closely the targeted reduction in solar absorption can be met through the various proposed albedo modification techniques.

Solar-Constant Experiments

In the hierarchy of attempts to simulate the effects of albedo modification, the most idealized experimental protocol is to reduce the global mean absorption of sunlight by simply reducing the amount of sunlight incident on the top of the atmosphere. This quantity is characterized by a parameter known as the "solar constant," which is a measure of the power output of the Sun. The amount of solar energy absorbed by Earth in a simulation can be reduced by any desired amount by simply dialing down the value of the solar constant in a model, which is essentially equivalent to reducing the brightness of the Sun. This protocol is easy to implement in any climate model and, therefore, is well suited to multimodel comparison projects. The forcing achieved in solar-constant experiments has a lot in common with that resulting from introducing a very uniform aerosol layer into the stratosphere (Kalidindi et al., 2014), but it has less in common with the more inhomogeneous forcing resulting from marine cloud brightening or regionally limited modifications of stratospheric aerosols. Solar-constant experiments provide considerable insight into the fundamental climate processes involved in determining the joint response to increased CO_2 and reduced solar absorption, but they do not incorporate some important effects connected with the vertical redistribution of heating in that atmosphere, notably the stratospheric heating that would result from increasing the stratospheric aerosol content (Kalidindi et al., 2014). They also do not incorporate the effects of injected substances on atmospheric chemistry, on cloud properties, or on the transformation of direct-beam to more diffuse sunlight.

There is by now a quite considerable literature on solar-constant experiments, which the committee does not attempt to survey comprehensively. Earlier work with sunlight reduction studies is reviewed by Caldeira et al. (2013). The most extensive analysis of solar-constant experiments has been carried out as part of the G1 experiment of the multimodel intercomparisons of the Geoengineering Model Intercomparison Project (GeoMIP) (Kravitz et al., 2013a; see Box 3.1), which allow a search for robust signatures using a standard experimental design. Because the GeoMIP simulations are of limited duration (under a century), the deep ocean does not have time to come into equilibrium with the climate forcing. These G1 and $4\times CO_2$ (a quadrupling of the CO_2) simulations therefore do not provide an indication of how the climate would evolve if the albedo modification were maintained for centuries, allowing the deep ocean to respond, although because the changes in surface flux (heat, moisture, momentum) are much smaller than the changes produced by CO_2 forcing the ocean response is also smaller. These conclusions should apply generally to all albedo modification simulations done so far, including those with a more sophisticated representation of the albedo modification process.

Here the committee highlights only a few key results of the G1 experiment of GeoMIP. Figures 3.1 and 3.2 show temperature changes produced from a quadrupling of CO_2, and the result of a reduction in sunlight sufficient to return the global average surface

BOX 3.1 GEOENGINEERING MODEL INTERCOMPARISON PROJECT (GEOMIP)

More than a dozen modeling groups have participated in a modeling intercomparison project—referred to as GeoMIP—to examine the effects of albedo modification (Kravitz et al., 2011a). The first set of experiments as part of the fifth phase of the Coupled Model Intercomparison Project (CMIP5) focused on four scenarios related to stratospheric aerosol albedo modification (Kravitz et al., 2013a), but other experiments under this framework will add experiments on marine cloud brightening and cirrus thinning.

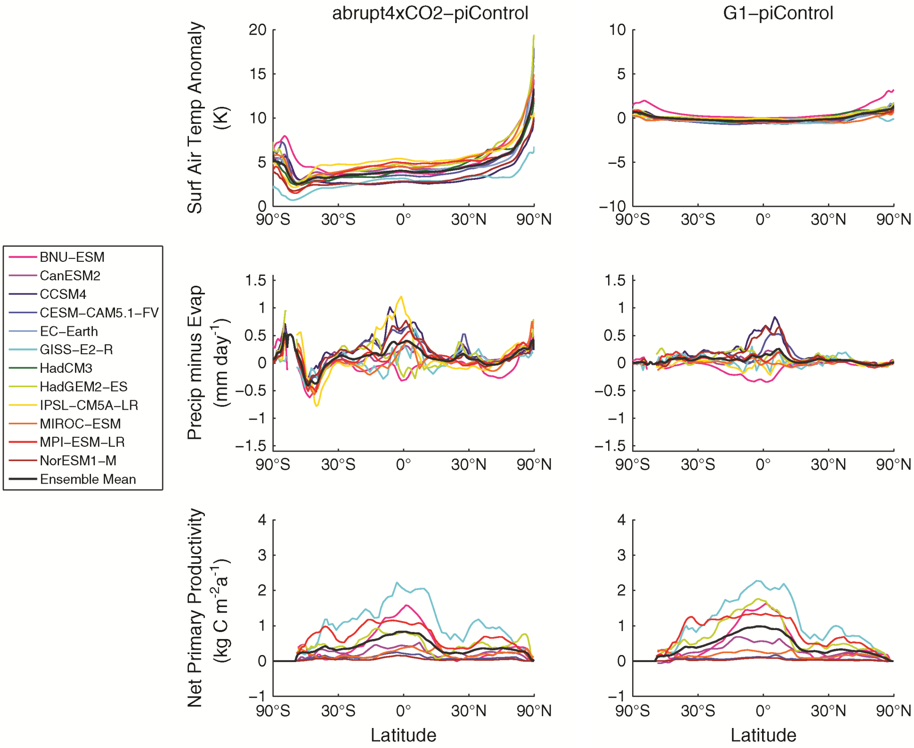

FIGURE 3.1 Zonal average anomalies in surface air temperature (K; land + ocean average; 12 models), precipitation minus evaporation (mm/day; land average; 12 models), and terrestrial net primary productivity (kg C m^{-2} yr^{-1}; land average; 8 models) for all available models. All values shown are averages over years 11-50 of the simulations. The *x* axis is weighted by cosine of latitude. SOURCE: Kravitz et al., 2013a.

temperature to a reference (approximately preindustrial) state. The reduction in sunlight reduces the mid- to high-latitude warming, which exceeds 5°C at the South Pole and 10°C at the North Pole, to about 1°C and reduces the surface temperature change in the tropics from about 5°C warmer (4×CO_2 simulation) to 0.2°C to 0.5°C cooler (G1 simulation) than the reference states. This general pattern, which is robust across all solar-constant experiments, occurs because reducing the solar constant in such a way as to offset the global mean CO_2 radiative forcing undercompensates this forcing in the high latitudes (where there is comparatively little sunlight to reflect) but makes up for it in the global mean by overcompensating in the more highly illuminated tropical regions. Atmospheric and oceanic heat transports redistribute the excess heating from one place to another, which reduces the geographic inhomogeneity of the tempera-

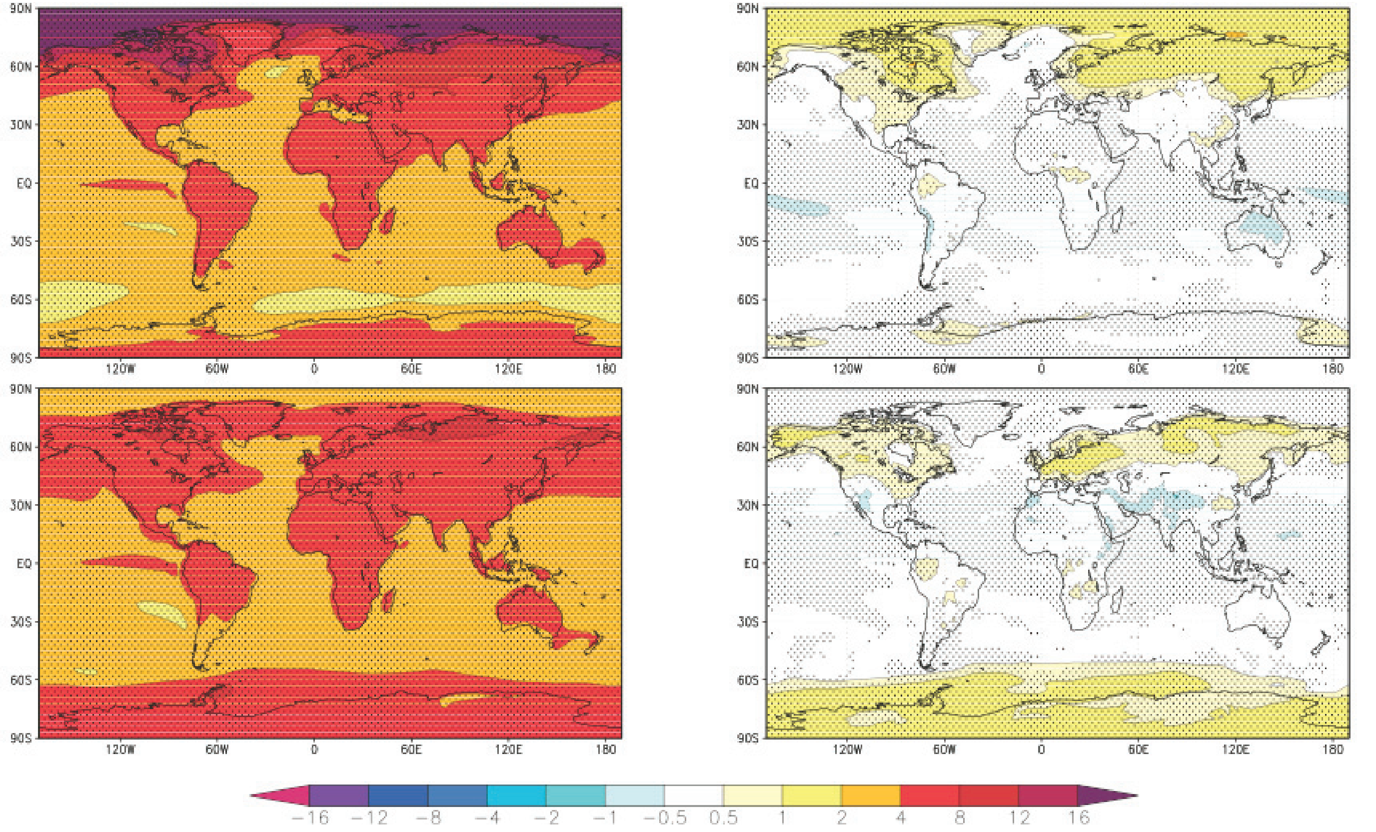

FIGURE 3.2 Left: Temperature changes produced from a quadrupling of CO_2. Right: The resulting temperature change from a reduction in sunlight sufficient to return the global average surface temperature to a reference state (approximately preindustrial state). Results are for all-model ensemble annual average surface air temperature differences (K) averaged over years 11-50 of the simulation. Top row shows December-January-February average, and bottom row shows June-July-August average. Stippling indicates where fewer than 75% of the models (for this variable, 9 out of 12) agree on the sign of the difference (typically where projected temperature changes are small). SOURCE: Kravitz et al., 2013a.

ture response but does not eliminate it. Despite the agreement among models on the latitudinal pattern of temperature responses, there is considerable disagreement among the models in the GeoMIP G1 ensemble as to the sign of the temperature response over much of the tropical land area because there are very small changes in those areas.

Figure 3.3 summarizes the global mean precipitation response in the GeoMIP G1 experiment albedo modified states. Energy is required to sustain evaporation and precipitation must ultimately balance evaporation, so the surface energy balance plays an important role in determining precipitation changes. Reduction in the amount of sunlight reaching the surface tends to decrease precipitation, especially in the warm tropics (Pierrehumbert, 2002, 2010, Chap. 6). Stabilization of the surface layer produced by changes in heating and cooling rates (the result of heating aloft from CO_2 concentration increases, and sunlight reduction reducing surface heating) reduces mixing near the surface, causing further changes in both evaporation and precipitation (Cao et al., 2012; Gregory et al., 2004; Kravitz et al., 2013b). As expected from these fundamental theoretical considerations, the combination of CO_2 and absorbed sunlight sufficient to

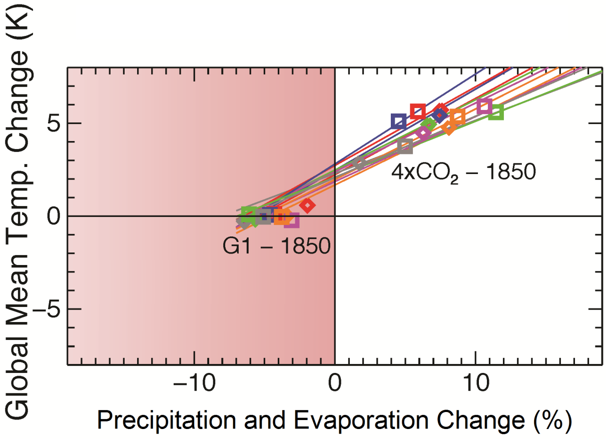

FIGURE 3.3 Global mean precipitation and temperature changes in GeoMIP experiment G1, relative to the preindustrial state. Each symbol represents the results of an individual model in the ensemble. Results for the unmodified 4×CO_2 state are also shown, for comparison. The G1 simulations were designed to restore global mean radiative balance, not global mean precipitation and evaporation (on the global mean, precipitation equals evaporation). If the goal were to restore global mean precipitation (and evaporation), the model simulations would have projected some residual warming. For each model, a linear fit (colored line) is derived from annual and global precipitation changes versus temperature changes between 4×CO_2 experiment and 1850 conditions using the first 10 years of each simulation. SOURCE: Based on Tilmes et al., 2013.

restore the preindustrial value of global mean temperature reduces evaporation and precipitation relative to the preindustrial state. The amount by which evaporation and precipitation are reduced varies considerably from one model to another, and analysis of the mechanisms accounting for the intermodel spread is a subject requiring further research. One could in principle aim to compensate for CO_2-associated temperature changes or precipitation changes (or some combined metric) but one could not simultaneously eliminate both global mean temperature changes and global mean precipitation changes (Ban-Weiss and Caldeira, 2010).

The climate system's response to the joint effects of an increase in CO_2 and a decrease in absorbed solar radiation is complicated by the land-sea contrast. Changes in the hydrological cycle over land are strongly affected by the land's smaller and varied heat capacity, flow driven by terrain changes, and albedo variations, driving complex circulation changes that transport moisture to and from land masses. Figure 3.4 shows the pattern of changes in the hydrological cycle in the GeoMIP G1 ensemble simulations. Albedo modification affects both precipitation (shown in the top row) and evaporation (shown in the middle row). Net atmospheric water vapor transport to specific locations equals the balance of precipitation minus evaporation (P – E, shown in the bottom row of Figure 3.4).

The precipitation changes shown in Figure 3.4 are regionally inhomogeneous. Reduction in sunlight reduces the CO_2-induced increase in extratropical precipitation. These albedo modification simulations were performed with the goal of offsetting top-of-atmosphere radiation imbalance and not for optimizing hydrologic quantities. Because the contour interval was chosen so as to reveal the global pattern, which is dominated by high precipitation and high precipitation changes in the tropics, this figure does not characterize the residual extratropical precipitation anomaly prevailing in the albedo-modified case (upper right panel). Globally averaged root-mean-square (RMS) changes in annual mean precipitation at model grid scale caused by high CO_2 levels are reduced by about 55 percent in these albedo modification simulations; over land, these RMS changes in precipitation are reduced by about 50 percent (Kravitz et al., 2013b).

The tropics primarily exhibit reductions in precipitation, except for a narrow strip over the Pacific Ocean. The ensemble of models robustly shows less precipitation and evaporation over the Amazon basin (relative to preindustrial levels), but there is substantial disagreement as to the sign of the precipitation response over Africa. Given that the unmodified high-CO_2 state also shows considerable regions of reduced precipitation, the situation could be crudely summarized by saying that a globally uniform reduction in sunlight is better at eliminating CO_2-induced increases in precipitation than it is at eliminating CO_2-induced reductions in precipitation. In these simulations, sunlight

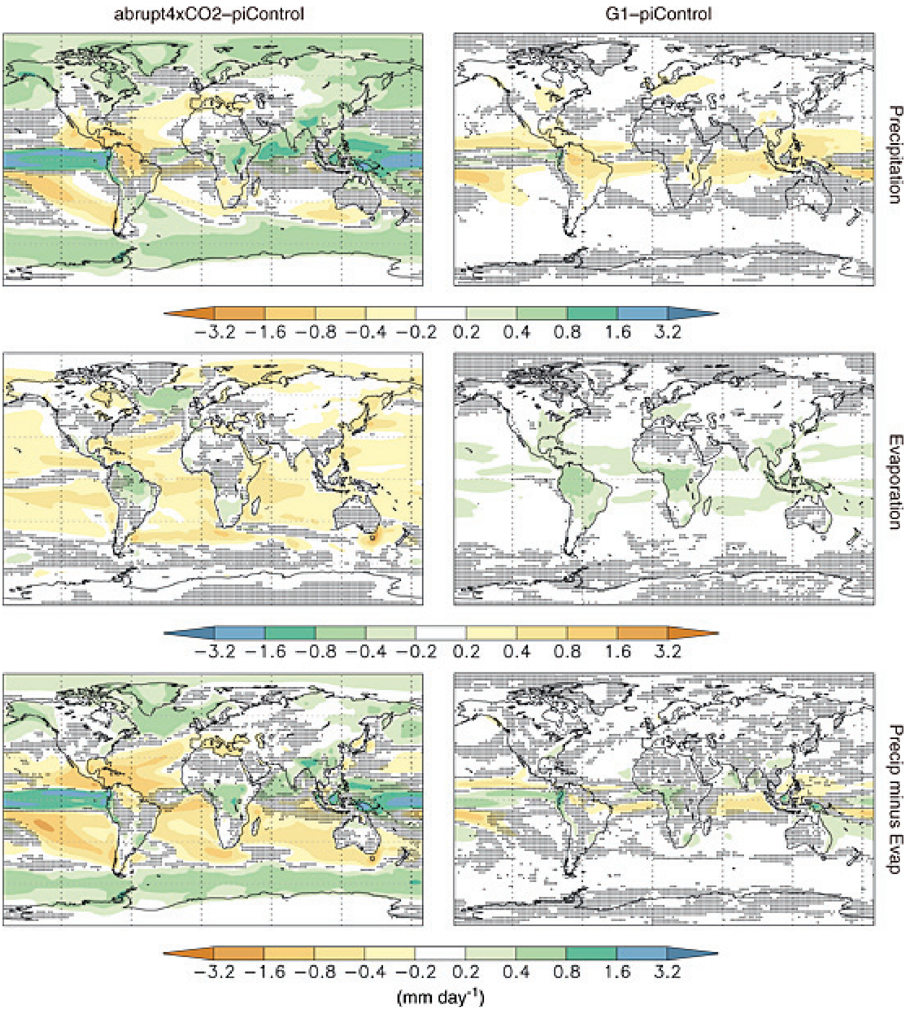

FIGURE 3.4 Average hydrology changes produced from a quadrupling of CO_2 (left column) and the result of a reduction in sunlight sufficient to return the global average surface temperature to a reference state (approximately preindustrial state; right column). Results are for all-model ensemble annual average hydrology differences (mm/day) averaged over years 11-50 of the simulation. Top row shows precipitation, middle row shows evaporation, and bottom row shows precipitation minus evaporation. Stippling indicates where fewer than 75 percent of the models (for this variable, 9 out of 12) agree on the sign of the difference. SOURCE: Kravitz et al., 2013a.

reduction reduces the amount of change in precipitation caused by high CO_2 levels, but the pattern of reduced precipitation zones in the sunlight-modified state still differs appreciably from that in the unmodified high-CO_2 state.

Figure 3.4 (middle row) also shows that in the sunlight-modified state evaporation decreases as well as precipitation, especially over land. The changes in evaporation have a spatial pattern that is similar to that for precipitation changes, but they are opposite in sign (Kravitz et al., 2013a). Globally averaged RMS changes in annual mean evaporation at model grid scale are reduced by about 39% in these albedo modification simulations; in contrast, over land, RMS changes in evaporation increase by about 10% (Kravitz et al., 2013b), largely due to the biophysical effects of CO_2 resulting in the reduced evaporation from land plants no longer being offset by the acceleration of hydrological cycle response to warmer temperatures. The tropics exhibit widespread areas with reductions in evaporation, including over the Amazon basin and central Africa.

The change in precipitation minus evaporation (shown in the bottom row) provides an indication of the change in the amount of moisture imported to land areas, which in steady state is equal to runoff in rivers and streams. Areas in which there is substantial runoff are usually places where there is sufficient soil moisture to maintain plant life. Over much of the land area evaporation changes approximately equal changes in precipitation, with a few exceptions (e.g., drying in some parts of the Amazon and moistening in some parts of Africa). Larger shifts in the net moisture supply are seen in the unmodified high-CO_2 state over even broader areas; thus, in these simulations, the sunlight reduction reduces but does not eliminate these effects of high CO_2 concentrations. Over the ocean, precipitation minus evaporation is the difference of two large numbers, each subject to modeling challenges; the residual has large associated uncertainties. Over land, maximum evaporation is bounded by precipitation, so the model can be thought of as predicting the fraction of precipitation that evaporates, which is a number ranging from 0 to 1. Over much of the land, absolute magnitudes of changes in precipitation minus evaporation are small, and thus there is considerable disagreement as to sign among the models in the ensemble. Nonetheless, the general implication is that regions experiencing a reduction in precipitation do not necessarily become more arid; rather, the situation could be described as the hydrological cycle spinning down by 5 percent to 10 percent (Figure 3.2), with less rain falling but less rain evaporating back into the atmosphere. Globally averaged, albedo modification decreased the RMS difference in annual mean precipitation minus evaporation at grid-scale resolution by about 66 percent relative to the high-CO_2 case without albedo modification; over land, albedo modification reduced RMS differences in precipitation minus evaporation by about 53 percent, despite the fact that these simulations were not designed to optimize the reduction in water delivery to land (cf. Ban-Weiss and

Caldeira, 2010). More research is needed to evaluate the impact of this altered climate state on agriculture, natural ecosystems, and water resources.

Because land responds quickly to insolation changes, the response of the seasonal cycle to albedo modification is expected to be different over land versus ocean, leading to changes in the seasonal cycle of the land-sea contrast which may affect precipitation patterns through their influence on atmospheric circulations, especially in the tropics. Additionally, even when the land-sea temperature contrast approaches equilibrium, the land surface has a tendency to cool more than the ocean (Joshi et al., 2013). When the land surface cools more than the ocean, this tends to cause air masses to ascend less rapidly or descend more rapidly over land and vice versa over the ocean, which would tend to weaken summer monsoonal circulations and thus contribute to a reduction in precipitation over land in response to deployment of albedo modification (Cao et al., 2012). This tendency toward weakening of the monsoons is in the opposite direction of a similar tendency for CO_2-induced warming to strengthen monsoons, but the two effects do not precisely cancel out.

Figure 3.5 shows the response of the monsoon precipitation and evaporation in various regions to CO_2 with and without sunlight reduction at a level that fully offsets the top-of-atmosphere energy balance from increased atmospheric CO_2. The figure confirms that increased atmospheric CO_2 concentrations tend to increase the strength of the monsoons, and that albedo modification has the tendency to reduce monsoon strength. These model results indicate that albedo modification at this level may overcompensate monsoonal strength, leaving some monsoons weaker than, but closer to, the preindustrial state (particularly over land) than the world without sunlight reduction. Albedo modification often produces evaporation changes that are similar in magnitude but opposite in sign to precipitation changes (Figure 3.1). Thus, in the albedo-modified GeoMIP simulations, no significant change in precipitation minus evaporation is seen relative to the preindustrial control in most monsoon regions, despite the fact that these simulations were not optimized to achieve this objective (Kravitz et al., 2013b). If the goal were to restore monsoonal strength to a level optimized to match a preindustrial world, the albedo modification may need to be applied at a reduced level, which would likely leave some residual global warming. There is considerable regional disparity in the monsoon response among models, making it difficult or impossible to tune the sunlight reduction strategy so as to optimize the response in all regions. There is also a large spread in predictions of monsoon response. At this level of sunlight reduction, the Indian monsoon response in the albedo-modified state ranges from about a 10 percent increase to about a 15 percent decrease. This underscores the difficulty of predicting monsoon response with the current state of modeling—with or without taking albedo modification into account.

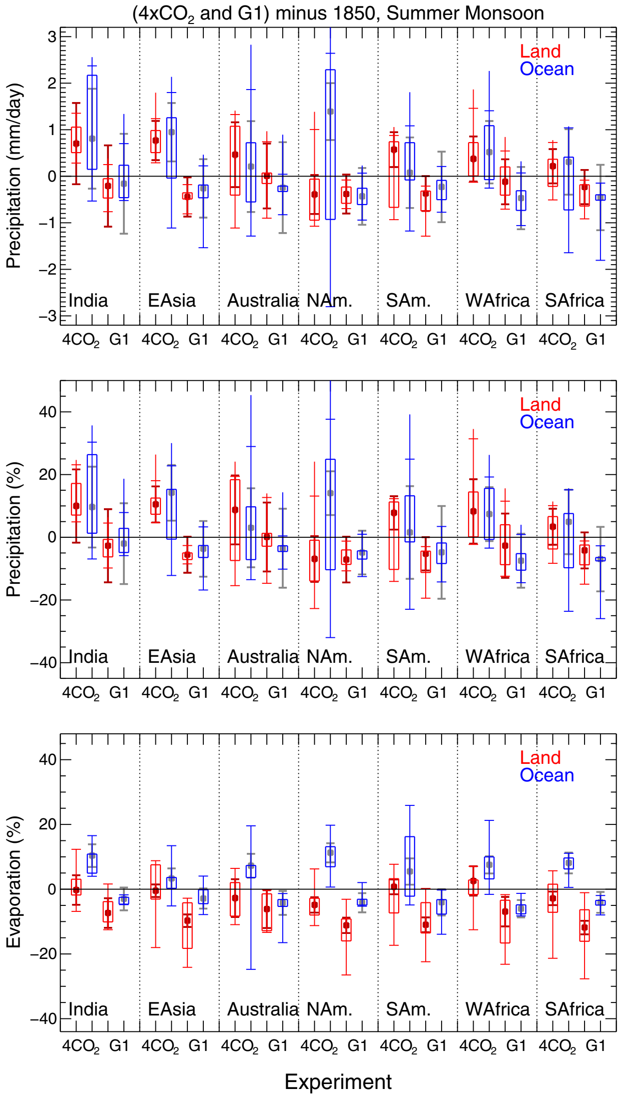

FIGURE 3.5 Impact on the monsoon precipitation and evaporation for seven different regions around the globe. The left two values for each region show the perturbation due to a 4×CO$_2$ increase. The right two values show the effect of albedo modification at a level designed to balance the global top-of-atmosphere energy flux. The length of the whiskers indicates the uncertainty in model response. SOURCE: Tilmes et al. (2013).

Experiments with a Uniform Increase in Stratospheric Aerosol Optical Depth

The next step up in the hierarchy of complexity is to simulate stratospheric aerosol injection, assuming the stratospheric aerosol optical depth (essentially, a measure of the mass concentration of aerosol particles in the stratosphere) to be horizontally uniform and simply increasing it to produce a negative forcing sufficient to counter the CO_2 forcing. This approach is also fairly simple to implement in a wide range of climate models. Other studies, still quite idealized, rescale an externally calculated stratospheric aerosol optical depth, incorporating the effect of inhomogeneity of aerosol distribution, evolution of the particle size, and geographical distribution of aerosols. These idealizations do not account for feedbacks due to changes in stratospheric chemistry, but they do allow for the incorporation of at least some effects of stratospheric heating and a latitudinally and seasonally varying aerosol forcing. An extensive set of simulations of this sort is reported by Ricke et al. (2010, 2012), though these studies did not specifically analyze the effects of stratospheric heating. The results are broadly consistent with the GeoMIP study with regard to the pattern of temperature change and reduction in precipitation, but Ricke et al. (2010) analyzes a broader range of albedo modification magnitudes than was considered in GeoMIP. That study found that, when greater amounts of albedo modification were applied to offset the warming from higher CO_2 concentrations, the regional deviations in temperature and precipitation from the preindustrial climate became more pronounced, but in almost all places the changes were much reduced relative to the high-CO_2 state in the absence of albedo modification. There were also substantial differences in the character of the climate deviation from the preindustrial state, even between regions as close as India and China (Figure 3.6) projected in these single-model simulations. (This is not the case in many simulations performed with the more idealized solar-constant protocol using many models seen in the lower left panels of Figure 3.4.) The range of albedo modification magnitudes covered in this simulation serves as a reminder that it is possible to choose different targets than simply restoring global mean temperature to its preindustrial value. For example, a small amount of albedo modification would bring the climate state of India and China closer to the preindustrial origin of Figure 3.6. In the earlier (lower-CO_2) case, it would be possible to choose a midrange amount of albedo modification, which would restore the temperature in China to its preindustrial value, while leaving the global mean warmer than preindustrial levels. However, this choice still leaves the precipitation in China lower than preindustrial levels, the temperature in India cooler than preindustrial levels, and the precipitation in India higher than preindustrial levels.

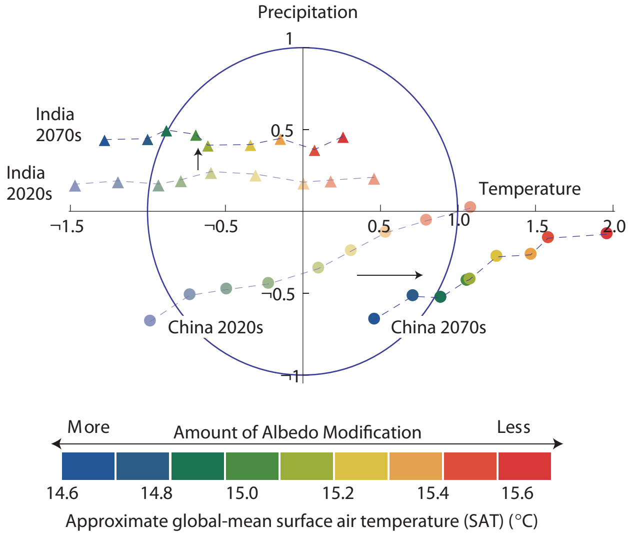

FIGURE 3.6 Modeled response to different levels of average global albedo modification over time in India and China. Interannual-variability-normalized regional temperature and precipitation summer (June, July, and August) anomalies (averages for the 2020s minus the 1990s, and the 2070s minus the 1990s) in units of baseline standard deviations for the region including India (triangles) and the region including eastern China (circles). Albedo-modified climates for these two regions migrate away from the baseline in disparate fashions. SOURCE: Modified from Ricke et al. (2010).

Risks of Dependence on and Abrupt Termination of Albedo Modification

Because CO_2 is removed from the atmosphere only slowly by ocean uptake and other geological processes, its climate forcing persists for millennia even if emissions cease, and the multimillennial influence becomes stronger as the cumulative amount of CO_2 emitted increases (Archer et al., 2009; NRC, 2011b; Solomon et al., 2009). Theoretically, it may be possible to withdraw this CO_2 from the atmosphere with carbon dioxide removal (CDR) technologies, but there are currently technical and economic barriers to implementation on a large scale (see companion volume *Climate Intervention: Carbon Dioxide Removal and Reliable Sequestration*).

In contrast to the long lifetime of CO_2 in the atmosphere, the atmospheric lifetime of substances that have been proposed for use in albedo modification are on the order of a year or less (as discussed in detail later in this chapter). Therefore, although it takes relatively little mass of injected aerosol particles (or precursor gases) to cause an albedo change sufficient to offset the radiative forcing due to a doubling or even quadrupling of CO_2, that aerosol mass would need to be renewed more or less continuously, as long as an offset for CO_2 forcing was intended.

One can imagine a large number of scenarios in which albedo modification might be deployed (e.g., MacMartin et al., 2014; Wigley, 2006), ranging from ones involving a short-term deployment to ones that require maintenance for millennia. The duration of the deployment affects the kind of climate risks that can be addressed.

Deployment of CDR could help provide an exit strategy within timescales as short as a century or so, for a broad range of albedo modification strategies, but, as mentioned above, deploying CDR at such scales is very challenging. Unless accompanied by CDR, albedo modification strategies whose goal is to limit peak warming in the absence of early and stringent emissions reduction would likely require that the deployment be maintained over the span of time required for natural processes to remove sufficient amounts of CO_2 from the atmosphere (which, for high CO_2 concentrations, could be millennia) or risk returning to the undesirable climate conditions that prompted the deployment initially. The class of risks associated with long-term reliance on albedo modification in this class of deployments can be called *millennial dependence risk*.

The Royal Society (2009) assessment rejected strategies requiring millennial dependence, finding that "[b]ecause of uncertainties over side effects and sustainability [albedo modification techniques] should only be applied for a limited period and accompanied by aggressive programmes of conventional mitigation and/or CDR, so that their use may be discontinued in due course" (Royal Society, 2009, Recommendation 3.3). To illustrate some issues associated with deployments aimed at permanently avoiding CO_2-induced warming, and to bring the timescale issue into sharper focus, the committee considers the examples of climate intervention proposals aimed at offsetting the long-term warming due to CO_2 emissions in the extended representative concentration pathway (RCP)4.5 and RCP6.0 emissions scenarios (Zickfeld et al., 2013). RCP4.5 assumes fairly aggressive emissions controls, though not quite sufficient to keep warming under 2°C; RCP6.0 assumes less restrained emissions. The top panels in Figure 3.7 show the CO_2 radiative forcing in the two RCP scenarios. In both scenarios, the rate of CO_2 emission peaks on or before the year 2100, the rate of CO_2 emission declines sharply thereafter in such a way as to keep concentration fixed for the next 200 years, and emissions cease entirely by the year 2300. Substantial amounts of radiative forcing persist for many centuries after the cessation of emissions. The combined green- and red-shaded regions in the top panels show the amount of radiative forcing that would need to be offset by albedo modification in order to keep the net radiative forcing below 2.5 W/m^2, which is approximately what would need to be done in order to keep the CO_2-induced warming under 2°C, assuming a midrange climate sensitivity;

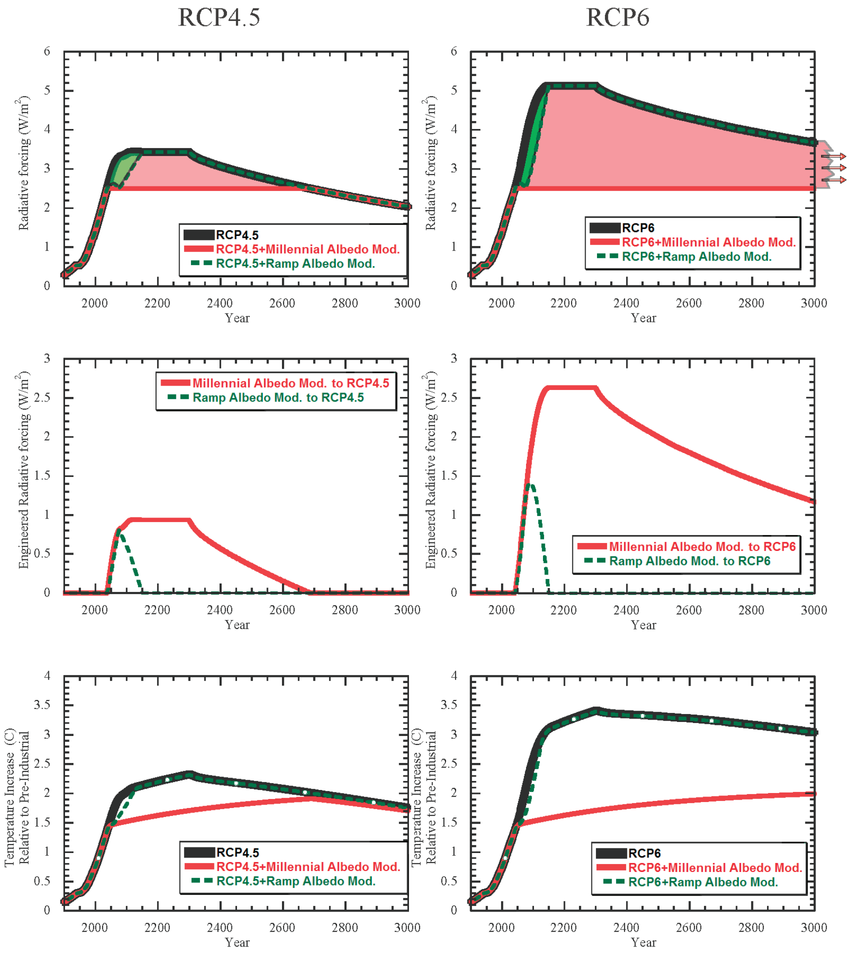

FIGURE 3.7 Radiative forcing and climate intervention commitment time. Results in the left column are for the RCP4.5 emissions scenario, while results in the right column are for RCP6.0, which involves higher emissions. The top row shows the CO_2 radiative forcing for the two scenarios (thick black line), based on Zickfeld et al. (2013). The solid red line in these panels depicts a target radiative forcing to be achieved by albedo modification, designed to never exceed 2.5 W/m^2, whereas the dashed green line corresponds to a strategy in which the radiative forcing is only subject to a cap for the first 75 years, whereafter albedo modification is gradually phased out over the next 75 years. The shaded green region indicates the period of time over which albedo modification is applied in the limited-duration phase-in/phase-out strategy, while the red shaded region shows the duration of commitment in the permanently capped strategy. The middle row shows the corresponding amount of radiative forcing change that albedo modification needs to accomplish, as a function of time. The bottom row translates the radiative forcing trajectories of the top row into global mean temperature using the simplified energy balance model described by Pierrehumbert (2014). The limited-duration albedo modification strategy shown by the green dashed lines is able to slow down the initial stages of the warming but does not visibly reduce the peak warming or delay the time at which the peak warming is attained.

these estimates do not take into account the possible effects of albedo modification on the carbon cycle (see section "Modeled Climate System Responses to SAAM" below). The middle panels show time series of the amount of reduction in solar radiation that would be needed to achieve the target climate and provide an indication of the level of albedo modification effort required over time. Even in the lower emission scenario—for which the unmodified climate exceeds the 2°C target by a small amount—to permanently avoid CO_2-induced warming, the climate intervention actions would need to be maintained to nearly the year 2700. To achieve this goal for the RCP6.0 emissions scenario, albedo modification efforts would need to be maintained at a substantial level even in the year 3000, and it would in fact be several thousand years more before the CO_2 radiative forcing decays to the point that climate intervention could be terminated without a substantial temperature increase. In a situation where the amount of CO_2 emissions mitigation accomplished has proved insufficient to avoid crossing a temperature target on the order of 2°C (or similar), meeting such a target by means of albedo modification would require a millennial or even multi-millennial deployment to actively maintain climate intervention without interruption, unless techniques to greatly accelerate CO_2 removal from the atmosphere (CDR) are deployed at very large scale. All the extended RCP scenarios used in this calculation assume that anthropogenic CO_2 emissions cease entirely by the year 2300 or earlier, implying that either CO_2 emission mitigation eventually becomes effective or that the supply of fossil fuel runs out.

Without a near-millennial or longer deployment of CDR, albedo modification could delay but not avoid the crossing of a temperature threshold (MacMartin et al., 2014; Wigley, 2006). By itself albedo modification would only temporarily delay warming, unless the albedo modification effort was continually maintained over the period of substantial excess atmospheric CO_2 concentrations, which is anticipated to last millennia. Delaying warming could be useful if the additional time allowed measures to adapt to the eventual warming to be put into place or allowed deployment of CDR methods. It may also be useful in addressing climate damages tied to the rate of warming, though reliance on albedo modification may also introduce risk of making such damages worse if CO_2 concentrations are increasing while it is deployed, and the albedo modification is prematurely and abruptly terminated.

The green dashed curves and green shaded regions in Figure 3.7 give an example of a strategy whose goal is to delay, rather than prevent, warming. These provide examples of what can be accomplished with a short-duration deployment. Specifically, the albedo modification follows the same trajectory as the millennial case for the first 75 years (allowing for a gradual phase-in of the procedure), whereafter it is phased out over the next 75 years. The ramp strategy achieves a 25-year delay in the time of crossing of a 2°C warming threshold in the lower-emission case, and a 20-year delay in the higher-emission case. Smith and Rasch (2012) have explored options for century-scale deployments. Limited-duration deployments might be useful if stringent emission controls have kept CO_2 emissions to relatively low levels, when additional time is needed for adaptation, or if significant negative emissions (CDR) are possible.

Because air, land, and the upper ocean respond quickly to changes in radiative forcing, an abrupt termination of albedo modification would result in rapid warming, with global mean temperatures rising within a decade or two to levels close to what would have been experienced without albedo modification (Jones et al., 2013; Matthews and Caldeira, 2007). The possibility of rapid warming is a novel and potentially severe risk not present in the unmodified high-CO_2 state, in which temperature increases more slowly over time. As a result, the choice of a climate future in which a high CO_2 concentration is compensated by a high degree of albedo modification risks putting Earth's climate in a precarious state. Phasing albedo modification in or out over many decades, such as might be done to give human and natural systems a chance to better adapt to the resulting temperature change (MacMartin et al., 2014; Wigley, 2006), would reduce the time span over which Earth was subject to termination risk, but an abrupt termination risk will always be present if albedo modification is being used to counter a substantial fraction of the CO_2 forcing.

The climatic impacts of abrupt termination were specifically considered by Matthews and Caldeira (2007), Brovkin et al. (2009), Llanillo et al. (2010), and Jones et al. (2013), but rapid post-termination warming was also confirmed by Robock et al. (2008), Jones et al. (2010), and Berdahl et al. (2014), and there are no simulations of abrupt termination that conflict with these predictions of rapid warming. The upper panel of Figure 3.8 shows the warming upon termination in a series of GeoMIP solar-constant simulations (Jones et al., 2013) of the response to increasing CO_2 at a rate of 1 percent per year, offset by reduction in solar radiation that is terminated abruptly at year 50. As noted in that study, the inclusion of realistic aerosol effects would not substantially change the rapidity of the warming, because aerosols disappear within 1 to 2 years from the stratosphere. The lower panel, from Llanillo et al. (2010), shows that very similar results are obtained from a highly simplified energy balance climate model and also illustrates that the longer sunlight reduction is used to offset continually increasing CO_2, the larger the effect that is caused by termination.

The amount of warming following termination depends on the climate sensitivity—a quantity that is highly uncertain for the actual climate and which varies significantly among models. It is difficult to infer climate sensitivity from observations of a warming climate without albedo modification, and it would be more difficult to do so in a cli-

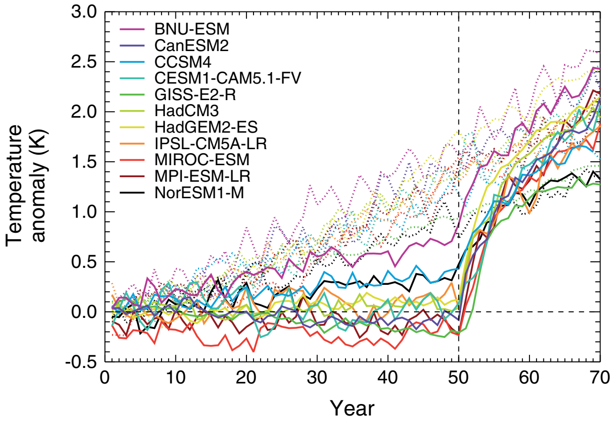

FIGURE 3.8 Multimodel results for simulation of abrupt termination of albedo modification in GeoMIP solar-constant experiments (Jones et al., 2013). Dashed lines show the climate response to the increasing CO_2 without reduction in solar radiation.

mate subject to strong (and possibly uncertain) albedo modification. Hence, it would be difficult for inhabitants of a strongly albedo-modified high-CO_2 world to know in advance what magnitude of climate change they would face upon abrupt termination (Matthews and Caldeira, 2007).

Both Jones et al. (2013) and Berdahl et al. (2014) confirm that the rapid warming is accompanied by a rapid loss of sea ice, particularly in the Arctic. Jones et al. (2013) and McCusker et al. (2014) point out that upon abrupt termination some regions simultaneously experience rapid warming and rapid precipitation decreases, increasing the stress on arid regions (though there is only weak consensus among models as to where the stresses are the highest).

Abrupt termination could lead to significant ecosystem, agriculture, and societal impacts that would not have existed had albedo modification never been deployed, but these potential impacts are largely unknown at this time. If the consequences of warming due to CO_2 were severe enough to trigger an emergency deployment of albedo modification and no effective adaptation effort was put in place during the period of deployment, it is likely that an extremely rapid onset of a warming of the same magnitude would have even more severe consequences. Few studies so far have specifically addressed the impacts of post-termination warming. Xia et al. (2014) conclude that an abrupt termination would have a negligible effect on rice production in China. They also find that an abrupt termination would reduce maize production by about 12 percent relative to levels that were achieved during the albedo modification deployment, but these yields are still higher than would have been obtained in the preindustrial condition without CO_2 fertilization of land plants. Jones et al. (2013) do not find any marked effect of either albedo modification or abrupt termination on the multimode mean global net primary productivity (which is often taken as a rough proxy for agricultural and ecosystem impacts) despite the massive and rapid climate change; this is difficult to reconcile with robust indications of food security issues in a warming world (e.g., NRC, 2011). However, there is considerable disagreement among the individual models of Jones et al. (2013) as to the baseline net primary productivity, the response to unmodified global warming, and the response to abrupt termination of albedo modification. Furthermore, the multimodel ensemble mean global net primary productivity shows a steady increase even in the control run in which the world warms in response to increasing CO_2 without offsetting by albedo modification. Although the mechanism of this increase was not diagnosed, it would be consistent with a dominance of CO_2 fertilization effects when interpreted in conjunction with the minimal effect of albedo modification termination on net primary productivity. If so, this is a source of concern requiring further inquiry, because the CO_2 fertilization effect in land ecosystem models is very model dependent and subject to considerable uncertainties (Rosenzweig et al., 2014). Overall, there is need for a better understanding of the effects of albedo modification and its abrupt termination on agricultural and natural ecosystems.

The risk of severe impacts of abrupt termination increase with the magnitude of albedo modification deployed. In particular, if CO_2 emissions continue during the time over which albedo modification is deployed, and are canceled out by increasing the amount of albedo modification, then the severity of impacts of abrupt termination will steadily increase. It is in futures where CO_2 is very high or climate sensitivity turns out to be high that albedo modification is most likely to provide benefits, leading McCusker et al. (2014) to conclude: "We are left with the disconcerting situation in which [albedo modification] is most useful precisely when its associated risks are the greatest." An unmodified, hot, high-CO_2 climate also incurs serious risks. Determining the circumstances under which these risks should be traded for the risks of abrupt or more gradual termination is a challenging problem, which the committee does not address. The surest way to minimize risks of both sorts is to continue and expand efforts to mitigate CO_2 emissions, which would minimize the amount of climate change with which any eventual albedo modification would need to cope.

There are many technologies that humanity already relies on which could cause substantial harm if their use were to cease abruptly. However, human history offers no precedent for the maintenance over a millennial timescale of a technological intervention of sophistication and global scope comparable to albedo modification. Further research would be useful to ascertain the ability of society to sustain albedo modification over such a long timescale in the face of other societal, political, and ecological challenges.

ALBEDO MODIFICATION STRATEGIES

Climate Intervention by Stratospheric Aerosol Albedo Modification (SAAM)

Climate intervention using realistic strategies involves atmospheric injection of aerosols or aerosol precursors. Aerosols (solid or liquid particles suspended in the air) of natural and anthropogenic origin are found everywhere in the atmosphere. They affect the planet's energy budget by scattering and absorbing sunlight, and by changing cloud properties (Seinfeld and Pandis, 2006). They also play a role in the chemistry of the atmosphere and carry nutrients and disease from place to place. Humans have changed the amount of aerosols in the atmosphere through pollution emissions, and by changing natural aerosol sources through land and water use. Aerosols that originate directly from a source (e.g., dust, soil, smoke particles from fires, and bacteria or viruses) are generally called "primary aerosols." Aerosols that develop from gases (natural and anthropogenic) that condense into a liquid or solid form (e.g., particles containing sulfate, nitrate, and organic carbon) are often called "secondary aerosols." Aerosols are mostly removed from the atmosphere by dry deposition, sedimentation, or scavenging by clouds.

Aerosol particles higher in the atmosphere are not removed as quickly as those near the surface. Aerosols found high in the atmosphere have a longer lifetime[1] than those found near the surface because they are far from clouds and the surface where they would be removed on very short timescales (days).

Aerosols interact with sunlight passing through Earth's atmosphere. When aerosols scatter sunlight back to space they cool the planet; when they absorb sunlight they warm the air locally but can cool the atmosphere below them. The best estimates of the net effect of atmospheric aerosols are that they cool the planet. One of the broad classes of proposed techniques for altering the Earth's energy balance involves increasing the number of aerosols in the stratosphere (a layer with a base called the tropopause between about 8 and 18 km above the surface, extending to about 50

---

[1] Scientists usually refer to the average time a particle resides in the atmosphere in terms of a "lifetime" or "residence time" where lifetime is defined as the time required for the concentration of a substance to be reduced by a factor to 1/e times the original concentration.

km). Theory and models suggest that increasing the number of aerosols that scatter sunlight back to space will cool the planet. Scientists have considered deliberately introducing aerosols into the stratosphere primarily because aerosols have a much longer lifetime in the stratosphere (on the order of years) compared to lower altitudes (where lifetimes are on the order of days to weeks). Producing or injecting aerosols in the stratosphere would minimize the amount of aerosols needed to produce a specified amount of cooling because the same amount of aerosols would stay in the atmosphere longer and produce more cooling than at lower altitudes.

Both scattering and absorbing aerosols will reduce sunlight reaching the surface of the planet. A range of aerosols has been considered for modifying the energy budget of the planet (see below section, "Proposed Mechanisms for SAAM"). Most of the methods that propose to use stratospheric particles to cool Earth are likely to produce similar characteristics with regard to their effects on global mean surface temperature and precipitation, but they can differ in important regards with respect to the amount of stratospheric heating they produce and their effects on stratospheric chemistry. The committee's discussion focuses primarily on injection of sulfate aerosols or their precursors into the lower stratosphere. This is the most-studied technique and is also the one that most closely mimics the way large volcanic eruptions cool the climate.

Basic Physics, Chemistry, and the Life Cycle of Stratospheric Aerosols

Formation, evolution, and removal of stratospheric aerosols. Most stratospheric sulfate aerosols are formed as a result of transport into the stratosphere of natural and anthropogenic gases that contain sulfur originating nearer the surface (e.g., carbonyl sulfide, sulfur dioxide [SO_2], and sulfuric acid [H_2SO_4]). Explosive volcanoes also inject SO_2 into the stratosphere. These gases undergo a series of chemical reactions that add oxygen atoms to the source gas (through a process called oxidation) which eventually leads to the formation of H_2SO_4 in the gas phase. In the stratosphere H_2SO_4 can either nucleate to form new small particles or condense on existing particles, making those particles larger. Particles usually form near the tropical tropopause and some evaporate as they are lifted to higher altitude. Those remaining lower down near the tropopause eventually migrate toward the polar regions where they pass into the troposphere, either transported by the wind through midlatitude tropopause folds or by sedimentation. The average residence time of a particle in the lower stratosphere is approximately 1 year. After eventual transport into the troposphere, the particles undergo relatively rapid mixing processes by weather events, turbulence, and cloud-scale overturning. The aerosols are then rapidly scavenged (timescales of days to weeks) by acting as nucleation sites for cloud ice or liquid particle formation. These processes are described in more detail in recent textbooks of stratospheric chemistry and summarized in a report on stratospheric aerosols (SPARC, 2006). Figure 3.9 shows a summary from that report of important processes in the lifetime of stratospheric aerosols.

Most of the sulfuric acid gas found in the stratosphere is formed by reaction of SO_2 with the hydroxyl radical (OH), the main oxidant of the chemical reactions occurring there. The SO_2 itself comes from (1) transport of natural and anthropogenic SO_2 from the troposphere, (2) oxidation in the stratosphere of gaseous precursors (natural and anthropogenic), and (3) direct injection of SO_2 by strong volcanic eruptions. Most observations (for Pinatubo) and models are consistent with a lifetime for SO_2 of order 30 to 35 days (Liu and Penner, 2002; Read et al., 1993). Nevertheless, for large volcanic eruptions, the OH concentration may not be constant but may decrease due to a combination of increased water vapor flux, decreased incident solar radiation, and possibly heterogeneous reactions (Robock et al., 2009a). Modeling studies (Robock et

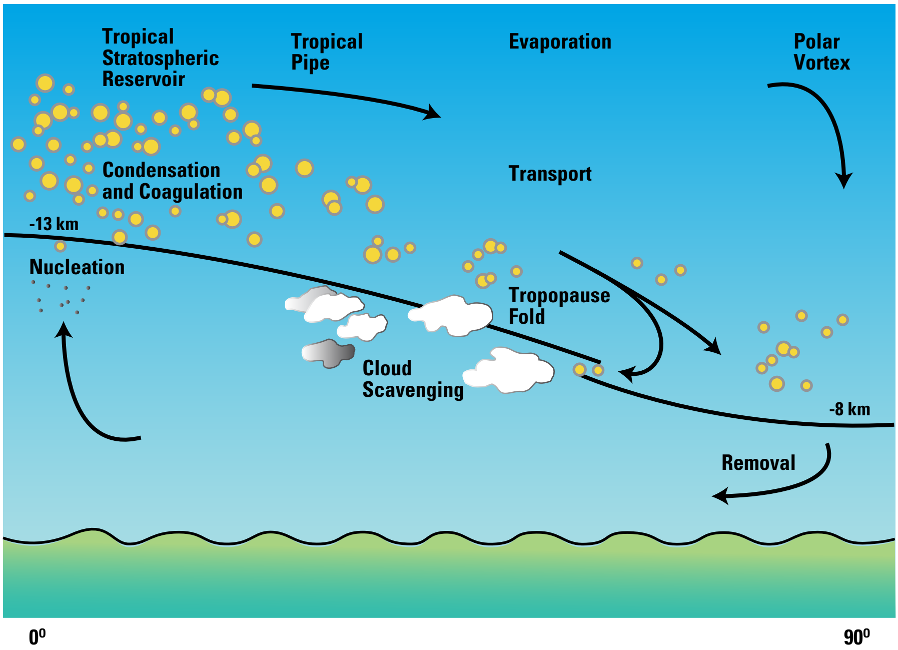

FIGURE 3.9 The life of natural stratospheric aerosols. The aerosol particles are formed by nucleation in rising tropical air and grow by condensation and coagulation as they are carried aloft. They eventually move to mid- and high latitudes where they may be removed by mixing across the tropopause. SOURCE: Hamill et al., 1997.

al., 2009a) that include coupled stratospheric chemistry find that the lifetime of any given molecule of SO_2 is longer compared to studies without coupled stratospheric chemistry because the oxidation rate of SO_2 is limited by the lack of reactants (see also Bekki et al., 1996).

There is a well-established theory for the formation (referred to as "nucleation") of H_2SO_4 particles from sulfuric acid vapor in the presence of water vapor. This mechanism is thought to be the primary mechanism leading to new particle formation in the stratosphere, although ion-induced nucleation may also play a role (Arnold et al., 1982; Campbell et al., 2014). For a given addition of SO_2, the trade-off between new particle formation (leading to more but smaller particles) and coagulation and condensation (leading to larger particles) depends on the temperature and ambient concentrations of gaseous sulfuric acid and preexisting sulfate particles (number and size), mediated by the size of the SO_2 concentrations that produce the sulfuric acid (Timmreck, 2012). The concentration of the gases and aerosols that govern these processes is determined by chemical reactions, physical processes (like Brownian motion and particle sedimentation, to name only a couple of processes), and molecular, turbulent, and larger-scale mixing by the winds that govern the aerosol and gas concentrations. Although the basic physics and chemistry that describe new particle formation, condensation of gases on existing particles, particle evaporation, and the coalescence processes that reduce particle number and increase particle size are well understood, subtle details matter a lot in determining the evolution of particle number and mass, and the subsequent role of those particles in the climate system. More work is needed in characterizing these processes in nature (through measurements) and in modeling (through better model treatments and a careful comparison with observed features of aerosols and their precursor gases) before scientists can produce truly accurate models of stratospheric aerosols and their effects on climate.

The effectiveness of possible mechanisms for introducing sulfate aerosols into the stratosphere—injecting SO_2 gas that oxidizes to H_2SO_4—is determined by stratospheric chemistry and transport patterns. There have been some initial studies on this (see below section, "Model Estimates of Aerosol Forcing from SAAM"), but this is still an area that requires substantial research.

Impacts of stratospheric aerosols on climate. Stratospheric sulfate aerosols scatter and absorb sunlight, and they also absorb and emit energy at infrared wavelengths. Their radiative impact depends on the particle size. They are primarily scatterers of sunlight at typical sizes found in the stratosphere, and thus cool the planet, but they can also contribute to local heating of the atmosphere. Even purely absorbing particles in the stratosphere have a cooling influence on Earth's surface despite having a heating influence on the stratosphere because the absorbing particles block some of the sunlight that would otherwise reach the surface (Ban-Weiss and Caldeira, 2010). Stratospheric aerosols change the amount of sunlight passing downward through the tropopause and thus have climate effects such as those discussed in the idealized studies above.

Stratospheric aerosols provide sites for heterogeneous chemistry, and some of that chemistry can lead to ozone depletion. Thus, changes in stratospheric aerosol can also affect climate indirectly, by influencing ozone. Ozone is a critically important atmospheric constituent (see WMO [2011] and IPCC [2013a] for modern and comprehensive reviews) in the Earth system. It is one of the major oxidizing agents of the atmosphere, and it participates in many important chemical reactions. Ozone absorbs and emits energy in many parts of the energy spectrum, and its absorption of sunlight produces a notable warming in the stratosphere. It is also a greenhouse gas, absorbing and emitting energy at infrared wavelengths. The heating and cooling produced by ozone change can thus drive circulation changes (IPCC, 2013a; WMO, 2011). Ozone also absorbs light in the ultraviolet region of the energy spectrum (hereafter called UV-B light). Since stratospheric aerosols also scatter UV-B light, reducing the amount reaching the surface, there is the potential for the compensating changes between ozone loss (which will increase surface UV-B) and increasing aerosols (which will decrease surface UV-B) in the total change. The amount of UV-B light reaching the surface has significant implications for surface ecosystems and human health. Increases in surface UV-B light would be expected to lead to increases in skin cancer in humans (see, e.g., McKenzie et al., 2011; Rogers et al., 2010; Stern, 2010).

In scattering sunlight, stratospheric aerosols reduce the direct beam of sunlight and also increase the ratio of diffuse to direct sunlight reaching the surface. This means that while less sunlight reaches the surface (cooling the planet), the light tends to come from more directions, so it penetrates into plant canopies more effectively, exposing more leaves to light, which has impacts on photosynthesis and makes shadows less sharp. Reducing total light reaching the surface tends to reduce light available for photosynthesis, but increasing the diffuse light allows plant canopies to photosynthesize more efficiently. Changing photosynthetic activity can change plant productivity and the capacity of plants to act as a carbon sink. Measurements following the Pinatubo eruption indicate that plant productivity and carbon sink went up (Gu et al., 2003), suggesting that the increase in diffuse light is more important to plant growth than the decrease in the sunlight reaching the surface. The heating and changes to ozone associated with increased stratospheric aerosols can also affect tropopause temperatures with consequent effects on water vapor input to the stratosphere. The added water in the stratosphere affects the climate of the stratosphere and stratospheric chemistry, with additional implications for surface climate (Heckendorn et al., 2009). High clouds may be influenced by stratospheric aerosols (Box 3.2).

There are many factors that influence the interactions between stratospheric aerosols and ozone. The chemical interactions generally involve the presence of inorganic chlorine, water vapor, and sulfate aerosols, as noted in a series of studies (Anderson et al., 2012; Drdla, 2005; Drdla and Müller, 2010; Hanisco et al., 2007; Homeyer et al., 2014; Peter and Grooß, 2012; Sayres et al., 2010; Schwartz et al., 2013; Shi et al., 2001; Solomon, 1999), along with the convective injection of compounds from the boundary layer (Hanisco et al., 2007; Pittman et al., 2007; Salawitch et al., 2005; Weinstock et al., 2007).

Increases in stratospheric aerosols might alter the radiative balance and chemistry of the stratosphere, and the Earth system more broadly. These are areas of active research, and recent studies on these topics are described in the below sections ("Observations and Field Experiments of Relevance to SAAM," "Modeled Climate System Responses to SAAM," and "Environmental Consequences of SAAM").

BOX 3.2 EFFECTS OF AEROSOLS ON CIRRUS CLOUDS

Cirrus clouds are high-altitude ice clouds. Thick cirrus clouds have a net negative impact on radiative forcing (Kubar et al., 2007), cooling by reflecting sunlight back to space and warming by trapping outgoing infrared energy through a greenhouse effect. Radiative forcing by thin cirrus clouds is dominated by the greenhouse effect that produces a net positive forcing tending to warm the climate. Observations indicate the net impact of high cirrus clouds is to warm the planet, but the effect of the addition of aerosol particles on this net impact is complex to predict. The net effect of high clouds is a small residual of two large numbers, both of which depend on microscopic cloud properties, and is therefore very difficult to model. Change in the number and size of cloud particles affects cloud lifetime and the balance between the infrared and solar effects of the clouds.

As stratospheric aerosol particles mix into the troposphere, they may influence cirrus clouds in at least two ways. First, they can influence the very complex balance between homogeneous and heterogeneous nucleation processes that produce cirrus ice crystals. The effects depend on both the size of the particles transported to this region from the stratosphere, and the ambient particles, by changing the relative importance of the heterogeneous and homogeneous ice nucleation in the region. It is not clear how cirrus clouds would change if stratospheric aerosol increases were to occur (Cziczo et al., 2013; Froyd et al., 2010). Most model simulations have assumed that homogeneous ice nucleation dominates in cirrus clouds, but there are clearly regions where heterogeneous nuclei are numerous enough to alter this assumption. Second, the radiative heating occurring in the region of stratospheric aerosols can change the stability of the upper tropospheric layers, affecting the vertical velocities that are important to ice crystal formation.

Observations and Field Experiments of Relevance to SAAM

No well-documented field experiments involving controlled emissions of stratospheric aerosols have yet been conducted. Some volcanic eruptions have injected large amounts of sulfur dioxide gas into the stratosphere, and observations of these eruptions and their impact on climate can serve as natural experiments for testing our understanding of albedo modification processes (Robock et al., 2010, 2013). The observed cooling following large eruptions provided much of the initial stimulus for the idea that albedo modification could help offset effects of warming due to anthropogenic CO_2 increase, and attempts to model the observed effects of volcanic eruptions can provide some insight into the complexity of the processes and some of the unknowns that still need to be addressed. The climate effects of a single pulse of aerosols such as that produced by volcanoes would differ in important ways from the effects of a sustained effort to maintain a persistent aerosol layer (Box 3.3). Nonetheless, volcanoes provide an excellent opportunity to test and improve our understanding of relevant physical processes. However, there are many challenges and limitations associated with the use of volcanic eruptions as analogues for SAAM, which are discussed in Appendix D, but they do represent the only feasible large-scale experiments (natural or otherwise) in stratospheric attenuation of a large fraction of solar energy. As such, they offer our best opportunity to develop insights into SAAM. Moreover, as "events of opportunity," they do so without introducing substantial and risky human perturbation to the climate system.

Very large eruptions—the size of El Chichón (1982) or Pinatubo (1991)—produce a detectable climate response that can be used to test simulations of both aerosol forcing and the consequent response of climate, but even smaller eruptions—the size of the Sarychev eruption (2009)—can provide a useful test of our ability to observe and to simulate stratospheric aerosol processes (Kravitz and Robock, 2011; Kravitz et al., 2010, 2011b). Large eruptions can also serve as a test of the effect of increased particle surface area on ozone destruction, of our ability to model the associated atmospheric chemistry, and of other impacts.[2] The effect of large volcanic eruptions on Earth's radiation balance can persist for several years before their concentrations return to background values.

To indicate what is known about stratospheric aerosol effects on the planet, the committee focuses here on the 1991 eruption of Mount Pinatubo, because scientists have the best observational data for it. The Pinatubo eruption, on June 14-16, 1991, injected

---

[2] Other eruptions, such as Tambora in 1815, caused global climatic anomalies that led to widespread crop failure and famine (Oppenheimer, 2003).

BOX 3.3 ARE VOLCANIC ERUPTIONS GOOD ANALOGUES FOR STRATOSPHERIC AEROSOL INJECTION?

The short answer is yes and no. Volcanic eruptions that inject large amounts of sulfur dioxide gas into the stratosphere are believed to have much the same effect (at least initially) as proposed methods to engineer the climate by purposeful injection of stratospheric aerosols and, thus, can serve as natural experiments for testing our understanding of albedo modification processes (Robock et al., 2010, 2013). Indeed, it was the observed cooling following large eruptions that provided much of the initial stimulus for the idea that albedo modification could help offset effects of warming due to anthropogenic CO_2 increase. Attempts to model the observed effects of volcanic eruptions have provided some insight into the complexity of the processes and some of the unknowns that still need to be addressed. In addition to blocking sunlight, the aerosols absorb incoming solar infrared and thermal heat from below, heating the stratosphere. Thus, the response to the volcanic eruption is not just cooling of Earth's surface, but also reductions in rainfall over land and a winter warming pattern from the stratospheric heating. However, there remain discrepancies between models and observations that require improved ability to track the aerosol evolution and accurately reflect the radiative transfer that controls the stratospheric heating. Furthermore, there are several differences between volcanic eruptions and purposeful albedo modification that make the volcanoes imperfect analogues. Past eruptions have occurred under conditions of enhanced stratospheric chlorine and bromine concentrations and, thus, have incurred larger stratospheric ozone decreases than might be the case in the future. Eruptions are point-source releases of a range of particles, whereas any albedo modification would aim to produce a more spatially uniform distribution of more uniform aerosols. In addition, eruptions are short-lived phenomena, not lasting long enough to strongly affect, for example, ocean temperatures to the point of altering the heat and density transport processes that control ocean circulation. Because land temperatures respond more quickly than ocean temperatures, volcanoes cause more cooling over land relative to ocean than would be caused by a sustained aerosol layer; this would be expected to contribute to decreased precipitation over land following a volcanic eruption. Albedo modification would need to be maintained for a long time period, with lasting effects on ocean temperatures and circulation, ecosystems, sea ice, and other aspects of the climate system, producing feedbacks not seen to date in volcanic eruptions. See Appendix D for further discussion of the volcano analogy and Box 3.5 below for observational requirements for making better use of volcanoes as natural experiments.

14 to 26 megatons of SO_2 into the stratosphere with concentrations peaking near 25 km and reaching as high as 30 km (Read et al., 1993). This was converted to H_2SO_4 particles over the next 1 to 2 months, with mode radii initially observed peaking at 0.1 μm radius, similar to background aerosol sizes, but developing a bimodal distribution having a distinct second peak near 0.5 μm by November 1992 which lasted until May 1993 (Goodman et al., 1994). Initial concentrations were more than 10 times higher than background.

The volcanic eruption took place in the western Pacific (15.1°N, 120.4°E) and the stratospheric sulfate aerosol plume was observed to extend from 20°S to 10°N after 100 days. After 150 days both SO_2 and H_2SO_4 had reached beyond the tropics in both hemispheres (Read et al., 1993; Russell et al., 1996). Stratospheric concentrations of H_2SO_4 aerosols remained above background well into 1993. The optical depth of the total stratospheric aerosols had a lifetime (for reduction by a factor of 1/e) of around 1.5 years near 19.5°N (Russell et al., 1996).

Numerous changes were observed following the Mount Pinatubo eruption, including changes in temperatures. Figure 3.10 shows one estimate of the lower tropospheric temperature change following the Pinatubo eruption of 1991 by Soden et al. (2002). Other studies (Canty et al., 2013; Thompson et al., 2009) have estimated that the globally averaged surface air temperature reduction from Pinatubo is somewhat lower (0.2 to 0.4 K).

In addition to reflecting sunlight and changing surface temperature, there are many other impacts. For example, observed effects of large volcanic eruptions on the planet include changes to stratospheric ozone (O_3) levels. Column ozone (O_3) averaged over 60°S to 60°N decreased by about 4 percent following 1991, but changes in halogens (e.g., chlorine and bromine gases) were also responsible for some of this decline (Chipperfield et al., 2007, Fig. 3-21). Sulfate particles in the lower stratosphere provide surfaces for the chlorine to activate into forms that deplete ozone. Two-dimensional (Tie et al., 1994; WMO, 2003, Section 4.5.3.4) and three-dimensional (e.g., Chipperfield,

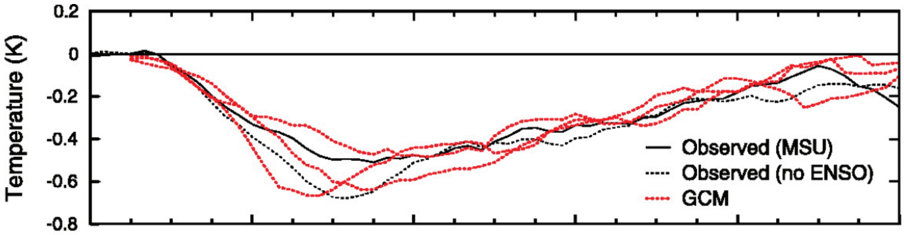

FIGURE 3.10 Comparison of the observed (black lines) and model-predicted (dashed lines) global-mean (90°N-90°S) changes in lower tropospheric temperature after the eruption of Mount Pinatubo. The observed anomalies are computed using a 1979 to 1990 base climatology and expressed relative to the pre-eruption value, defined here as the mean anomaly for January 1991 to May 1991 (MSU, microwave sounding unit; No ENSO, observations adjusted to remove the effects of El Niño–Southern Oscillation). The model anomalies are computed for each ensemble pair as the difference between the control and Mount Pinatubo experiments. All of these time series have been smoothed using a 7-month running mean. SOURCE: Soden et al., 2002.

1999, 2003; Stolarski et al., 2006) model studies have shown the chemical effects of volcanic eruptions and it is well known that the presence of enhanced particles in the stratosphere can cause significant ozone loss through heterogeneous chemical reactions, which was demonstrated by studies on Mount Pinatubo (WMO, 2003, 2011). The volcanic effect on column ozone results from heterogeneous catalytic conversion of HCl and $ClONO_2$ to ClO which then, in combination with the hydrolysis of N_2O_5, titrates NO_x from the system. As a result the dominant removal process for O_3 is the rate-limiting step $ClO + BrO \rightarrow Cl + Br + O_2$ (Salawitch et al., 2005; Solomon et al., 1996). Thus, chemical ozone losses from volcanic sulfate injection are largest at times of peak chlorine and bromine, and volcanic impact on ozone at preindustrial halogen levels is estimated to be small or even positive (Tie and Brasseur, 1995).

Dynamical changes resulting from the Mount Pinatubo eruption also contribute to ozone change (Hadjinicolaou et al., 2005). Differences in the effects of Pinatubo between the Northern Hemisphere (NH) and Southern Hemisphere (SH) are not well understood. Models show a SH effect as large or larger than the NH effect, though this is not seen in data (Chipperfield et al., 2007). Stolarski et al. (2006) showed that such effects may be due to interannual variability.

Changes in precipitation following the 1991 eruption were also studied. Trenberth and Dai (2007) examined possible changes in precipitation and associated river runoff associated with the Pinatubo eruption. Global average precipitation decreased by 0.07 mm/day between late 1991 and early 1992 compared to the 1979-2004 average. Global average land precipitation during 1992 was about 10 percent (3.1 standard deviations) below normal while river discharge was also about 10 percent (3.7 standard deviations) below normal. However, this event is confounded by El Niño occurring during the same time period. After removal of El Niño effects on the time series (from 1950 to 2004) using regression, the natural variability in precipitation and runoff is reduced by almost 44 percent and 36 percent, respectively, and effects of Pinatubo stand out much less. However, the 1992 anomalies are still significant at the >99 percent confidence level.

Some studies have suggested that increased aerosol from Pinatubo produced an increase in stratospheric sulfate particles, leading to an increase in optically thick cirrus clouds (Minnis et al., 1993) and in cirrus cloud cover (Wylie et al., 1994), but, ultimately, observational analyses of the aerosol effect on cirrus clouds during Pinatubo are inconclusive, as pointed out by Robock et al. (2013): Ackerman and Strabala (1994) and Minnis et al. (1993) find changes, but Luo et al. (1997) do not. The effect of particles from volcanic eruptions on ice nucleation is still under investigation. Roderick et al. (2001) suggested that Pinatubo also increased the diffuse light entering plant canopies, leading to increased photosynthetic activity and the capacity of plants to act as a carbon sink.

Numerous recent studies have highlighted the difficulty of simulating the observed evolution of stratospheric aerosols (Auchmann et al., 2013; Foley et al., 2014; Muthers et al., 2014; Thomason and Peter, 2006; Timmreck, 2012; Toohey et al., 2013; Weisenstein and Bekki, 2006), including aerosol size, amount, and location. Models also find it difficult to reproduce other effects on the Earth system, including the diurnal cycle of surface temperature, impacts on the carbon cycle, transport and deposition of aerosol to high latitudes, and changes to atmospheric dynamics (Auchmann et al., 2013; Foley et al., 2014; Toohey et al., 2013).

The ability of models to reproduce the observed signatures produced by volcanic eruptions therefore provides a real challenge to models and a necessary, but not sufficient, test of the ability of models to accurately simulate the processes important to climate and climate change associated with SAAM. Because volcanic eruptions occur relatively infrequently, and stratospheric aerosols return to background values within a few years, volcanic impacts do not persist. Since SAAM introduces a persistent source for stratospheric aerosols, and a persistent forcing, it may involve interactions in Earth system components that are not present following volcanic eruptions, so these simulations are only an incomplete test of the relevant interactions (see Box 3.3). Nevertheless, the simulations provide the single most stringent test of the processes relevant to SAAM available today. More comprehensive and thorough studies using existing observations and improved observations gathered from future eruptions would be extremely useful as testbeds for model evaluation and model improvement.

A somewhat broader perspective on the state of the art in volcanic response modeling is provided by Driscoll et al. (2012), which is the most comprehensive assessment to date of the ability of coupled ocean-atmosphere models to reproduce the winter (December-January-February) volcanic response. This study surveyed the volcanic response after nine different eruptions in all the CMIP5 models which included volcanic forcing. All of the models considered computed the ocean and sea ice response using a dynamic ocean circulation model coupled to the atmosphere, but out of the 13 models discussed, only one computed aerosol properties starting from the injection of sulfur dioxide instead of imposing aerosol characteristics based on observations. Despite the fact that most of the models had the advantage of constraining the aerosol properties based on observations, the ability of the models to reproduce the average winter temperature pattern and circulation response is very poor, although some of this lack of response may have been associated with modeled El Niño–Southern Oscillation (ENSO) frequencies, which cannot be controlled. The multimodel mean simulation is dominated by a weak cooling, with very little evidence of the observed polar warming (Figure 3.11). This is due to the inability of most of the models to accurately reproduce the atmospheric circulation change forced by stratospheric heating (Driscoll et al., 2012). Based on these results, Driscoll et al. (2012) question whether existing modeling capabilities are adequate for assessing the impact of SAAM climate interventions, though it is also a possibility that the more spatially and temporally uniform aerosol layers that global SAAM schemes aim to achieve would pose fewer modeling challenges.

There is considerable variation in response among the models in the CMIP5 ensemble, and some models do better than others at reproducing some features of the winter response. Thomas et al. (2009a,b) performed a detailed analysis of the winter response to Pinatubo in the ECHAM-5 model. They found improved winter surface temperature responses using observed aerosol properties, specified sea surface temperatures, and quasi-biennial oscillation phase (see also Stenchikov et al., 2004). Nevertheless, some discrepancies between the modeled and observed response pattern remain (see especially Fig. 5 of Thomas et al., 2009b).

Proposed Mechanisms for SAAM

Budyko (1974) was the first to suggest a deliberate method to increase aerosols in order to increase planetary albedo by flying aircraft into the lower stratosphere and burning sulfur-bearing compounds. Since that time, a variety of mechanisms for delivering sulfur-containing species to the lower stratosphere have been suggested (Rasch et al., 2008a), including aircraft, rockets, artillery, and pipes elevated to high altitudes carrying aerosol precursors.

In addition, a variety of types of particles have been suggested for introduction into the stratosphere to enhance the planet's reflectivity. This includes (1) sooty aerosols associated with combustion often called "black carbon" and sometimes discussed in nuclear winter studies (Kravitz et al., 2012b; NRC, 1985; Robock and Toon, 2010; Turco et al., 1990) that strongly absorb sunlight, (2) dust particles that could be viewed as more benign once deposited on the ground (Bala, 2009; NRC, 1992), and (3) artificial aerosols that could potentially be designed with specific scattering and adsorption properties and that can take advantage of light-driven migration of particles to guide them to particular atmospheric locations (e.g., Keith, 2010). Although there are various particle types that could be added to the stratosphere to enhance Earth's albedo, most of the studies described below discuss sulfate aerosols.

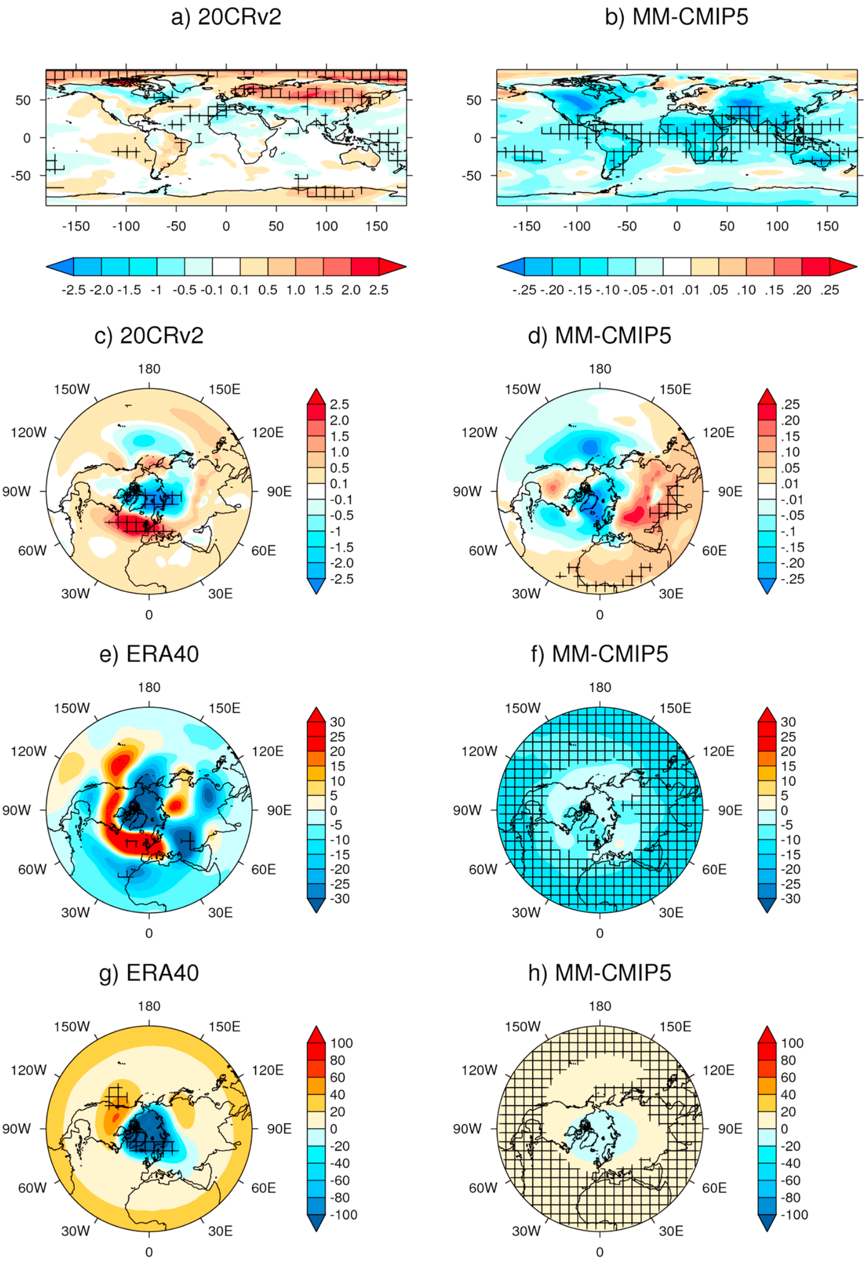

FIGURE 3.11 Composite surface temperature response for the two winters following nine volcanic eruptions: (a) observed and (b) CMIP5 multimodel mean of simulations. ENSO effects have not been removed, though these are expected to be smaller as a result of averaging. Note different scales for the two figures. SOURCE: Driscoll et al., 2012.

Model Estimates of Aerosol Forcing from SAAM

Aerosol production efficiency, transport, evolution, and loss vary with altitude, temperatures, and winds, among other factors. All methods that introduce aerosols into the stratosphere are expected to affect the reflection and absorption of energy (the aerosol forcing), which will then vary with time and season, unlike the idealized studies discussed in the previous section. The aerosol mass and number, and subsequent forcing, will be sensitive to (1) the mechanism used to produce and deliver the aerosol; (2) the location of the injection; (3) the vertical and horizontal transport processes that mix the aerosols (timescales of days to years); and (4) the chemistry and physical processes that produce, change, and deplete the aerosols (nucleation, condensation, evaporation and sublimation, coagulation, sedimentation, and scavenging). Figure 3.12 shows an example of the distribution of aerosols and the associated radiative forcing from a modeling study using a simple emission scenario.

Studies involving more realistic aerosol injection scenarios are in their infancy compared to sunlight reduction studies, and details regarding the formulation of the physical processes that control aerosol forcing and response matter a lot to study conclusions. Various modeling approaches have been used to explore SAAM that tend to fall into three distinct classes, or generations, based on their level of complexity in treatment of aerosol processes. First-generation studies used "bulk" formulations, where only total aerosol mass is predicted and the aerosol size distribution is assumed; second-generation studies used "modal aerosol formulations," where mass is predicted together with limited size distribution information; and third-generation studies used "sectional aerosol treatments," which attempt to follow the full size distribution.

First-generation formulations include studies by Jones et al. (2010), Kravitz et al. (2012a), Rasch et al. (2008b), and Robock et al. (2008). These studies assumed the source gas for the aerosols was SO_2 and generally concluded SAAM could produce substantial planetary cooling. Details (altitude, latitude, temporal injection strategies, and aerosol size) varied across studies but most concluded that less than 10 million tons of sulfur per year (MtS/yr) would be sufficient to counter the forcing associated with a doubling of CO_2 concentrations (~4 W/m^2). Atmospheric mixing would tend to distribute tropical injections in the lower stratosphere globally, and injections in a single hemisphere at high latitudes would dissipate more rapidly than an equatorial source but generally spread to the subtropics over a season (Robock et al., 2008).

Although many of the first-generation simulations of aerosols did not attempt to model the evolution in the size of aerosol particles, this is an important process

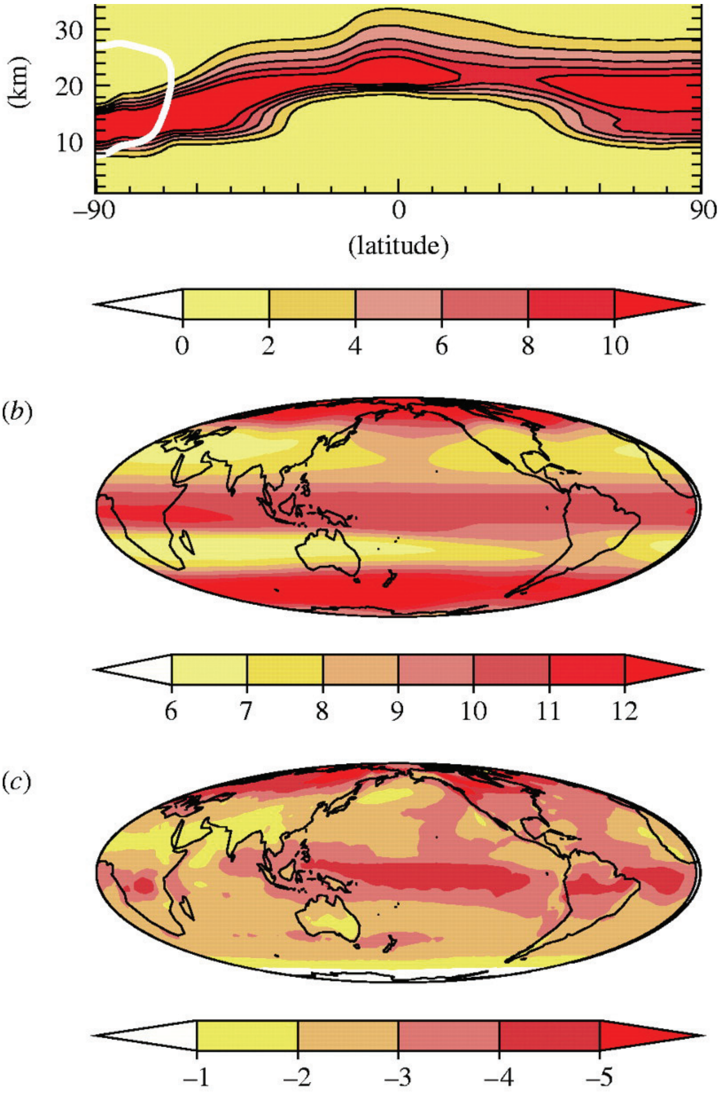

FIGURE 3.12 Example of albedo modification aerosols for June, July, and August from a 20-year simulation for a 2 MtS/yr emission: (a, b) aerosol burden (g/m^3 and g/m^2, respectively) and (c) forcing (W/m^2). The white contour in (a) shows the region where temperatures fall below 194.5 K and indicates approximately where ozone depletion may be important. SOURCE: Rasch et al., 2008b.

because large particles with diameters larger than about 0.6 μm reflect sunlight less effectively for a given aerosol mass (Penner et al., 2001) and fall faster, thus having a shorter lifetime, also making them less effective. Particle size also affects the strength of stratospheric heating, and ozone destruction (via the amount of surface area available for inhomogeneous chemical reactions). More comprehensive treatments of aerosol formation and evolution using second- and third-generation approaches (English et al., 2012; Heckendorn et al., 2009; Niemeier et al., 2011) have followed the early studies. Typically, climate models (e.g., Niemeier et al., 2011) use "modal" representations of particle size evolutions, which may be adequate (i.e., within 25%) if tuned to represent the more complete and substantially more expensive sectional models (Mann et al., 2012; Weisenstein et al., 2007). Clearly sectional models may also have difficulty, in comparison with Pinatubo measurements (see Heckendorn et al., 2009).

Studies with more complete treatments concluded that substantially higher injection rates would be needed because processes treated very simply in earlier studies (condensation on existing particles, coalescence, and accretion) act to produce larger particles than previously estimated (large particles descend more rapidly into the troposphere, where they are removed more rapidly and, as noted above, scatter sunlight less efficiently than small particles). English et al. (2012) summarized estimates for models that included a better treatment for aerosol microphysics and found that the injection rate for SO_2 to obtain a 6 MtS burden is five times higher than the injection rate predicted by simulations that assumed prescribed size distributions (e.g., Rasch et al., 2008a). The more comprehensive studies found that an increase in the SO_2 injection rate from 1 to 10 MtS/yr produced an increase in the peak column mass of sulfate by a factor of 5 and an increase in the peak aerosol optical depth (AOD, a measure of the aerosols' ability to attenuate light, which is thus related to the amount of cooling) by only about a factor of 3. AOD was reduced disproportionately for the larger injection rates because those rates produce larger particles. The peak in effective radius at 90 hPa (~16 km) varies from 0.4 to 0.6 μm in the three models studying albedo modification that employed second- and third-generation aerosol microphysics (English et al., 2012; Heckendorn et al., 2009; Niemeier et al., 2011). The more comprehensive treatments indicated that at least 10 MtS/yr (approximately the amount of sulfur injected by the Mount Pinatubo eruption) would be needed annually to maintain a radiative forcing of -4 W/m^2, roughly equal to but opposite that associated with a doubling of atmospheric carbon dioxide.

Studies have also explored the sensitivity of the albedo modification strategy to the characteristics of the aerosol source, changing the amplitude, source type (SO_2 gas, H_2SO_4 gas, or sulfate particles), and latitudinal extent (e.g., restricted to near the equator or pole, or extending over a broad band of latitudes, or a hemisphere). More realistic "plume" simulations that allow for faster rates of coagulation have only been performed in one model (Pierce et al., 2010). English et al. (2012) found, in contrast to Robock et al. (2008), that steady tropical SO_2 injection does not produce a hemispherically symmetric albedo modification, but instead produces albedo modification that is higher in the Northern Hemisphere (see Fig. 2 of English et al., 2012). A low bias was also found in their Southern Hemisphere Pinatubo results (English et al., 2013), so this result should be confirmed in other models, but it nonetheless may have important consequences for tropical precipitation (see the discussion of Haywood et al. [2013] in Box 3.4).

The most cost-effective strategy may be to have aircraft deliver a sulfate precursor to the lower stratosphere and inject it there where it is converted to gaseous SO_3 or H_2SO_4 (English et al., 2012; Pierce et al., 2010). The above studies used "sectional treatments" that allow an additional improvement in the representation of aerosol evolution for an increase in computational cost. Pierce et al. (2010) concluded that the direct injection of gas-phase H_2SO_4 would result in higher H_2SO_4 aerosol burdens than injecting the same amount of SO_2. An important component of that study was the use of a subgrid-scale "plume" model that treated the evolution of particles from just downstream of the source injection until it was diluted to a much larger region for the first 2 days following the precursor emission. English et al. (2012) did not attempt to treat the plume evolution, injecting the aerosols uniformly within model cells of a few-hundred-kilometer horizontal extent, and a few kilometers thick, and they did not find the improvement in efficacy associated with injection of H_2SO_4 seen in the Pierce et al. study, presumably because this process was neglected. It is clear that the technology associated with the injection (e.g., source, composition, and injection rate) matters, and the treatment of the aerosol distribution as it evolves in the plume downstream of the emissions is also very important. English et al. (2012) also estimated increases in upper tropospheric aerosol content by up to a factor of 100 when 10 MtS/yr of emissions were introduced, with potentially important consequences for high clouds.

The studies also indicated that different scenarios (e.g., latitude, altitude, and source type) with the same overall injection rate can increase the burden of aerosols by roughly 50% (see English et al., 2012, Fig. 6; Niemeier et al., 2011, Fig. 2). This discussion highlights the importance of the treatment of aerosol microphysics for the development of the aerosol size distribution and the sensitivity of the albedo modification for a given injection protocol to highly uncertain aspects of the modeled aerosol microphysics. Modeling of aerosol microphysics is still an area of active research, and more work is needed.

BOX 3.4 REGIONAL ALBEDO MODIFICATION

Several studies have looked at the possibility of doing a regionally focused deployment of albedo modification, in particular in the Arctic in response to the rapidly declining levels of Arctic sea ice. Robock et al. (2008) also explored Arctic injections and found that these scenarios produced much smaller aerosol loading, because the removal rate of aerosols is about four times faster in the Arctic than in the tropics. They found that the rapid horizontal mixing of aerosols in the stratosphere, with a lifetime of months or longer, would make it difficult or impossible to fine-tune the geographic pattern of albedo modification through control of the position and timing of SO_2 injection. High-latitude injections would spread to cover a substantial fraction of the hemisphere, though concentrations remain higher in the higher latitudes. The more localized albedo modification did achieve an increase in the amount of sea ice relative to the unmodified high-CO_2 case, but the climate response was not confined to the Arctic. They noted the potential for significant changes to precipitation in (Indian and Asian) monsoons, and to rainfall in the Sahel region of Africa. That study identified precipitation changes in those regions, but the differences were generally not identified as significant according to formal statistical tests.

Those signatures are consistent with a more recent study by Haywood et al. (2013), which noted that volcanic eruptions that injected aerosols into the Northern Hemisphere preceded three of the four strongest years of Sahelian droughts, and their model also produced a systematic shift in tropical rainfall patterns due to stratospheric aerosol injection. Northern Hemisphere injections shifted Sahelian rainfall southward, leading to serious drought conditions in the Sahel, and Southern Hemisphere injections shifted rainfall northward (similar shifts in rainfall were also apparent over South America). Such shifts in precipitation in regions of high and vulnerable population could have substantial impacts and much more work is needed to identify the robustness of the response.

A recent study by Tilmes et al. (2014) examined model simulations of idealized regional dimming experiments compared to a business-as-usual emissions simulation. They demonstrated that both local and remote feedback mechanisms are important to the surface energy budget in the Arctic. They found that it was necessary to use a local reduction of solar radiation four times stronger than the global reduction in order to preserve Arctic sea ice area and that even with regional Arctic dimming, a reduction of the oceanic meridional overturning circulation and a shutdown of the Labrador Sea deep convection were possible. They concluded that "Arctic regional dimming does therefore not provide a possible solution for containing Arctic sea ice for a business-as-usual greenhouse gas emissions scenario."

Although one might also anticipate differences between models in the transport of particles within the stratosphere, there has been little study of this aspect, possibly because of differences in experimental design between studies. Most studies to date have designed their simulations independently, for example using different experimental protocols or different assumptions about emissions. A more careful assessment can be performed through model intercomparisons in which emission characteristics (e.g., aerosol size, amount, and emission region) are carefully prescribed and treated uniformly between models and simulations. Furthermore, the range of possible choices as to which processes to include and the complexity with which they should be represented makes controlled intermodel comparisons more difficult to carry out and analyze. Compared to solar-constant reduction simulations, realistic aerosol injection simulations are in their infancy, but a recent model intercomparison project—GeoMIP (Box 3.1)—may help with this.

Model results from the GeoMIP experiment G4 (RCP4.5, 5 MtSO_2 tropical injection of sulfate each year for 50 years, followed by 20 years of cessation) have been examined by only three models that included interactive aerosols, and one of them appears to have had some inconsistencies (Model for Interdisciplinary Research on Climate—Earth System Model—Chemistry [MIROC-ESM-CHEM]) (Ben Kravitz, private communication). Nevertheless, the two remaining models have been compared (Ben Kravitz, private communication). These results show differences of a factor of 2 in the predicted burden of sulfate between the GISS-E2-R and HadGEM2-ES models over Antarctica in July, but results for the two models are similar over the Arctic and other locations and seasons. This difference may potentially be due to removal processes, rather than transport.

Modeled Climate System Responses to SAAM

Because of the relatively long lifetime of stratospheric aerosols described in the previous sections, the aerosol distribution and aerosol forcing will eventually spread, and models indicate it would be difficult to restrict the aerosol forcing to less than most of a hemisphere, although it may be possible to achieve some nonuniformity latitudinally. In the scenarios considered to date, aerosol burdens and forcing become sufficiently uniform that many of the idealized studies exploring temperature and precipitation responses to regional and global reductions in solar irradiance are also relevant to understanding the climate response to SAAM. In this section we briefly describe the climate responses that are common to the idealized studies discussed previously, but then we focus most attention on climate responses and issues that are unique to SAAM.

Temperature, water vapor, and precipitation. As in the idealized experiments, model simulations suggest that if stratospheric aerosol albedo modifications were increased to compensate for a forcing from a doubling or quadrupling of CO_2, equatorial surface temperatures would be somewhat cooler than an unperturbed planet, polar temperatures somewhat warmer, global averaged precipitation would likely be reduced, and the planetary response to SAAM termination would be much like that described in the section "Timescale Mismatch, Risks of Millennial Dependence, and Constraints on Strategies for Limiting the Duration of Reliance on Albedo Modification" in Chapter 2.

Robock et al. (2008), Rasch et al. (2008b), and Jones et al. (2010) explored the planetary response to steady tropical injections producing stratospheric aerosol perturbations that were quite symmetric between hemispheres. Using a first-generation bulk model, Robock et al. (2008) found tropical injection at a rate of 5 $MtSO_2$/yr (equivalent to one Pinatubo eruption every 4 years) produced a mean cooling of 0.3°C to 0.4°C relative to the unmodified state, and 10 Mt/yr produced a cooling approximately twice as great; for example, the forcing and response is approximately linear with respect to emissions. (Note that this degree of cooling is not borne out by models that treat more comprehensive particle microphysics [English et al., 2012; Heckendorn et al., 2009; Niemeier et al., 2010].) Jones et al. (2010) used a second-generation bulk aerosol model and estimated a temperature response approximately twice as large for a similar emission scenario. All three studies documented reduced precipitation relative to the preindustrial climate like that seen in the section "Idealized Simulations of the Effects of Albedo Modification" earlier in Chapter 3. Robock et al. (2008) and Jones et al. (2010) noted some effects on monsoon circulations. Recent modeling results as part of the GeoMIP set of experiments show that global temperature and precipitation changes are generally closer to preindustrial values with albedo modification (G3 simulations) compared to continued climate change without mitigation, but that "global temperature and precipitation are still redistributed globally" (Anderson and Ault, 2014). Several studies have explored the idea of regional albedo modification (Box 3.4). The discussion in Box 3.4 is also of relevance to climate interventions which were intended to produce a globally uniform aerosol layer, but which for one reason or another inadvertently resulted in significant regional inhomogeneities.

Clouds. As described in the section describing possible impacts below, stratospheric aerosols may affect clouds, but their impact remains poorly understood. Kuebbeler et al. (2012) noted that increases in stratospheric aerosol loadings will likely lead to an increased upper tropospheric temperature, stabilizing the upper troposphere, decreasing vertical velocity, and ultimately reducing ice crystal nucleation rates and producing optically thinner cirrus clouds. They estimated optically thinner cirrus clouds could exert a strong negative cloud forcing in the longwave which contributes possibly as much as 60% to the overall net forcing. However, their model did not include feedbacks of the stratospheric injection on stratospheric ozone, which is predicted to decrease (see "Environmental Consequences of SAAM" section below) and might lead to decreases in temperature. On the other hand, Cirisan et al. (2013) argued that the net radiative effect of aerosol-induced changes to number concentrations in high clouds should be small, but this study did not include feedbacks to temperature and humidity in the upper troposphere. Uncertainty in high cloud feedbacks represents a major uncertainty in estimating the climate response of a given amount of stratospheric aerosol injection.

Ozone and indirect radiative effects. Tilmes et al. (2008, 2009), Heckendorn et al. (2009), and Pitari et al. (2014) explored the impact of SAAM on ozone depletion and concluded that SAAM sufficient to counter a doubling of CO_2 would delay ozone recovery (due to the decrease in halogens) by a few decades. In one example from these studies, Pitari et al. (2014) in a GeoMIP model intercomparison estimated that in order to counter a fourfold increase in CO_2 concentrations, sulfate aerosol surface area density similar to conditions a year after the Mount Pinatubo eruption would be required, and there would be measurable impacts on ozone distributions and surface UV-B radiation. They estimated that if active chlorine (ClO_x) concentrations were characteristic of values expected in 2040-2049 that chemical reactions on the sulfate aerosols would decrease the globally averaged ozone by less than 1% (ozone would increase slightly at low and middle latitudes and decrease more strongly in polar regions). These changes are substantially smaller than the ozone depletion measured between 1980 and 2000 from ClO_x (McKenzie et al., 2011). They also concluded that any increase in UV-B radiation at the surface due to ozone depletion would be offset by the screening by the aerosols themselves in the tropics and midlatitudes, while in polar regions the ozone destruction effect would dominate the aerosol screening effect, and the surface UV-B radiation would increase by 5% on average, with 12% peak increases during springtime. Because ozone is a radiatively important gas (in the solar and longwave), changes in stratospheric ozone would also produce changes to the tropopause radiative forcing, estimated for the 2040-2049 decade to be less than $-0.1\ W/m^2$. Because ClO_x would continue to decrease after 2050, the suppression of other ozone-destroying reactions (involving nitrogen) becomes more important than destruction of ozone by ClO_x, and SAAM was estimated to increase total stratospheric ozone after 2050.

Tilmes et al. (2009) used a whole-atmosphere model with a fully resolved representation of the stratosphere and concluded that the detailed stratospheric response had an important effect on the geographic pattern of the tropospheric and surface response to stratospheric aerosol injection. In particular, the high-latitude response to stratospheric aerosol injection was much weaker in the simulations with a resolved stratosphere than in simulations that did not adequately compute the stratospheric response. The weakened polar response implies a less effective offset of CO_2-induced polar warming, which is important insofar as preserving Arctic sea ice and permafrost is an often-assumed goal of albedo modification. Stratospheric heating can affect the stratospheric water budget, particularly when the aerosol distribution is significantly nonuniform. Accurate simulation of the stratosphere-troposphere connection requires fully resolved stratospheric dynamics and is currently a considerable modeling challenge.

Sea ice. Berdahl et al. (2014) carried out a limited multimodel study of the Arctic response to two stratospheric aerosol-injection scenarios intended to produce a globally uniform (rather than Arctic-limited) albedo modification. The scenarios were constructed to fix the top-of-atmosphere energy balance at 2020 levels (which already has a positive energy flux into the Earth system) or fix the stratospheric aerosol forcing at 2020 levels while CO_2 forcing continued to increase. They found, not surprisingly, that global mean warming and reduction of sea ice continued past the year 2020, because the model experiments were (by design) not intended to entirely counter the radiative forcing by greenhouse gases. In these simulations, aerosol injection delays, but does not prevent, the ultimate loss of September Arctic sea ice. There was also considerable discrepancy among the models as to the effectiveness of the aerosol injection at delaying the loss of sea ice, but further work will be needed to ascertain the source of this discrepancy. This also gives a good indication of the additional kinds of simulations that may become available as GeoMIP2 progresses.

Land biosphere and carbon cycle. Land biosphere models and global carbon-cycle models have been integrated into three-dimensional coupled atmosphere-ocean physical climate models and have been used to assess the likely response of the land biosphere and global carbon cycle to inadvertent human-induced changes to atmospheric composition and climate (IPCC, 2013a). These models project that, under the anthropogenic climate change scenarios considered by the Intergovernmental Panel on Climate Change (IPCC), higher carbon dioxide concentrations would likely increase productivity of the land biosphere nearly everywhere (a result of CO_2 fertilization), but human-induced climate change tends to decrease biological productivity in the tropics and midlatitudes (a result primarily of heat stress and secondarily of water stress) and tends to increase biological productivity in the northern high latitudes (IPCC, 2013a, Fig. 6.2). Insofar as albedo modification approaches are able to offset climate change effects of increased atmospheric greenhouse gas concentrations, they would be expected to have no effect on the increased productivity that would be expected as a result of increased atmospheric CO_2 concentrations, but they might tend to increase the productivity of the land biosphere in lower latitudes due to the removal of heat stress in the tropics. These expectations are supported by idealized studies performed as part of the GeoMIP project (Figure 3.13; Kravitz et al., 2013a).

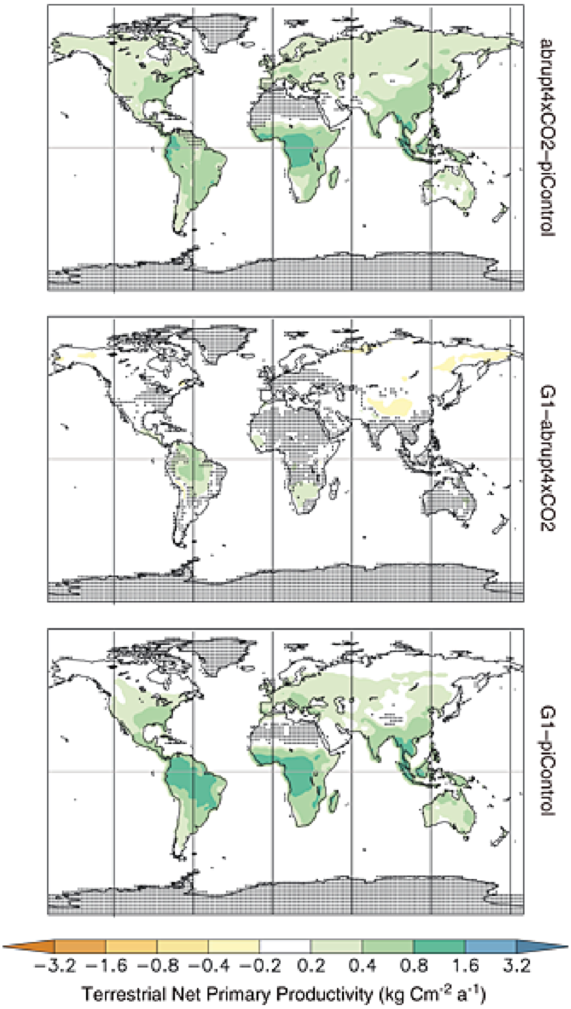

FIGURE 3.13 All-model ensemble annual average differences in terrestrial net primary productivity (kg C m^{-2} a^{-1}), averaged over years 11-50 of the simulation. For these panels, "abrupt4xCO_2" is a climate with a quadrupling of the CO_2 concentration, "G1" is a climate with a quadrupled CO_2 and a reduction in sunlight sufficient to return the global average surface temperature to a reference state, and "piControl" is the preindustrial climate. Top panel shows abrupt4xCO_2-piControl, middle panel shows G1-abrupt4xCO_2, and bottom panel shows *G1-piControl*. Stippling indicates where fewer than 75 percent of the models (for this variable, 6 out of 8) agree on the sign of the difference. SOURCE: Kravitz et al., 2013a.

In climate model projections with a dynamical representation of the carbon cycle, the land biosphere takes up more carbon with albedo modification than it would have in the absence of albedo modification, and because of cooler ocean surface temperatures the ocean also takes up more carbon (Matthews and Caldeira, 2007). Thus, atmospheric CO_2 increases may be moderated somewhat (<20 percent; Matthews and Caldeira, 2007) by carbon-cycle response to large-scale albedo modification. These simulations did not consider the increases in diffuse radiation that would be caused by stratospheric aerosols, which would be expected to further increase carbon sequestration by the land biosphere (Mercado et al., 2009). Changes in the total amount of sunlight are anticipated to have much smaller effect on net primary productivity (Bala et al., 2002; Kravitz et al., 2013a; Matthews and Caldeira, 2007).

One concern about albedo modification for the purposes of intentional climate modification is the projection that precipitation would decrease globally (Bala et al., 2007) (see also discussion associated with Figure 3.3). However, at global scale, precipitation must balance evaporation, and the decrease in precipitation is associated with decreased evaporation, resulting largely from a moistening of the boundary layer over the ocean (Cao et al., 2012). An important question for the land biosphere is thus how atmospheric water vapor transport to the land biosphere is affected by albedo modification. This net transport represents the balance of changes in precipitation and evaporation. The results of the GeoMIP project (Kravitz et al., 2013a; Figure 3.4) indicate that "precipitation minus evaporation anomalies are less than 0.2 mm day^{-1} in magnitude over 92 percent of the globe, but some tropical regions receive less precipitation." Further discussion of changes to the hydrological cycle from albedo modification is found in the "Idealized Simulations of the Effects of Albedo Modification" section above.

Detailed projections of land biosphere models at regional scale have large uncertainties, but the models indicate the sign of likely responses to various climate forcings. For example, if soils were projected to become parched, the models would project low amounts of net primary productivity. The GeoMIP results (Kravitz et al., 2013a) and results from other modeling groups (cf. Bala et al., 2002; Matthews and Caldeira, 2007; Naik et al., 2003) indicate that, at global scale, albedo modification by stratospheric aerosols in a high-CO_2 world would have little detectable effect on land biological productivity in most places but could in some places cause significant increases or decreases in land biological productivity. Relative to the preindustrial state, a high-CO_2 world with albedo modification is projected to have higher biological productivity in nearly all land areas, largely due to CO_2 fertilization. These projections of changes in biological productivity of natural ecosystems are consistent with projected changes in expected crop yields (Pongratz et al., 2012; Xia et al., 2014). Climate models do not project substantial consequences of sudden termination on the land net primary productivity beyond what would have occurred had albedo modification never been implemented (Jones et al., 2013; Matthews and Caldeira, 2007), although what sudden termination would mean at the species level remains an open question.

Increased net primary productivity on land is not necessarily a positive outcome for natural ecosystems. Changes in the amount and quality of light, and the patterns of precipitation and evaporation, as well as changes in atmospheric composition and possibly other factors like cloudiness and winds could be expected to disturb natural ecosystems with consequences that at this time are difficult to predict. For example, it is entirely possible that net primary productivity would increase in some areas but that this increase in net primary productivity would be accompanied by the extinction of some native flora and fauna. Furthermore, almost all of the model results described above are based on a limited set of idealized studies, many of which considered dimming the sun instead of actually representing atmospheric aerosols. Many of these simulations did not consider effects of diffuse radiation or include adequate representations of nutrient dynamics. All such simulations are greatly simplified compared to the real world, and further work is required to reduce the uncertainty in these projections.

Acid deposition. Although SAAM would substantially increase the amount of stratospheric sulfate, it is a small source and sink of sulfate compared to other natural and pollution sources that contribute to the acidity of land and ocean and is not expected to have an important impact on planetary ecosystems (see section "Environmental Consequences of SAAM").

Observational Requirements for SAAM

Observational requirements for SAAM should be at a level sufficient to quantify the evolution of the source material introduced to form aerosol particles and the resulting radiative response. This would include quantifying the amount of source material (SO_2 or sulfuric acid) injected, its rate and direction of spread with time, the formation of H_2SO_4, the size of the particles formed, their effect on cirrus clouds, and their effect on Earth's radiation budget. These requirements are relevant to activities initiated as a result of a concerted world effort or via unilateral and uncoordinated actors. Important impacts on climate are anticipated with albedo modification activities of 1 W/m^2 of radiative forcing reduction or less. Detection of this amplitude of SAAM would require determination of Earth's solar radiation budget to an accuracy of better than 1 W/m^2.

The current U.S. aerosol monitoring from space relies on the MODIS,[3] MISR,[4] and OMPS[5] instruments, and the CALIPSO[6] mission, although a number of other aerosol products are available on instruments from Europe and Canada.[7] The stated accuracy for MISR AOD is about 0.03 or 10 percent, whichever is larger. The MODIS team reports their sensitivity as 0.03 ± 5 percent, which in practical terms is similar to the accuracy of MISR over ocean, since the AOD over ocean is generally low. These accuracies can be compared to the predicted peak zonal average increase in AOD for a 1 MtS/yr injection rate of around 0.05 (English et al., 2012). Such a nearly full-blown experiment would be barely detectable. A modeled 10 MtS/yr injection produced a peak zonal average increase in AOD of 0.2 and so should be easily detectable with current instrumentation.

The OMPS instrument measures SO_2 as well as AOD, but it is a limb profiler. The stated limb profiler sensitivity is 3×10^{-6} km^{-1} for a 1- to 2-km vertical resolution. Thus, this instrument should be capable of monitoring changes of order 0.001 in AOD. However, as this is a limb measurement, it integrates over a path along the line of sight; through the lower stratosphere, for example, the path is effectively 300 to 400 km long, so an aerosol feature would have to be concentrated along the actual line of sight of the limb sounder during occultation to detect something as thin as 0.001 in AOD. The advantage of this instrument, however, is that, in addition to obtaining perturbations to SO_2, the approximate altitude of the aerosol layer would be known. This provides a great advantage for validation of model results.

The CALIPSO instrument uses backscattered radiation from a downward-pointed lidar, which can give information on the vertical distribution of the detected aerosols in the fairly narrow region where the lidar is pointing. The European/Japanese EarthCARE satellite mission, scheduled for launch in 2015,[8] will also use this technology. Winker et al. (2009) estimated that a single shot from the CALIPSO lidar is not accurate to 0.01 $km^{-1}sr^{-1}$ so horizontal averaging is used to improve the detection of backscattering coefficients from aerosol layers. However, Kacenelenbogen et al. (2011) compared results from the Version 2 CALIOP AOD retrievals to those from other instruments and found they were significantly smaller than other retrievals.

As noted in the section examining the processes that produce H_2SO_4, it might be important to also obtain measurements of the aerosol size distribution in order to

---

[3] Moderate Resolution Imaging Spectroradiometer.

[4] Multi-angle Imaging SpectroRadiometer.

[5] Ozone Mapping Profiler Suite.

[6] Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation.

[7] See https://sites.google.com/site/iavceirscweb/nrtso2 and http://odin-osiris.usask.ca.

[8] See http://www.esa.int/For_Media/Photos/Highlights/EarthCARE.

aid in determining the efficacy of injections. However, current remote sensing instrumentation is not very sensitive to aerosol size and is unlikely to be able to pick up a signal from stratospheric injection. Thus, detection of a stratospheric injection signal would depend on the specifics of the observation (see discussion of OMPS detection above, for example). Among the current generation of instruments, we can retrieve about three to five size bins with MISR, provided that the total column midvisible AOD exceeds about 0.15 or 0.2. A multiangle, multispectral, polarimetric imager could improve on current capabilities. With a next-generation instrument, with polarization sensitivity on the order of 0.5 percent, in addition to the 1 percent to 3 percent absolute radiometric calibration similar to MISR and MODIS, we expect greater sensitivity to particle size distribution. Qualitatively, such an instrument would be expected to provide an additional measure (moment) of the particle size distribution (e.g., giving mean effective radius plus size distribution width or variance), but the quantitative sensitivity is not well constrained at this point, and no specific instrument design is slated for building and launch. Aerosol size distributions can be measured from balloon-borne instruments, as was demonstrated after the eruption of Mount Pinatubo, but these measurements are limited in spatial coverage.

The lifetimes of the above instruments and satellites were estimated as part of the Midterm Assessment of Earth Science Decadal Survey Report, which was based on the 2011 NASA Senior Review of each instrument. According to that report, MODIS on Terra is expected to last through 2017, and MODIS on Aqua through 2018 (extended to 2022 in the 2013 NASA Senior Review) (both limited by mission life, not instrument life). MISR is expected to last through 2017 (Terra life expectancy); OMPS on NPP was not covered as part of the Senior Review, but could be expected to last through its design life plus 4 years (the long-term average used for the original Decadal Survey), so it should last through 2019. CALIPSO is expected to last until 2016.[9]

In addition to the capabilities above, it would be wise to maintain a stratospheric monitoring capability in order to capture information relevant to albedo modification in the event of a volcanic eruption that injected SO_2 into the stratosphere (Box 3.5).

Environmental Consequences of SAAM

A variety of consequences are anticipated to arise from significant changes in stratospheric aerosols. The processes producing these changes are described in the sections

---

[9] Details supplied by Stacey Boland, personal communication.

BOX 3.5 OBSERVATIONAL REQUIREMENTS FOR MAKING BETTER USE OF VOLCANOES AS NATURAL EXPERIMENTS

Observational capabilities must be in place to determine the following quantities in order to make effective use of volcanic eruptions as natural experiments:

- Mass, composition, and vertical distribution of the substances injected into the atmosphere by the eruption;
- Resulting aerosol properties and their evolution in space and time, as well as associated changes in stratospheric chemistry, notably related to ozone; and
- Changes in radiative forcing. This includes top-of-atmosphere measurements of albedo change, perhaps supplemented by ground-based or aircraft-based short-wavelength radiation measurements, but there is also a need to monitor long-wavelength (infrared) changes, since these are involved in aerosol-induced stratospheric heating.

Sufficiently large eruptions will produce a temperature response in the upper atmosphere as well as at Earth's surface, which will also need to be monitored as a basis for testing simulations of the response of climate to the eruption. The chief impediment to characterizing climate response is separating the volcanically forced response from effects due to natural variability such as El Niño or the Quasi-Biennial Oscillation, and it is unlikely that any improvements over the existing temperature and precipitation monitoring network would significantly ameliorate the problem. It would also be desirable to monitor the response of cirrus clouds to the eruption, though distinguishing between microphysical effects of the volcanic aerosols and cirrus changes arising from the general climate response is likely to be a challenge.

Advanced preparation will be needed if scientists are to make the best use of the next major volcanic eruption. Although Pinatubo is the best characterized eruption to date, ironically our ability to monitor stratospheric aerosols has deteriorated since that time, with the loss of the Stratospheric Aerosol and Gas Experiment (SAGE) II and III satellite-borne instruments. SAGE III was capable of limb-scanning measurements of aerosol optical depth as well as vertical profile measurements of aerosol optical depth. If the SAGE III on ISS launch is successful, some of this capability will be restored. SAGE III on ISS is scheduled to be the first mission launched by the commercial Space-X vehicle in 2015, and to be deployed on the International Space Station (ISS). The ISS platform and its low-inclination orbit are not ideal for aerosol monitoring but would provide some useful capability. Maintaining SAGE III on ISS or a similar capability for the next several decades is a minimal requirement; it is possible that a more economical platform, more specifically targeted to stratospheric aerosol monitoring, could eventually replace the SAGE family. The Optical Spectrograph and Infrared Imaging System (OSIRIS) satellite-borne instrument has been used effectively in the post-SAGE years (Kravitz et al., 2011b), but this instrument is running past its designed lifetime and may not last much longer.

Some capability for monitoring Earth's radiation budget and the factors that influence it already exists. These include instruments such as the Clouds and the Earth's Radiant Energy System (CERES) satellite instruments, which measure the various components of Earth's radiation

continued

BOX 3.5 CONTINUED

budget, and the CALIPSO mission, which measures the vertical structure of clouds and aerosols. Any improvements that could be made with regard to accuracy, coverage, and spatial resolution would greatly enhance the ability to understand the nature of the volcanic response and address shortcomings in the ability to simulate it accurately. Moreover, while the most recent CERES instrument, launched on Suomi-NPP, is expected to operate for at least several more years, CALIPSO, which has been operational for nearly 8 years, is well past its 3-year design life.

There is also a need for a deployable rapid-response observational task force, but any such capability would need to have multiple uses so that the considerable investment required would not lie fallow between major eruptions. Ground-based and airborne lidar instruments—which work by emitting and measuring how much laser light bounces back from aerosols—are valuable for characterizing the volcanic plume and resulting aerosols; lidar has been used effectively in characterizing recent eruptions (Kravitz et al., 2011b). There may also be a role for selective deployment of ground-based and airborne radiometers for the purposes of refining estimates of the amount of solar radiation transmitted through the stratospheric aerosol mass. Some in situ monitoring of stratospheric chemistry, particularly targeted at ozone chemistry, would also be needed. Data collection alone will not be sufficient; there also needs to be an appropriate level of investment in data analysis, running simulations for comparison, and subsequent model development to correct shortcomings.

If there were a standing monitoring capability to rapidly respond to a volcanic eruption, the question would remain as to whether an eruption would be expected in the next few decades. At this point, it is not possible to predict future volcanic eruptions with more than a few days lead time at best and not all eruptions can currently be predicted. Using statistics from the past 1,500 years, there have been 50-year periods with no large eruptions (1912-1963) and 50-year periods with as many as four large eruptions, including the largest, the 1257 Samalas eruption. Analysis of data from 1750 to the present suggests that the time period is too short to give reliable estimates of return periods for large explosive eruptions (Ammann and Naveau, 2003; Deligne et al., 2010).

As such, a rapid response system may be heavily subscribed for the purpose of posteruption observations, or undersubscribed, depending on the amount of volcanic activity. A wise strategy would be to have a dual use for such a system so that it would be available for rapid and sustained deployment immediately following a volcanic event but would also be useful even without substantial eruptions. Such a capability would have significant value for basic atmospheric research, providing data that would improve process models as well as large-scale climate models.

"Idealized Simulations of the Effects of Albedo Modification" and "Modeled Climate System Responses to SAAM" above, and are repeated here for clarity:

- Increased aerosol will affect stratospheric ozone depletion. Current understanding indicates that ozone depletion should diminish in the future as halogen levels decrease.

- There may be impacts on UV-B light reaching the surface, affected by the ozone depletion, and the aerosols themselves. Current understanding indicates the changes would be small.
- If SAAM were employed, there would be changes to precipitation, surface temperature, and soil moisture that may have an impact on ecosystems. Current understanding indicates the changes would be much smaller than those experienced if SAAM were not employed.
- Sunlight intensity would be reduced, but the amount of sunlight arriving from different directions would increase due to scattering on the aerosols (resulting in an increase in the ratio of diffuse to direct sunlight). More sunlight would reach into the plant canopy, increasing photosynthesis, again with possible impacts on natural and managed ecosystems. Sunlight reduction could also affect home heating and solar power facilities.
- Introduction of stratospheric aerosols is likely to slightly increase the acidity of the snow and rain reaching the surface. The effect is estimated to be a very small fraction of the acidity increases associated with industrial pollution today. Thus, any important effects might be counteracted by controlling anthropogenic emissions within the troposphere (Kravitz et al., 2009; Rasch et al., 2008b).

There is also of course the possibility of environmental consequences that scientists have not yet identified. It is interesting to consider how scientists would identify an environmental consequence (including detection and timescale). It should be more straightforward to characterize the impacts on chemistry, light intensity, and precipitation. On the other hand, it will be much more difficult to detect impacts on ecosystems.

Technical Feasibility of SAAM[10]

To date, there have been no deliberate attempts to deliver sulfate aerosol precursors to the stratosphere with a controlled release and a monitoring program to assess the destiny of the source species as the aerosols form, evolve, disperse, and eventually disappear. As such, all estimates of the technical feasibility are currently theoretical, based on observations of aerosol forcing following volcanic eruptions, modeling studies, and some measurements of plume dispersions behind aircraft and rockets from the early 1970s (Turco and Yu, 1997, 1998, 2012). These studies are not sufficient to provide robust estimates of the development and evolution of the aerosol.

---

[10] See Appendix E for a larger discussion of feasibility.

For reference, artificially duplicating even a relatively small volcanic eruption such as Sarychev in 2009, which ejected 1.2 Tg of sulfur dioxide into the atmosphere, would require a substantial undertaking. The sulfur dioxide loading is roughly equivalent to the total payload capacity of 27,000 flights of an Airbus A330-300 aircraft, and even this comparison understates the difficulty of the injection as commercial aircraft cannot fly high enough to duplicate the required stratospheric injection levels. Specialized aircraft (or other injection platforms) would be needed to carry out the injection. It is unclear at present whether any substantially smaller-scale field experiment involving modification of the stratosphere could begin to compete in scientific payback with what can be learned through assiduous study of the volcanic response (Robock et al., 2010).

The main issue regarding the feasibility of this strategy is associated with an accurate characterization of the aerosol source as it is released into the atmosphere from the delivery mechanism (how much new particle formation, how much vapor deposition on existing particles, and how much coalescence of new particles) as the plume disperses. These characteristics influence decisions about the strategy of delivery and govern the efficacy of the strategy (radiative forcing per unit emission of sulfur). It is also possible that the environmental consequences mentioned above could lead to a decision that the strategy is infeasible.

Costs

Robock et al. (2009b) and McClellan et al. (2012) have estimated costs of various delivery mechanisms to take sulfur to the stratosphere, but they did not address the issue of then producing aerosols with a desired size distribution. McClellan et al. estimated costs based on new aircraft designs optimized for delivery of sulfur, followed by in situ oxidation, to be $1 billion to $3 billion per MtS/yr to the stratosphere (20 to 30 km) or $2 billion to $8 billion to deliver 5 Mt to the same altitude range. There are similar estimated costs for hybrid airships that produce a majority of lift force from buoyancy and a smaller percentage from aerodynamic forces, but their large surface area complicates operations in high-altitude wind shear, and development costs were more uncertain. Commercially available aircraft, although poorly suited for high-altitude flight and significantly more expensive per mass of aerosol, could be used to deliver aerosol source species to about 18 km for exploratory work. "Pipes suspended by floating platforms provide low recurring costs to pump a liquid or gas to altitudes as high as 20 km, but the research, development, testing and evaluation costs of these systems are high and carry a large uncertainty; the pipe system's high operating pressures and tensile strength requirements" (McClellan et al., 2012) make their feasibility very uncertain, and their ability to deliver aerosols distributed across broad swaths of the atmosphere is limited. Costs for rockets and guns appear to be significantly higher than for other systems, but they may also be suitable for exploratory research, or for delivery to very high altitudes. As a general caution, it is noted that many large-scale engineering projects experience higher costs than initially estimated, so all such cost estimates are likely to have significant uncertainties.

These estimates do not appear to account for costs associated with operating in an environment of high concentrations of SO_2 and sulfate aerosols, but there is some evidence these issues should be considered. Carn et al. (2009) pointed to an increase in the incidence of crazing of acrylic windows (Bernard and Rose, 1990; Casadevall et al., 1996), forward airframe damage, and accumulation of sulfate deposits (anhydrite and gypsum) in turbines that block cooling holes, causing engine overheating (Casadevall et al., 1996; Miller and Casadevall, 2000), following the El Chichón (1982) and Pinatubo (1991) eruptions. Increases in aircraft damage would presumably increase the cost of deployment.

The cost of a responsible deployment strategy involves not just the cost of aerosol injection, but the cost of observing systems and infrastructure to detect and attribute the magnitude of and response to albedo changes from stratospheric aerosol injection. Estimating the full costs of an observing system and infrastructure to do this was beyond the charge of this committee, but these costs are generally estimated to be significant, as typical satellite deployment costs often run into the billions of dollars.

Unresolved or Less Tangible Issues for SAAM

There are a variety of other issues that have been raised regarding SAAM. These issues are real, and they must be considered and balanced when considering the other consequences, and possible benefits, from SAAM. This section includes several examples but is not a comprehensive list. One example, as pointed out by Robock (2008), is that SAAM would tend to "whiten" the sky (Kravitz et al., 2012a), as well as produce more colorful sunsets by increasing the scattering of sunlight. In addition, changes in direct versus diffuse sunlight may produce changes in ecosystems in the long term. For example, they would be expected to stimulate productivity in the understory of land ecosystems. Changes in UV-B light could also have an effect. Various crops need to be studied, as well as further studies on natural systems, in order to better quantify these types of impacts. Other examples of these types of issues have been compiled elsewhere (Robock, 2008, 2014), and these types of issues may need to be considered as part of an assessment of environmental impacts of SAAM.

Summary and Statement of Research Needs for SAAM

There are many component processes that are not sufficiently well understood to produce quantitative characterization of processes important to SAAM, and unambiguous statements about how an intervention by SAAM would affect the planet are thus not possible. Several processes are particularly deserving of attention from both modeling and measurement points of view because they are critical to any implementation of SAAM and are unique to SAAM strategies of climate intervention:

- stratospheric aerosol microphysics (formation, growth, coalescence, and dispersion);
- impacts on chemistry (particularly ozone);
- impacts on water vapor in the upper troposphere and lower stratosphere; and
- effects of additional aerosol on upper tropospheric clouds.

Because these processes are simplified and approximated in models, it is difficult for models to produce quantitative (or even, in some cases, qualitative) characterizations of SAAM or any resultant impacts (good or bad) to the planet. More research (measurements and models) would be needed if more precise statements about SAAM and its potential to benefit or harm the planet are desired.

More and better observations would be useful to (1) fill in the blanks in understanding and model treatments, (2) more strongly constrain models, and (3) provide the testbed needed to evaluate model performance. Better models and a better understanding of their limitations would produce more confidence in the predictions. The committee attempts to identify a few obvious opportunities for producing better understanding and the reasons why we think these things are important.

Modeling

- Because models often disagree, it is important to compare them frequently—to each other (with varying details of complexity) and to observations. This motivates at least four kinds of intercomparison activities:
    1. Better intercomparison of climate models using varying treatments of aerosol microphysics and employing scenarios that are more strongly constrained (in terms of the type, amount, and altitude of precursor emissions) than have been hitherto performed by the GeoMIP studies would help in understanding model uncertainties and their projection of climate consequences. Historically, GeoMIP has focused most of its attention on solar dimming experiments. It is time to put more emphasis on aerosol formation and evolution, and subsequent impacts on clouds, chemistry, and cli-

mate. When differences are evident it is important to identify the reasons for the difference rather than produce an inventory of model simulation variations.

2. There is a variety of climate components that have as yet been almost entirely neglected, and more attention is merited, in particular toward (a) impacts on ocean circulations; (b) consequences to ecosystems from possible UV-B changes; (c) interactions of SAAM with dominant modes of interannual variability, volcanic eruptions, and other unpredictable or unpredicted events; (d) dynamic influences of the stratosphere on the troposphere, as they seem to have the capability for profoundly influencing the nature of high-latitude response, and therefore sea ice and glaciers. Other features (e.g., temperature) have received much more attention, but precipitation features (including monsoons) remain a particular challenge and continued attention is merited.
3. Intercomparison between global-scale model formulations of aerosol, clouds, chemistry, and aerosol dispersion and finer-scale models (box and plume models) is useful. Such comparisons would challenge the simplified formulations present in global models with the much more detailed formulation present in the fine-scale models. Only a few such comparisons have been made so far, and the relevant studies differ sufficiently to make identification of common features and deficiencies difficult. More uniform, internally consistent, and comprehensive comparisons would help.
4. Comparisons between global models and relevant observations, particularly those following volcanic eruptions, are useful. An increasing emphasis on comparisons with data sets constructed from present and future field studies and satellite data sets that are designed to challenge models could be helpful (see discussion below). Comparisons of model simulations to "*de minimus*" deliberate introduction of aerosol to assess aerosol microphysics, mixing processes, and impact on local atmospheric chemistry may also be useful.

- The response of the climate to volcanic eruptions is likely to provide one of the best opportunities for challenging a model's global characterization of SAAM and its impact on the environment. The ability of climate models to simulate the aerosol evolution, and the subsequent response of the Earth system to past and future volcanic eruptions, is a necessary but not sufficient test of any model's capabilities in assessing climate change. Improved observations discussed below could provide increasingly more comprehensive and stringent tests for climate models.

Field studies, lab experiments, and remote sensing. Although model intercomparison can give a sense of the uncertainty in model predictions, it cannot by itself establish that the models have included the correct physics to the correct level of fidelity. There is a need to develop experiments at the correct scale to test the models and model components and to have the tools available to observe the formation and removal of particles following a stratospheric volcanic eruption. Several actions would be beneficial:

- There is a variety of topics in which field and laboratory studies would help to improve understanding about components critical to SAAM. Some of these studies would probably fall into the category of "de minimus" studies, that is, studies that would have no measurable effect on climate but would provide information that would help in the development, calibration, and evaluation of models and the processes in models.
- At present it is not clear whether a small field experiment involving injection of substances into the stratosphere could resolve the outstanding scientific questions without being of a scale large enough to be considered as deployment (see, however, Keith et al., 2014). For proposals for small-scale projects that inject materials into the stratosphere with environmental risks comparable to ongoing commercial or other permitted activities and that address unresolved scientific issues pertaining to stratospheric aerosol injection, development and peer-reviewed analysis of those proposals should be considered by a transparent deliberative process to aid in developing clear guidelines (see Chapter 4).
- The committee sees opportunities and needs for better measurements in characterizing particle formation, particle growth, particle dispersion, and chemical and radiative consequences that are relevant to SAAM.
- There are also obvious opportunities to make better measurements of volcanic eruptions. The committee suggests that increased attention to satellite measurements of stratospheric aerosols and features that respond to aerosol perturbations would be useful to understanding the consequences of SAAM.
- A rapid-response observational capability to make better use of the next major volcanic eruptions (Box 3.5) would also be very useful in characterizing possible consequences of SAAM. This capability would involve space-borne capabilities for monitoring stratospheric aerosols (which would of necessity be multiple use, since large volcanic eruptions are infrequent) and rapidly deployable ground-based and airborne instruments. As discussed above, associated modeling work is required, particularly with models that resolve stratospheric dynamics and which model the chemistry bridging the injected substances to the formation of aerosols (see Appendix D for further details).

The committee emphasizes that the sociopolitical risks of both modeling and field research be considered, even for experiments that may yield useful scientific information, in light of public perceptions. This is further discussed in Chapter 4.

Albedo Modification by Marine Cloud Brightening

Low clouds, particularly over dark ocean surfaces, play a very important role in Earth's energy budget by scattering sunlight back to space that would otherwise reach and warm the surface. Because of the low albedo of the ocean surface and the "whiteness" of ocean clouds that very efficiently reflect sunlight back to space, rather modest changes in cloud albedo, cloud lifetime, or cloud areal extent might produce significant changes to both local and planetary albedo (Slingo, 1990). Low-lying stratocumulus clouds cover 20 percent to 40 percent of the world's ocean as a fraction of the daytime annual average, as illustrated in Figure 3.14 (Russell et al., 2013).

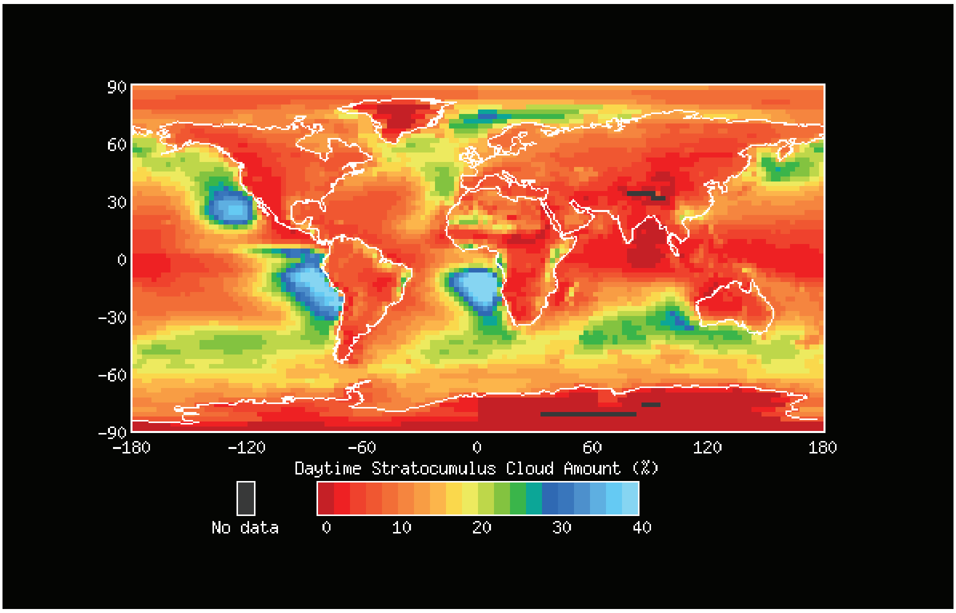

FIGURE 3.14 Daytime annual average stratocumulus cloud amount (%) over the 1983-2009 period, specifically the subset of low clouds that can be viewed from space without overlying clouds.
SOURCE: Figure adapted from Russell et al. (2013) using data obtained from International Satellite Cloud Climatology Project (ISCCP) D2 monthly means (http://isccp.giss.nasa.gov/products/browsed2.html).

Using simple theoretical arguments based on the work of Twomey et al. (1968), Latham (1990) suggested that it might be possible to deliberately introduce additional aerosols to act as cloud condensation nuclei (CCN) near the cloud base, increasing cloud drop number and changing the properties of clouds in their vicinity to make them more reflective. These ideas have come to be identified as "marine cloud brightening" (MCB). The processes that control this response of clouds to additional aerosol particles remain poorly understood (IPCC, 2007b), even though they are very important regulators of the energy budget of the planet. These low-cloud changes are often (but not always) assumed to occur over rather small regions of the planet, meaning that very large changes in local energy fluxes would be needed to produce a significant planetary-scale change.

Science Underlying the Marine Cloud-Brightening Concept

Twomey (1974, 1977) calculated that cloud systems with smaller and more numerous drops would reflect more sunlight than systems with bigger and fewer drops, all else being equal (size, cloud depth, and amount of condensed water). This is because the surface area of the smaller drops is larger (for the same volume of liquid water), and light scattering is proportional to surface area. Albrecht (1989) observed that cloud systems with smaller and more numerous drops might precipitate less easily. Later studies examined the possibilities that these more polluted clouds with smaller drops might hold condensed water for longer times, might persist for longer periods of time, and might extend over larger areas than they would if they were composed of fewer, larger drops. All of these mechanisms can influence the planetary albedo.

Liquid drops in warm clouds always originate on aerosol particles, typically through a drop formation mechanism first described by Köhler (1921). The proclivity of aerosol particles to serve as nuclei for drop formation depends on the aerosol size, chemical composition, and surface properties. Larger particles (typically >1 μm in diameter) with compositions that interact easily with water vapor (hydrophilic particles) are called cloud condensation nuclei. Aerosol particles that take up water vapor more readily form cloud drops more easily than those that do not, and larger hydrophilic particles "compete" with other particles, growing to cloud drops rapidly in a saturated air mass and eventually either forming precipitation or evaporating after they are exposed to unsaturated air for a time.

MCB is an attempt to increase the albedo of cloud systems by introducing extra aerosol particles to serve as CCN in air masses that participate in cloud formation. There are many different types of clouds, and each type is driven by subtle but important differences in the balance of processes that govern cloud formation and evolution. Different cloud regimes are likely to have differing susceptibility to brightening strategies. Various theoretical, observational, and empirical approaches can be used to identify clouds that are susceptible to aerosol brightening, that is, most likely to be brightened effectively by particles (see Figure 3.15) (Oreopoulos and Platnick, 2008; Salter et al., 2008). These and other studies suggest that regions in the eastern subtropical ocean basins typically occupied by "marine stratocumulus clouds" (low, layered clouds over ocean regions) are most susceptible to aerosol changes.

The lifetime of aerosol particles in the marine boundary layer is largely driven by the frequency of frontal precipitation and local drizzling, meaning that it is highly variable but typically 2 to 5 days in the northeastern and southeastern Pacific and the southeastern Atlantic where marine stratocumulus occur frequently (Coakley et al., 2000). The short particle lifetimes make it possible to produce big local changes to the cloud albedo and radiative forcing that vary significantly in space and time, a signature that is quite different from the idealized forcing distributions discussed in sunlight reduction studies and stratospheric aerosol albedo modification strategies where the aerosol forcing can spread globally or across most of a hemisphere.

Conceptually the basic MCB idea is quite clear, but in reality, the processes that control cloud droplet formation are incredibly complex and difficult to include in global models. Aerosol-cloud interactions are one of the major challenges in climate modeling today (IPCC, 2013a).

The first complication is that, within the simple physics described by Twomey (1974), the quantities that are held constant (total water content of the air) and those that vary (aerosol size and composition distribution) contribute to determining the cloud's maximum supersaturation, a quantity that in turn is affected by the cloud droplet number concentration and the aerosols in the air parcel. This introduces a damping effect by which increased numbers of CCN (at constant specified supersaturation) cause a decrease in actual maximum supersaturation; this decreases the fraction of the available CCN that activate in cloud because the higher CCN number results in a lower maximum supersaturation. Or, in other words, deliberately adding more particles (CCN) reduces the fraction of CCN that can activate to become clouds because there is a limited amount of total water content of the air. Because this effect is instantaneous (i.e., it affects the supersaturation at the same time as it changes the cloud albedo), it is generally considered part of the aerosol forcing rather than a separate feedback. This relationship is evident in aircraft-based measurements of CCN proxies and cloud droplets (Leaitch et al., 1992; Martin et al., 1994). This effect means that as aerosol concentrations continue to increase, the corresponding increase in cloud albedo is reduced,

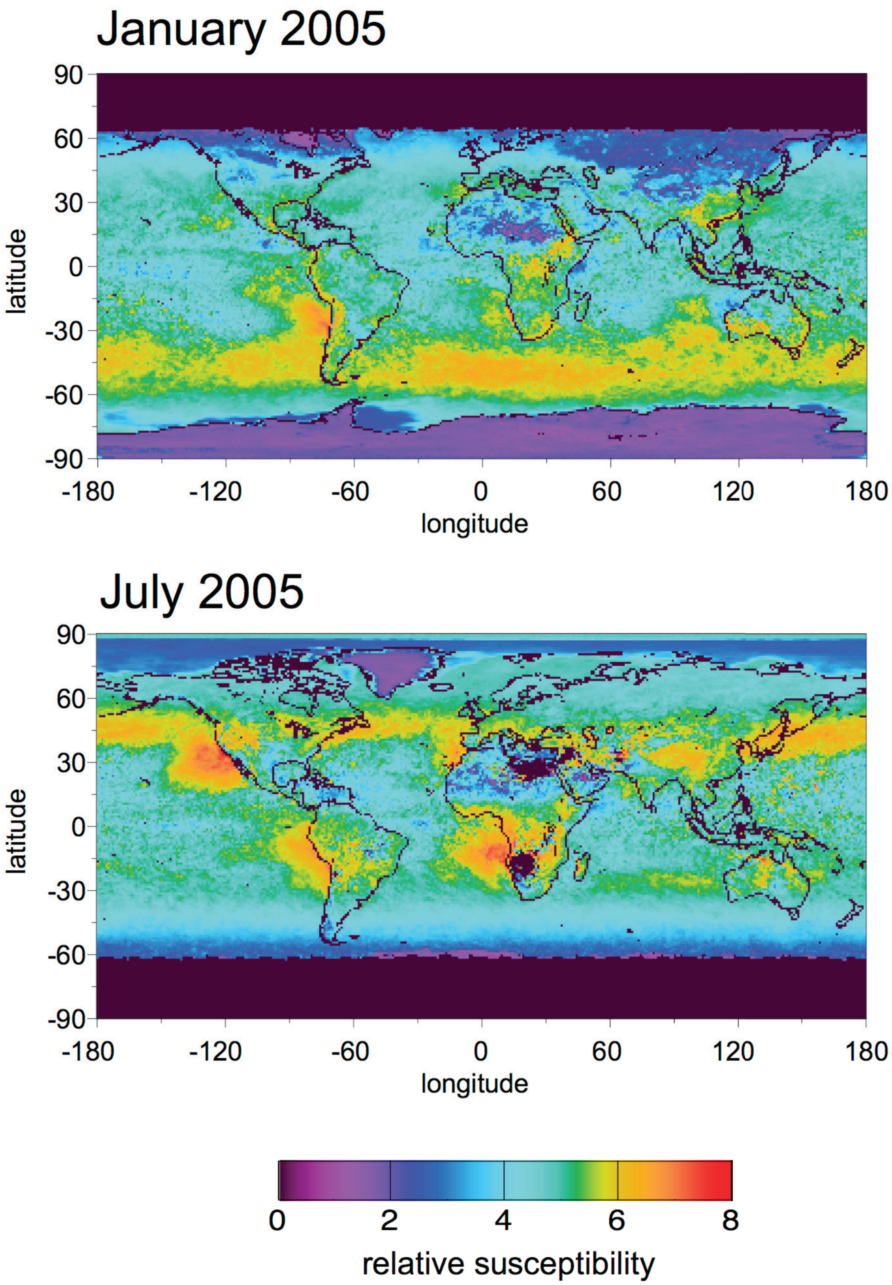

FIGURE 3.15 The relative susceptibility of marine clouds following Oreopoulos and Platnick (2008). Purple indicates regions where clouds are not particularly susceptible to aerosol effects; red indicates clouds that are susceptible.

but because the supersaturations of warm clouds cannot be measured, there are few quantitative observations that can be used to estimate the magnitude of this effect.

Several other limitations are important to consider. For clouds that reflect nearly 100 percent of the incoming visible radiation, the addition of aerosols has little effect on albedo through the Twomey mechanism of changing drop size. For this reason, large cumulus clouds (typically taller than they are wide) and those associated with storm systems and substantial precipitation are not susceptible to aerosol modification of albedo. There can, of course, be other feedbacks in cumulus clouds that change cloud precipitation, extent, or lifetime (Rosenfeld et al., 2013) that have subsequent effects on cloud forcing. In addition, this process is currently better understood for warm clouds (those containing liquid water rather than ice), so high-altitude clouds that are primarily ice have not been targeted until recently (Mitchell et al., 2011; Storelvmo and Herger, 2014). For these reasons, the focus of MCB has been stratocumulus clouds in the planetary boundary layer, typically occurring in the lowest 1.5 km of the atmosphere.

Because the boundary layer is typically well mixed, buoyancy of a particle plume is not required as neutral buoyancy will result in mixing to the height of the temperature inversion. Timescales for this are estimated to be 1 to 3 hours (Lu and Seinfeld, 2006). One important exception is complex, multilayered boundary layers, in which multiple temperature inversions characterize the lowest stratocumulus layer seen by satellite. In this case, particles will typically only mix efficiently within the lowest layer, and yet albedo is often dominated by the topmost stratocumulus layer (Russell et al., 2013), unless it is sufficiently thin as to allow substantial reflection from lower layers. This results in a reduction in the albedo effect of particles.

To date, observational and modeling work has focused most comprehensively on marine stratocumulous clouds. However, there is still substantial uncertainty on the processes that control MCB potential for effectiveness. Additional observations are likely needed to reduce this uncertainty, and studies that provide controlled (or nearly controlled) experiments in the atmosphere are likely to provide better constraints for comparison to model behavior.

Observations of Marine Cloud Brightening

There is ample evidence that cloud albedo is strongly affected by aerosol particles and that mankind is able to influence the albedo of clouds. Figure 3.16 shows an example of "ship tracks," bright areas of clouds produced by aerosol particles in the exhaust emissions of commercial cargo ships which act as CCN in the marine boundary layer off the coast of California. Ship tracks were first reported in satellite observations by

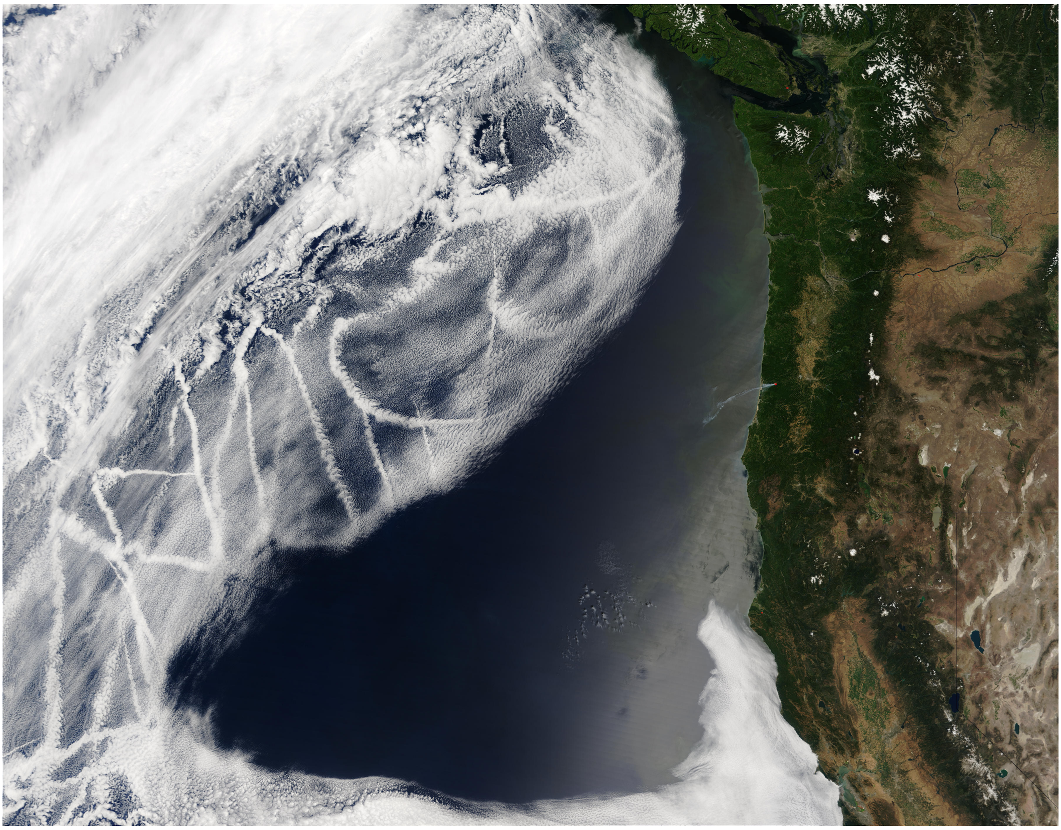

FIGURE 3.16 Ship tracks satellite image retrieved by NASA's Terra MODIS instrument. SOURCE: http://visibleearth.nasa.gov/view.php?id=66963.

Conover (1966). These plumes are emitted by large, mostly commercial ships motoring at speeds of 20 to 30 kts and emitting particles at rates of 10^{19} particles/s with ambient windspeeds of 5 to 15 m/s (Hobbs et al., 2000).

There are existing commercial and experiment-specific examples of cloud albedo modification that can be used to provide both an observational signature of cloud albedo modification and proof of concept of the particle emission and scavenging rates that can be expected in typical marine boundary layers.

Three recent experiments promise to provide essential information on uncertainties associated with cloud albedo modification, including the effects of multilayered clouds in the marine boundary layer: E-PEACE[11] off Monterey in 2011 (Russell et al., 2013), SOLEDAD[12] in coastal marine clouds off San Diego (Schroder et al., 2014), and MAGIC[13] with ongoing transects from Los Angeles to Honolulu. E-PEACE provided detailed evidence of multilayered cloud structure from ship-based ceilometer and aircraft profiles and 94-GHz Doppler radar. Adding to the information collected on these prior campaigns, MAGIC expands the spatial and temporal coverage of this information on marine boundary layer cloud structure with its year-long measurements on California-to-Hawaii transects. The ship-based cloud radar will provide particularly valuable information on the structure of marine boundary layer stratocumulus clouds.

Table 3.1 summarizes several recent experiments that investigate the effects of aerosols on marine stratocumulus. Some of these experiments, notably MAST, E-PEACE, and MASE I/II, focused on the aerosol-cloud interactions from particles emitted by large cargo ships into marine stratocumulus. Although the engine stack emissions of cargo ships are not efficient as a technique for albedo modification because their potential for cooling is largely offset by the enormous CO_2 cost of 100,000 gallons of fuel per day, on track-forming days cargo ships may cause twice as much cooling as warming (using a 100-year time horizon; Russell et al., 2013). As such, they provide observational evidence of both individual and overlapping tracks causing cloud albedo modification. Furthermore, the frequency of track formation over ocean regions provides initial statistics that illustrate how often cloud albedo modification is observed (typically 50 percent of cloudy days in some northeastern Pacific regions [Coakley et al., 2000]) despite the continuous presence of cargo ships in many regions. However, such studies also make it clear that current model understanding and predictive capabilities are not sufficient to know either a priori or by satellite retrievals which cloud conditions are "susceptible" (i.e., support the modification of cloud albedo) and which are not.

Russell et al. (2013) studied cloud interactions using controlled emissions of particles from smoke generators on a vessel much smaller than a cargo ship, burning ~500 gallons of diesel per day rather than 100,000 gallons of bunker fuel per day. One interesting result of this study is that the cloud albedo modification was effective only a very small fraction of the time, even in clouds that are classified by satellite and models as likely to be susceptible. This provides preliminary but nonscalable data on how much additional particle emissions would be needed to achieve the intended effect on planetary albedo compared to what is currently implemented in global models. However, the experiment did demonstrate that simple existing technology

---

[11] Eastern Pacific Emitted Aerosol Cloud Experiment.

[12] Stratocumulus Observations of Los-Angeles Emissions Derived Aerosol-Droplets.

[13] Marine ARM GPCI Investigation of Clouds; http://www.arm.gov/campaigns/amf2012magic.

TABLE 3.1 Selected Relevant Publications from Previous Aerosol-Cloud Interaction Experiments on Marine Stratocumulus

Experiment	Publications	Key Findings (for aerosol-cloud interactions)
MAST (NE Pacific)	Russell et al., 1999	Observed changes in drop distributions and LWC profile.
	Hobbs et al., 2000	Drizzle and LWC changes in ship tracks relative to unperturbed clouds.
	Frick and Hoppel, 2000	Case studies of four ship emissions that produce ship tracks.
	Durkee et al., 2000	Test of aerosol-induced ship track hypothesis.
	Noone et al., 2000a; 2000b	Case studies illustrating background pollution effects on albedo sensitivity.
	Ferek et al., 2000	Ship emission characterization and size distributions.
DECS NE Pacific)	Sharon et al., 2006; Stevens et al., 2005	Rift POCs study; variability in cloud drizzle characteristics due to natural processes and emissions.
DYCOMS II (Nocturnal) (NE Pacific)	Stevens et al., 2003	Characterization of POCs in nocturnal marine boundary layers.
	Twohy et al., 2005	CN/CCN/CDN relationships are linear.
	Petters et al., 2006	CCN closure for marine boundary layer particles.
	Hawkins et al., 2008	Composition independence of particle activation in the aged boundary layer.
	Faloona et al., 2005	Entrainment rates and variability in the nocturnal marine boundary layer.
	van Zanten and Stevens, 2005	Drizzle in nocturnal boundary layer in intense precipitation pockets.
CIFEX	Wilcox et al., 2006	CCN increases correlated to CDN and reflected radiation for constant LWP.
MASE I/II (NE Pacific)	Hersey et al., 2009; Lu et al., 2007, 2009; Sorooshian et al., 2007, 2009a,b	Ship tracks had smaller cloud drop effective radius, higher $N_{c,}$ reduced drizzle drop number, and larger cloud LWC than adjacent clean regions, but trends were obscured by spatial-temporal variability. Aerosol particles above cloud tops are enriched with water-soluble organic species, have higher organic volume fractions, and are less hygroscopic relative to subcloud aerosols.
CARMA	Hegg et al., 2009	Source attribution of CCN and aerosol light scattering.

continued

TABLE 3.1 Continued

Experiment	Publications	Key Findings (for aerosol-cloud interactions)
VOCALS-REx (SE Pacific)	Bretherton et al., 2010	Offshore drizzle not explained by CCN decrease.
	Feingold et al., 2010	Oscillations in aerosol concentrations correspond to precipitation cycles.
	Wood et al., 2011	POC regions had enhanced drizzle and LWC.
E-PEACE (NE Pacific)	Russell et al., 2013	Frequent multilayered low stratocumulus in the marine boundary layer.
	Sorooshian et al., 2012	Comprehensive cloud drop chemistry sampling.
	Coggon et al., 2012	Wide-reaching impacts of ship-emitted particles.
	Chen et al., 2012	Reversed cloud albedo effect in some ship tracks.
	Wonaschutz et al., 2013	Hygroscopic growth of organic particles below and in cloud.
SOLEDAD (NE Pacific)	Modini et al., 2014	Cloud supersaturation and role of sea salt particles as cloud condensation nuclei.
	Schroder et al., 2014	Role of black carbon particles as cloud condensation nuclei.

NOTE: LWC, liquid water content; POC, pocket of open cells; CN, condensation nuclei; CCN, cloud condensation nuclei; CDN, cloud droplet number; LWP, liquid water path; MAST, Monterey Area Ship Track experiment; DECS, Drizzle and Entrainment Cloud Study; DYCOMS II, Second Dynamics and Chemistry of Marine Stratocumulus experiment; CIFEX, Cloud Indirect Forcing Experiment; MASE, Marine Stratus/Stratocumulus Experiment; CARMA, Cloud Aerosol Research in the Marine Atmosphere experiment; VOCALS-REx, VAMOS Ocean-Cloud-Atmosphere-Land Study Regional Experiment.
SOURCE: Updated from Russell et al., 2013.

can provide a cheap and effective means of cloud albedo modification with a cooling-to-warming ratio of 50:1, as calculated for a 100-year time horizon (Russell et al., 2013).

Since the global mean reflectance scales with global area, the magnitude of the cooling effect will scale with the area of stratocumulus clouds covered as well as with the residence time of the particles. On the average, particles last 5 to 7 days in the troposphere (Seinfeld and Pandis, 2006). However, empirical evidence tracking particle enhancements from ship tracks suggest a typical lifetime of 24 hours with some ranging to 48 and 72 hours (Coakley et al., 1987).

Proposed Mechanisms for Marine Cloud Brightening

Particles smaller than 1 μm diameter that are emitted near the surface to influence cloud albedo have a lifetime of just a few days. Because aerosol lifetime near the surface is very short, aerosol emissions will remain relatively close to their source (there would not be time for the winds to blow them more than a few hundred kilometers before they are removed by scavenging or deposition), and aerosols would need to be replenished on an ongoing basis over a large area. The footprint of cloud albedo modification of stratocumulus clouds by controlled emissions could involve just one ship (with speed 10 to 20 kts) that can emit particles that will be spread by the ship motion and the wind over 4 to 6 hours to cover an area of 100 km^2, as is illustrated schematically in Figure 3.17 and from satellite observations in Figure 5 of Russell et al. (2013). For this coverage, ships on the ocean surface would ideally trace "racetracks" (or zig-zags) separated by 5 to 10 km (depending on crosswind speed). Each ship would trace out a track visible on the Advanced Very High Resolution Radiometer (AVHRR) and MODIS satellite-borne instruments (both of which have daily coverage). However, as Wood and Ackerman (2013) note, quantitative evidence of the aerosol-cloud effects would need to be provided by simultaneous aircraft and ship-based measurements in clean and polluted areas of the cloud and the boundary layer. To account for the large uncertainties in track width and lifetime, the tracks should likely be engineered 2 to 10 times higher in concentration than model-based estimates. Latham et al. (2012) proposed a larger experiment, using five ships to affect clouds covering an area of 10,000 km^2. Moreover, since the biggest uncertainty is the cloud type, a hypothetical large-scale deployment of MCB as a global albedo modification strategy would require a large fleet of vessels to be able to deploy in susceptible areas at short notice. The largest cooling effects could be achieved by staging several fleets around the world that are available for deployment on a daily basis and that can be scaled back to reduce energy and emission expenditures when suitable track-forming conditions are not available.

Recent results demonstrate that while both size and composition affect the efficiency with which particles activate to droplets, larger particles, and particles composed of hygroscopic material, are better CCN. Since surface and mass forces make the energetic (and monetary) cost of smaller, more hygroscopic particles more expensive than equivalently good CCN at larger, less hygroscopic compositions, hygroscopicity per se may not be a limiting parameter. Engineering considerations for aerosol production or delivery issues are likely not the limiting factor for achieving MCB albedo modification strategies (Russell et al., 2013). At typical ambient wind speeds in the clean regions of the Pacific Ocean, the types of emission rates that are required are 10^{17} to 10^{19} particles/s (Hobbs et al., 2000).

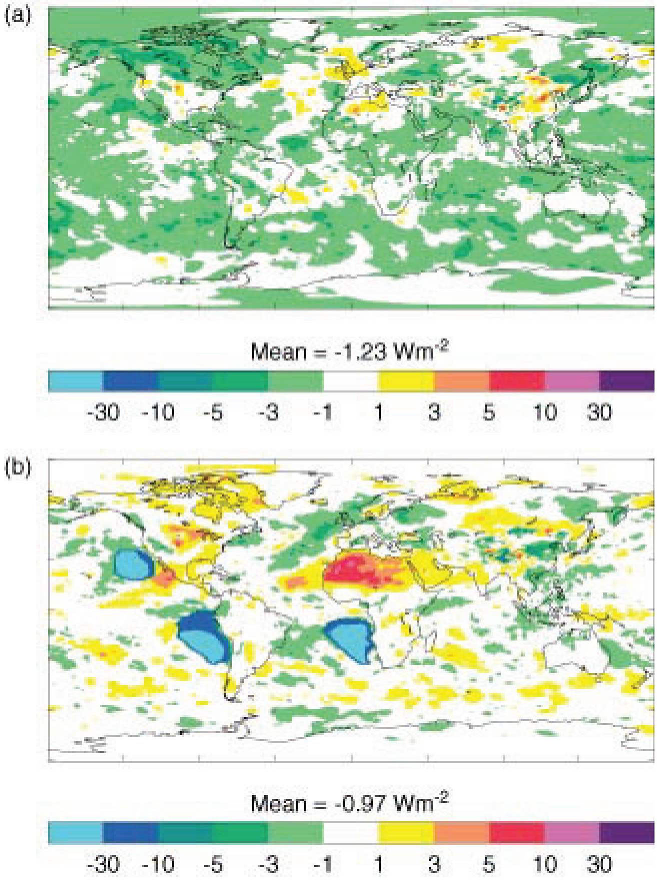

FIGURE 3.17 Annual mean radiative flux perturbation (W/m^2) for albedo modification via (a) stratospheric SO$_2$ injection at 2.5 Mt[S]/yr and (b) increasing cloud droplet concentration to 375 cm^{-3} in the marine stratocumulus cloud sheets at the eastern sides of the North Pacific, South Pacific, and South Atlantic. SOURCE: From Jones et al., 2011.

Latham (1990, 2002) suggested that seawater might be exploited as a source of small seawater droplets to be injected into the boundary layer, where they could evaporate and form small sea salt particles; sulfate aerosols produced by fertilization of marine biota, and organic aerosols produced by combustion have also been suggested (Wingenter et al., 2007). The methods are discussed later in this chapter in the "Delivery Mechanisms" section.

Challenges in the Implementation of Marine Cloud Brightening

Although it is clear that humanity can, and does, increase cloud reflectivity through aerosol emissions, in this section the committee identifies some of the reasons for uncertainties in estimates of the amount of brightening that might actually be achieved through inadvertent or deliberate aerosol injections.

There are reports of aerosol effects on cloud fraction (Rosenfeld et al., 2013), but there is no evidence that such effects can be sustained without nonaerosol redistribution of water. There are no modeling studies that explain local increases in cloud fraction (i.e., not regionally averaged increases associated with cloud lifetime due to smaller droplet size, e.g., Ackerman and Strabala, 1994) other than by changes in cloud dynamics that also redistribute water (or heat) from a saturated to a subsaturated region.

Regional scaling. Extrapolating the effects of particles on clouds from the microphysical scale to the regional scale is not linear (Martin et al., 1994). The reason that the microphysical effects demonstrated by Twomey may not scale to regions is that the Twomey phenomenon does not take into account mixing and other processes that can dampen and offset the effects measured on small scales. In this case, the committee considers regional scale to be of the order of 500 km^2. A single ship track of mean width 10 km that extends 50 km provides such an area. Russell et al. (2013) calculated that at 15 percent brightening (similar to the reflectance changed estimated by Coakley et al. [1987] for typical ship tracks), the cooling is equivalent to 0.4 nK cooling (average cooling over 100 years is calculated by reducing the cooling effect by the ratio of 12 hr/100 yr; CO_2 warming is calculated by linearly equating 280 ppmv CO_2 with a warming of 3 K, per Solomon et al., 2009).

Competitive effects. Leaitch et al. (1992) demonstrated that higher particle emissions do not result in equivalent increases in droplet number concentrations, because of suppression of supersaturation and other cloud responses. Moreover, Leaitch et al. (2010) and Chen et al. (2012) have shown that adding particles can also decrease the drop number concentrations (a "reverse" Twomey effect).

Susceptibility. Since the increase in reflectance due to drop size and number is only significant for clouds that are not already sufficiently thick (optically dense) that their reflectance may be modified by aerosol particles, the formation of "tracks" with aerosol-increased albedo depends strongly on the cloud properties (including superstaturation, updraft velocity, and layer structure) as well as on the background aerosol size and concentration (which is a function of wind speed, seawater composition, and wave conditions).

Modeled Climate System Responses to Marine Cloud Brightening

Producing a realistic representation of clouds and aerosols (and their interactions) that strongly affects the albedo of the planet (and indeed many other aspects of Earth's climate) is a huge challenge for models, contributing to their identification as one of the largest sources of uncertainty in Earth system modeling. Scientists have attempted to improve the understanding of these features in multiple ways:

- Scientists have developed a range of modeling approaches—from detailed process-level models of aerosols and clouds called "box models," to eddy-resolving "large eddy simulations" (LESs), to kilometer-scale "cloud-resolving models" (CRMs)—with varying levels of complexity in order to focus on different aspects of aerosols and cloud interactions relevant over small time and space scales, exploring these processes in simulations as short as a few seconds to a few days, in air masses ranging from a few meters to a few hundred kilometers.
- When interested in larger space scales, and longer timescales, scientists represent clouds and aerosols (and their interactions) in Earth system and climate models more simply, by "parameterizing" some of the processes, in order to reduce the cost of the calculation sufficiently to make regional or global calculations for days to centuries viable. Modelers "calibrate" the parameterizations with observations and detailed process models so that they agree approximately, but the appropriate representation of these processes remains an incredibly difficult challenge. Some of the resulting issues that are relevant to MCB are discussed later in this section.

Box, LES, and CRM studies. Bower et al. (2006), Feingold et al. (1998), and Russell et al. (1999) are among those to use a box model to study changes in cloud drop number in the presence of extra CCN. LES models were used by Ackerman et al. (1993) to show that aerosols play a role in preventing the collapse of the marine boundary layer in some meteorological conditions, and that ship emissions might act to prevent that collapse and promote cloud formation. The model study provided an early diagnosis of situations where aerosols promote cloud formation. More recently, Wang and

Feingold (2009a,b,) and Wang et al. (2011) used LES to explore the dynamic response of a marine stratocumulus cloud system to background polluted and pristine aerosol levels and local ship emissions. These studies produced a large number of relevant conclusions for MCB:

1. Aerosol particle concentrations played a strong role in influencing whether open (low-albedo) or closed (high-albedo) cellular structures formed (with very strong controls on albedo, precipitation, and cloud lifetime).
2. Aerosol particle concentrations also influenced the dynamical structures both within the cloud and in the vicinity of (but outside) the aerosol plume, driving the organization of the clouds both local to emissions and in surrounding areas, leading to a "cloud clearing" on the flanks of the aerosol plume, much like those seen in observations.
3. Turbulent motions rapidly mixed surface emissions vertically over a few hours throughout the surface boundary layer (typically less than 1.5 km).
4. Cross-wind horizontal mixing of aerosol particle emissions was relatively slow, distributing aerosols laterally over about 20 km in 24 to 48 hours.
5. Under some circumstances, ship emissions can actually break up cloud structures leading to reduced albedo, although reduced albedo was less common than increased albedo.
6. The presence of drizzle prior to the injection of aerosol particles reduced the efficacy of emissions in changing cloud albedo.

Additional modeling studies also indicate that more particle emissions, and more ships than originally estimated by Latham et al. (2008) and Salter et al. (2008), would be required to produce the desired CCN concentrations and marine cloud changes for these cloud types. Jenkins and Forster (2013) considered the change in buoyancy associated with the evaporation of water from the small seawater droplets that form the CCN and noted a measurable reduction in the efficacy of the aerosol source that would result from droplet evaporation (a 2 percent to 10 percent reduction in the albedo increase). Stuart et al. (2013) used ultrahigh-resolution and plume models to account for coagulation of aerosol particles after they were emitted and concluded that plume-scale coagulation could reduce the efficacy of marine cloud brightening by almost 50 percent.

Global studies. Clouds, aerosols, and their interactions are very difficult to represent at the coarse resolution needed for global climate simulations of months, years, centuries, or millennia, and compromises are necessary to implement such simulations. These compromises make it difficult to represent the shallow boundary layer clouds that are so important to MCB, leading to identifiable biases and deficiencies in their simulation of these clouds (Bony and Dufresne, 2005; Bushell and Martin, 1999; Lane et al., 2000; Roeckner et al., 2006; Sandu et al., 2010; Stephens, 2005; Tompkins and Emanuel, 2000). Each generation of climate model improves both the representation of cloud and aerosol processes as well as the resolution of the model into grid boxes. The fidelity and plausibility of cloud and aerosol processes and features in climate models are slowly improving (e.g., Boucher et al., 2013; Donner et al., 2011; Kay et al., 2012).

The costs and challenges of cloud and aerosol representations in GCMs have led to two approaches for studying MCB in climate models. In the first approach, some important characteristics of clouds are prescribed, for example, by prescribing cloud drop number in clouds. These characteristics are systematically varied to explore the consequences of cloud changes for climate if scientists had "perfect control of cloud properties." In the second approach, studies are performed that allow the full range of interactions within the climate model to take place by comparing simulations in the presence and absence of particles added at specified times and locations into the model boundary layer.

In the first class of studies, in which perfect control of cloud drop number was assumed, Latham et al. (2008), Jones et al. (2009), Rasch et al. (2009), Hill and Ming (2012), and Baughman et al. (2012) identified specific ocean regions that were represented in GCMs as particularly susceptible to MCB and then prescribed a cloud droplet number increase (different for each model). This produced changes in the cloud radiative forcing, and they then explored the atmosphere, ocean, and cryosphere responses to these changes. All of these studies increased the reflectance of the modeled subtropical marine stratocumulus regions off the west coasts of continents, as well as in some other seeded regions. One consistent response noted by many of these studies was a persistent cooling of the Pacific, similar to the "La Niña" phenomenon. All simulations indicated global mean cooling and an increase in polar sea ice, in spite of the regional nature of the albedo change.

Jones et al. (2009) increased cloud drop number in three regions of marine stratocumulus (around 3 percent of Earth's surface area) and found that up to 35 percent of the radiative forcing due to current levels of greenhouse gases could be offset by a very aggressive level of stratocumulus modification (~1 W/m^2) that delayed the warming by ~25 years (average reduction in energy reaching the surface of the seeded regions of about 30 W/m^2). They also noted significant shifts in important precipitation patterns, with increases in some regions and decreases in others (for example in the Amazon). However, these regional precipitation pattern changes are not found consistently across studies with other models.

Korhonen et al. (2010), Partanen et al. (2012), Jones and Haywood (2012), Alterskjær et al. (2012), and Alterskjær and Kristjánsson (2013) relaxed the constraint of the first-generation MCB studies by exploring responses to additions of sea salt particles at the surface. They all found significant cooling effects on the climate due to cloud albedo being increased by the aerosol indirect effect, but large differences in the spatial distribution of the temperature changes were found. This type of difference in predicted regional responses among models is not surprising because such differences are also seen in comparing simulations of precipitation changes due to global warming, since the processes that control precipitation are very uncertain in GCMs. Partanen et al. (2012) and Jones and Haywood (2012) also assessed the role of the direct radiative impact by the sea salt aerosols and found it to contribute significantly to the total radiative impact.

Some of these responses and feedbacks may be model dependent, and studies have not used a common experimental design, making comparison of the different studies difficult. Alterskjær et al. (2013) attempted to reduce these differences in a model intercomparison using a common experimental design to search for robust responses across three Earth system models (a similar but larger model intercomparison is now taking place under the GeoMIP program [Kravitz et al., 2013a]). In these studies, sea salt aerosol emissions between 30°N and 30°S were increased to offset the forcing from an RCP4.5 scenario between 2020 and 2070. The increased emissions were then terminated to explore the rebound effect. The models studied by Alterskjær et al. (2013) still had significantly different mechanisms for addition of sea salt particles, but forcing amplitudes and forcing mechanisms are closer than previous studies. Some models prescribed aerosol distributions and did not allow cloud processes to remove aerosols; others allowed those interactions to take place and used more complex treatments of aerosol-cloud interactions. Each model accounted for some direct and indirect radiative effects of the emitted sea salt aerosol particles. Each model had significant differences in formulations of aerosol-cloud interactions (some included only the effect of drop radius first studied by Twomey et al. [1968]; others included aerosol effects on precipitation microphysics discussed by Albrecht [1989]) and differing feedbacks, necessitating different increases in sea salt concentrations to cancel the forcing. Each model required a different amount of emitted sea salt aerosol particles increased to counter the greenhouse gas (GHG) warming in the decades around 2060. Some of these differences are summarized in Table 3.2.

For the final decade of the simulations (2060-2070) before terminating the sea salt aerosol particle emissions, the NorESM required an increase by a factor of 3.4 in emissions of the 0.13-μm sea salt particle mode but only a 3.4 percent increase in the total sea salt emission mass flux (equivalent to a fleet of about 7,600 injection vessels, assuming that these have the design and efficiency proposed by Salter et al. [2008]).

TABLE 3.2 Results from Intermodel Comparison Involving Three Earth System Models (MPI-ESM, IPSL-CM5a, and NorESM) Used to Explore Differences among the Models

Model	Equivalent Sea Spray Emissions (Mt/yr)	Average Surface Temperature (K) and Precipitation (mm) Change from GHG Forcing (2060-2020)	Average Surface Temperature (K) and Precipitation (mm) Change Produced by the Combination of GHG Forcing and MCB Albedo Modification
MPI-ESM	316	(+0.9, +0.04)	+0.2, –0.01
IPSL-CM5a	560	+1.3, +0.09	+0.2, –0.02
NorESM	266	+0.8, +0.05	+0.2, +0.01

NOTE: The different emissions needed to counter GHG warming are due to differences in the fraction of low clouds in the seeded regions and differences in treatment of the effect of the injected sea salt on precipitation release. MPI-ESM = Max Planck Institute for Meteorology Earth System Model; IPSL-CM5a = Institut Pierre Simon Laplace Climate Model; NorESM = Norwegian Earth System Model. SOURCE: Alterskjær et al., 2013.

The different emissions needed to counter GHG warming are due to differences in the fraction of low clouds in the seeded regions (producing changes in cloud albedo over a relatively smaller area) and differences in treatment of the effect of the injected sea salt on precipitation release (Albrecht, 1989), affecting the cloud lifetime and areal extent. As in the idealized studies described earlier, all three models employing MCB produced reduced evaporation, particularly from low-latitude oceans, and reduced precipitation over low-latitude oceans and storm-track regions compared to the simulations with forcing only from greenhouse gases. But in contrast to studies with uniform sunlight reduction, each model produced increased precipitation, cloud formation, and precipitation over low-latitude land regions in response to the localized cooling over the low-latitude oceans, reducing aridity in many low-latitude land regions as well as in southern Europe (Alterskjær et al., 2013). (This result is consistent with the idealized study of Bala et al. [2011] employing sunlight reduction only over ocean.)

Jones et al. (2011) directly compared the model differences in forcing and response between stratospheric aerosols and marine cloud brightening. Forcing differences are shown in Figure 3.17.

Models consistently indicate that MCB can reduce temperatures. Model simulations show that MCB targeted at susceptible marine stratocumulus will cool preferentially the eastern North and South Pacific and eastern South Atlantic, and will also cool globally and reduce Arctic warming. These results must be viewed with some caution. Cloud models and global model parameterization of marine stratocumulus remain much simpler than in the real world, and scientists recognize that they do not yet provide robust quantitative predictions of cloud responses to aerosol changes. There are still significant disagreements between model estimates of the Twomey effect compared to estimates from satellite measurements. Global models disagree in their predictions about MCB effects on the spatial distribution and intensity of precipitation, particularly when the MCB global average forcing exceeds 0.5 W/m^2 annual average.

Observational Requirements for Characterizing Marine Cloud Brightening

There are three types of observations that are needed to track and quantify the radiative effects of particles on cloud albedo: satellite reflectance sensors, described below; in situ aerosol and cloud instrumentation; and logistical metrics. For quantifying ecosystem impacts of cloud albedo modification, monitoring networks for nutrients and biota, as well as case-specific integrated modeling of potential teleconnections, are required. Technology for all of these aspects exists. Experiments that require large-scale, multigroup efforts using national aircraft and ocean research facilities could range in scale from $10 million to $100 million depending on the target region and time of the modification. An example of a small-scale experimental design is provided by E-PEACE, as shown in Figure 3.18.

Variants of this type of study designed to provide additional information about engineering issues and cloud responses to aerosol injection are described in two recent papers proposing field studies that might be used to extend previous work (Latham et al., 2012; Wood and Ackerman, 2013). These studies suggested a series of three staged field experiments that are successively more ambitious. The smallest field experiment would follow particles explicitly designed to be good CCN, monitoring size distribution, chemical composition, and cloud-forming properties close to the injection source, and their destiny as they disperse downwind in the boundary layer. The second would explore possible cloud responses to the injected aerosol using multiple aircraft and ships in a range of conditions and model those specific situations to see whether the models were capable of reproducing the observed aerosol and cloud evolution. The third would examine the impact of multiple injection sources over a limited area (perhaps 100 × 100 km^2) to characterize effects on cloud albedo and cloud forcing. Other variants are mentioned by Keith et al. (2014).

The evidence for cloud albedo modification is clear in AVHRR (on NOAA satellites) and MODIS (on NASA's Terra and Aqua satellites) after proper data post-processing (Durkee et al., 2000). Such signatures are not evident in high-traffic areas (Peters et al., 2011), making regional signatures difficult to detect. Tropical regions also lack consistent signatures

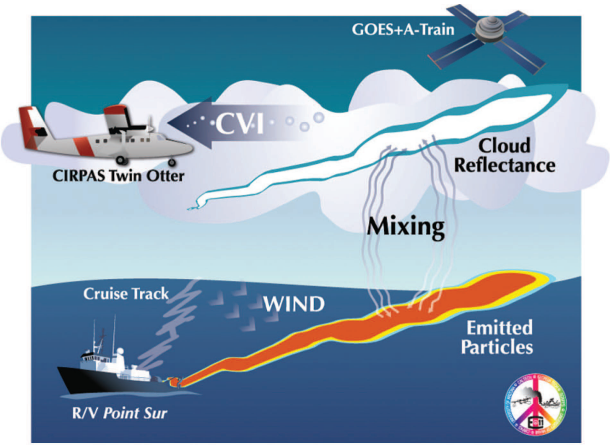

FIGURE 3.18 Illustration of E-PEACE design and observations of emitted particles in marine stratocumulus in July and August 2011 west of central California. The diagram shows the three platforms used in making observations of particle and cloud chemical and physical properties, namely, the R/V *Point Sur*, the Center for Interdisciplinary Remotely-Piloted Aircraft Studies (CIRPAS) Twin Otter, and the A-Train satellites and GOES. The design included using smoke generated on board the R/V *Point Sur* that was measured after emission by the CIRPAS Twin Otter in clouds. The satellite was used to measure the changes in reflectance of sunlight due to the effects of the emitted particles on the clouds. The counterflow virtual impactor (CVI) was used as an inlet for evaporating droplets as they were brought into the aircraft, allowing sampling of droplet chemical composition. SOURCE: Russell et al., 2013.

(Peters et al., 2014). With modern visible imagery and ship tracking (e.g., marinetraffic.com), the most obvious evidence for cloud albedo modification can be collected from emissions from controlled ships that "zig-zag" back and forth instead of transiting efficiently from one port to another (typically along standard shipping routes). Ships large enough to emit particles in midlevel seas (such as the R/V *Point Sur*, 135 ft long and 298 gross tons, http://marineops.mlml.calstate.edu/PS-Specs) are trackable with this existing technology; smaller or fuel-free ships (such as those proposed using Flettner rotors by Salter et al. [2008]) would still be trackable based on required route reporting at ports of call near the targeted region during susceptible cloud conditions. This type of ship activity would be a clear logistical signature of medium- or large-scale MCB deployment.

The CALIOP instrument on board the CALIPSO satellite identifies cloud and aerosol layers using polarized lidars at 532- and 1,064-nm wavelength. Overcast stratocumulus is sufficiently optically thick to extinguish the lidar before it reaches the surface, although in broken or scattered stratocumulus some fraction of the lidar backscatter will originate from the ocean surface.

In summary, the logistical signatures for ship traffic, fuel purchases, and other port activities likely will provide clear evidence of MCB activities. Satellite instrumentation exists to effectively monitor approximate changes in reflectance for large-scale marine cloud brightening activities. However, scientists lack sufficiently high temporal- and spatial-resolution measurements of albedo to enable us to separate the radiative changes of MCB from the natural variability. In situ observational instrumentation exists that could be deployed to effectively observe marine cloud brightening activities but they require expert operators and nonroutine analyses, likely located in open-ocean regions offshore that may be difficult to access.

Environmental Consequences of Marine Cloud Brightening

As described in the previous sections "Observations of Marine Cloud Brightening" and "Modeled Climate System Responses to Marine Cloud Brightening," there is some potential for undesirable side effects from MCB activities, repeated here for the reader's convenience. In particular, there is some potential for changes to precipitation patterns and amplitude (Bala et al., 2011; Jones et al., 2011; Rasch et al., 2009) and possibly for interannual variability (Russell et al., 2012), although modeling studies suggest the residual changes are likely less than those for stratospheric aerosol albedo modification and much smaller than for unabated greenhouse gas warming. As in the SAAM and idealized albedo modification strategies, MCB cannot return both temperature and precipitation patterns to preindustrial conditions, and residual temperature changes will also remain; for example, the tropics may cool more than the polar regions (see studies cited above, and Ricke et al., 2010; Tilmes et al., 2013).

MCB activities might introduce changes to the marine and terrestrial ecosystems through changes to clouds and cloud area that reduce the surface flux of sunlight. Changes to the albedo of stratocumulus clouds are likely to substantially alter the surface flux of sunlight; Latham et al. (2008) and Jones et al. (2011) estimated that using MCB at amplitudes sufficient to alter climate would decrease annual mean sunlight reaching the surface by 30 to 50 W/m^2 (~20 percent, approximately doubling cloud radiative forcing) locally in seeded regions. These changes in surface energy fluxes are likely to reduce local sea surface temperatures (e.g., Rasch et al., 2009) and their gradients, perhaps influencing important climate modes such as El Niño, and might also change deep ocean upwelling and mixing in the ocean surface layer that delivers nutrients to marine ecosystems, with possible effects on ecosystem services such as fish availability. These marine ecosystems also contribute to the natural aerosol concentrations in near-marine regions that are important in cloud formation (Quinn et al., 2014), so there may be feedback effects as well. Last, the change in sunlight reaching the surface may influence photosynthesis, and the potential cloud area changes from the brightening are likely to matter most. Changes to cloud opacity are unlikely to influence photosynthesis as strongly as changes to cloud lifetime or areal extent because photosynthesis is only weakly dependent on (direct and diffuse) sunlight intensity. These issues have not yet been explored in models or observations (via ship track or other studies), so potential consequences to ocean ecosystem productivity are very uncertain (Russell et al., 2012). In addition, it is important to recognize that impacts on ecosystems change with the scale of the intervention. Stafford-Smith and Russell (2012) have suggested that regional rather than global deployment of MCB or SAAM (or both) methods might have less serious negative consequences for ecosystems, since the complexity of larger systems provides some degree of resilience.

The use of NaCl or sea salts as the emitted particles would result in increased salt deposition, possibly affecting the salinity of the ocean surface layer in the regions in and surrounding which MCB is deployed. More needs to be done to improve estimates of the impact of deposition on downstream coastal and other continental ecosystems and to evaluate toxicity.

Technical Feasibility of Marine Cloud Brightening

There are important open questions for the feasibility of MCB at deployment scale. Theory, modeling, and observations indicate that the susceptibility of cloud albedo to increases in aerosol particle concentrations saturates, but the point of diminishing returns varies with cloud type and background aerosol amount. The natural variability of clouds is high, and many different cloud regimes exist that may respond differently to aerosol increases, complicating signature detection and making quantitative characterization of cloud susceptibility and effective radiative forcing (ERF) difficult. Since these differences in cloud responses are not well represented in models, observations are needed to improve our ability to quantitatively constrain these differences.

There are only a few situations (e.g., ship tracks) where there is clear evidence that the albedo of a specific cloud has been influenced by local variations in aerosol. In larger-scale cases, estimation of aerosol impacts on cloud properties requires a statistical analysis of a cloud system, generally in the absence of a systematic and quantitative method for varying aerosol concentrations near the cloud system, or a control to monitor similar cloud characteristics in the absence of a perturbation. This means that, to date, all estimates of the feasibility of MCB are restricted to (1) scale-up of simplified parameterizations by global models, (2) process-based models with limited larger-scale interactions or validation, (3) monitoring the response (or lack of response) of an individual cloud to particles released as pollution in ship of opportunity studies such as MAST (see Table 3.1), and (4) monitoring the response (or lack of response) of clouds to a smaller emission source of particles in a field experiment (E-PEACE) with different physiochemical properties than sea salt, or the combustion particles produced by shipping.

Delivery mechanisms. Although aerosol production and delivery issues are not expected to be the limiting factor for implementing MCB albedo modification strategies (Russell et al., 2013), at least three methods have been considered for delivering suitable aerosols into the marine boundary layer to brighten clouds. The first two methods may prove to be cheaper and have fewer unintended consequences than the third, but they rely on technology that requires development and scale-up.

- Latham (1990, 2002) suggested that seawater might be exploited to produce small seawater droplets and inject them into the boundary layer, where they could evaporate and form small NaCl-dominated particles; Salter et al. (2008) suggested methods and devices that might be used (but do not yet exist) to produce and deliver droplets into the marine boundary layer. Neukermans et al. (2014) and Cooper et al. (2014) discuss a prototype device in the laboratory capable of producing seawater droplets of the appropriate size range that may be able to be scaled up to rates relevant to field studies (e.g., $\sim 1 \times 10^{18}$ s^{-1}).
- Wingenter et al. (2007) suggested the use of dimethyl sulfide produced by fertilization of ocean biota as a source for CCN, although doubts about the method's efficacy have been voiced (Vogt et al., 2008; Woodhouse et al., 2008).
- Engine or smoke emissions could also be used as a source for CCN. Freighter emissions producing ship tracks indicate that combustion is an effective source of aerosols, although ship emissions were never designed or optimized for this purpose. E-PEACE (Russell et al., 2013) demonstrated that paraffin oil particles (e.g., material used for skywriting) could also be used effectively. Military-issue "smoke generators" are available that produce these rates at a CO_2 cost substantially lower than the exhaust from cargo ships. These typically use a high-boiling-point, unreactive hydrocarbon mixture such as paraffin oil (used commercially for transformers and for sky writing). The National Institute of Standards and Technology designates paraffin oil as environmentally "benign."[14]

---

[14] See http://www.loc.gov/rr/scitech/mysteries/skywriting.html.

The inherent problem in designing emissions for MCB is that producing submicron particles requires energy to produce particles with very high ratios of surface area to volume from a bulk liquid or a gas. Particle production from chemical reactions such as combustion uses chemical energy to make submicron particles; nozzle or spray technologies typically use mechanical force (pressure) to make small particles. In order to make MCB cost effective (in terms of both dollars and fuel usage or equivalent CO_2 emissions), the energy from particle production must be minimized. This constraint tends to favor particle production from phase changes or chemical reactions in situ (such as condensation of vaporized paraffin oil in a smoke generator) due to the engineering considerations in marine conditions, such as clogging from impurities of source material.

Efficacy. Current estimates of the long-term and large-scale efficacy of the MCB strategy (e.g., the radiative forcing per unit aerosol emission for different marine cloud regions) are generally based on theory and modeling studies, and they are not yet sufficient to provide robust estimates for radiative forcing or to identify limitations of the strategy, consequences to the development and evolution of cloud systems, possible far-field effects, or longer-term climate consequences involving feedbacks. In spite of these uncertainties, estimates have been made. Results are reported in a variety of "units." Sometimes the measure is expressed in terms of the emission rate (particles m^{-2}) times the area seeded (m^2) to achieve an effective radiative forcing sufficient to counter that from a doubling of CO_2. Latham (2002) initially estimated an injection rate of particles of $\sim 3 \times 10^6$ m^{-2} s^{-1} over a surface area of ~77,000 km^2.[15] Salter et al. (2008) revised that estimate to 1.5×10^6 m^{-2} s^{-1} over a similar area. These estimates are equivalent to a local increase in cloud albedo in marine stratocumulus regions of about 0.06, and for the purposes of comparing results between global models and high-resolution models it is sometimes easier to work in units of albedo. But these estimates are largely based on limited-scale observations, and the scale-up is likely to result in diminishing efficiency due to the reduced efficiency of Twomey effects at high aerosol concentrations.

More complete treatments of aerosol cloud interactions in modern climate model studies indicate the need for larger (Korhonen et al., 2010) and smaller emission rates (Alterskjær et al., 2012; Partanen et al., 2012) than the Salter estimate, but these estimates also ignore a variety of cloud and aerosol processes that may be important. Russell et al. (2013) showed that, even in a regime that is considered to have a high

---

[15] An area almost as large as the size of South Carolina (U.S. Census Bureau, 2012); South Carolina's total area is 82,933 km^2.

potential for MCB, the apparent susceptibility of clouds that is represented in models and observed from satellite can be reduced by factors of 2 to 10 due to multiple cloud layers, subgrid-scale drizzle, local clearing, and limited mixing. These studies highlight uncertainties in issues critical to a quantitative characterization of MCB, and the need for laboratory and field work.

Costs. Table 3.3 provides estimates of the potential costs and resources required for various levels of cloud albedo modification activity.

Summary and Statement of Research Needs for Marine Cloud Brightening

Research beyond the use of computational models is needed to address some of the key open questions on the potential for marine cloud brightening to be useful for albedo modification purposes. The reason is that the uncertainties of cloud susceptibility, scale-up, and feedbacks are not sufficiently understood to be included with confidence in models. These issues produce the largest uncertainty in quantifying marine cloud brightening feasibility and, hence, assessment of cost and risks.

An improved ability to characterize aerosol cloud interactions is needed. Field studies, improvements to model physics, and improvements in the agreement of models with measurements play a key role in demonstrating the understanding of these basic climate processes and help in characterizing MCB potential for albedo modification.

The committee identifies a number of research needs to address the current gaps in understanding of the efficacy and effects of MCB.

Field studies. Previous climate-focused field studies have produced substantial progress in understanding the aerosol-cloud interactions that are of relevance to MCB, but there are still aspects of these interactions that require better characterization. Field studies near existing uncontrolled emission sources provide very useful information and can be evaluated to see the extent to which observed albedo response matches modeled albedo response over some space and timescales. Some issues, however, can be more clearly exposed and understood using deliberate, controlled emission studies. In combination with each other, these observational strategies provide fundamental information on aerosol direct and indirect effects and boundary layer transport that are very important, but crudely treated in current atmospheric models. Together they also serve as a verification and calibration data set for models.

TABLE 3.3 Logistical Footprint at Various Scales for Hypothetical Cloud Albedo Modification

Likely logistical signature for 1 year	0.0001 W/m^2	0.01 W/m^2	5 W/m^2
Dollars required/expended* (expenditure breakdown: 80% for fuel; 10% personnel; 10% aerosol production material/ maintenance)	\$50k/week	\$5M/week	\$100M/week
Hardware (based on 300T ships with speed 10 kts)	1	100	2,000
Footprint (pattern: parallel tracks at 10-km spacing; location: ocean surface in marine stratus cloud regions: SEPac, NEPac, SEAtl)	5 km × 50 km nonoverlapping	100 km × 100 km	20 each 100 km × 100 km
People required (seamen, engineers, and technicians)	10 people	1,000	20,000
Fuel usage (given current ship technology)	500 gal/day	50,000 gal/day	1,000,000 gal/day

NOTE: Scaling of costs is assumed to be approximately linear in forcing due to trade-offs between increasing economies of scale and decreasing cloud susceptibility and accessibility. Costs for 5 W/m^2 are based on GAO-estimated \$5 billion annual cost (GAO, 2010). Costs for smaller-scale deployments are scaled linearly. Costs for 0.0001 W/m^2 are comparable to E-PEACE deployment. SOURCE: Russell et al., 2013.

Opportunities to improve understanding of relevant processes that can potentially be revealed much more clearly with small-scale controlled emissions studies include the following:

- *Comparing to a control*. Monitoring adjacent air masses or air masses prior to and following emissions would serve as an experimental control to contrast with the seeded clouds, and monitoring both the perturbed and control air masses would help identify the sensitivity to preexisting air mass properties (e.g., aerosol amount).
- *Tracking changes in a cloud system*. Extended monitoring of the properties of aerosols and clouds in regions after controlled emissions of aerosols are released, and in control regions, would provide information about the evolution of the size and composition of the introduced aerosols, and the possibility of dynamic responses to the seeding (evidence for cloud clearing) would also be useful.

- *Testing in different regions and seasons*. The dynamic responses to particles will vary for different regions and seasons of stratocumulus cloud. The boundary layer properties (including cloud height and thickness, number of layers, degree of decoupling, strength of inversion, subsidence rate, vertical velocities, and entrainment) may all be important factors in the amount of brightening and its persistence. Controlled in situ measurements in different regions would provide much more precise information and insights not available from satellite observations or opportunistic field studies.
- *Evaluating differences in emission strategy*. Studies using deliberately controlled emissions for hours or possibly for days, covering regions of varying areas, differing release durations and start times, or changing particle types would provide observations of the resulting differences in dynamic responses to seeding, providing information on cloud clearing, sensitivity to diurnal variation in the boundary layer, sensitivity to composition or size distribution of emissions, and so on. These effects probably operate nonlinearly to dampen or increase the brightening. Interactions between multiple adjacent seeded regions may also change the expected brightening.

Model studies. Models disagree with each other, and with observations of clouds, aerosols, and their interactions. These specific studies are recommended:

- Designing model studies to attempt to reproduce the field studies discussed above (particularly the controlled emission studies) could help reveal specific reasons for discrepancies, leading to improved parameterizations.
- Better intercomparisons between climate models using varying treatments of aerosol microphysics, employing scenarios that are more strongly constrained (in terms of the type, amount, and altitude of aerosol emissions) than have been hitherto performed by the GeoMIP studies, would help in understanding the reasons for climate simulation differences that lead to model uncertainties and their projection of climate consequences.
- Intercomparison between detailed models would be useful to resolve critical features and would provide benchmark simulations for the simpler formulations used in global models.
- Comparison between global-scale model formulations of aerosol, clouds, and aerosol dispersion in the subcloud layer, with finer-scale models (LES, aerosol dynamics, and plume models) could be useful. Such comparisons would challenge the simplified formulations present in global models with the much more detailed formulation present in the fine-scale models.

- There has not yet been any exploration of sensitivity of model response to model resolution, or the numerical methods used to solve the equations describing the important processes and their interactions. Studies of these aspects would eventually be important to ensure that predictions of model change are robust.

As with SAAM studies, there are many potential climate impacts from MCB that are essentially unexplored, and more attention is merited with both models and possibly field experiments if they can be done at smaller scales. The committee is specifically aware of a lack of knowledge about (a) impacts on ocean circulations, (b) consequences to ecosystems due to significant reductions in sunlight reaching the surface where MCB is operating, (c) interactions of MCB with dominant modes of interannual variability like ENSO and the Pacific Decadal Oscillation (PDO), and (d) the nature of the remote impacts to precipitation like that found in the U.K. Met Office model discussed previously (Jones et al., 2013). These processes are all likely to operate at longer timescales and be sensitive to forcing on larger space scales and should also be explored.

Other Methods

There are a number of other proposed techniques that are often considered in discussions of climate intervention broadly that also have to do with modifying the albedo and/or radiation balance of the planet. The proposals in this section have generally shown less promise in initial studies, are less developed than the ones described in the earlier sections of this chapter, or are only mentioned in passing in the literature. In particular, not enough is yet known about cirrus cloud modification to warrant a more extensive discussion at this time, although this proposed technique may have potential. Even though time and cost issues may differ among the specific technologies, those differences are at extents that are not yet well quantified due to the limited current state of development.

Space-Based Methods

There have been several proposals in the literature for placing scatterers or reflectors of some kind in space to reduce the amount of sunlight entering Earth's atmosphere. The options include a large opaque disk, a large transparent prism (Early, 1989), a large sail (NRC, 1992), a large diaphanous scattering screen (Teller et al., 1997), a large iron mirror (Mcinnes, 2002), trillions of small spacecraft (Angel, 2006); and a large ring of space dust (Pearson et al., 2006). The objects could be placed in low Earth orbit or at the L1 point.[16] Several of these ideas require the ability to manufacture in space, making them impractical at the current time. Overall, the committee has chosen to not consider these technologies because of the substantial time (>20 years), cost (trillions of dollars), and technology challenges associated with these issues (GAO, 2011; The Royal Society, 2009).

Surface Albedo

Several techniques have been proposed as potential mechanisms for increasing the albedo of the planet's surface, including painting the roofs of large numbers of buildings white, planting crops with higher albedos, covering deserts or other surfaces in highly reflective materials, and generating small bubbles in the ocean to brighten the ocean surface. In general, these techniques are judged to be of low potential use on the global scale because of generally low effectiveness and high costs. Several of these techniques are discussed as "soft geoengineering" (Olson, 2012) because of their low overall risk; that is, the implementation of any of them is easily reversible (e.g., painting roofs back to their original color, replanting original crops, and uninstalling reflectors). There is little to no research demonstrating the practical effectiveness of these techniques and little new research in these areas; the committee summarizes the arguments presented in other assessments.

White roofs. Painting rooftops and road surfaces white in urban areas has been proposed to increase the reflectivity of Earth's surface (Akbari et al., 2012; Lenton and Vaughan, 2009). This approach would have the potential co-benefit of reducing the need for air conditioning in sunny regions in the summertime, although there are questions about its potential impacts on local moisture and energy transport (Olson, 2012). Although this approach does not require the development of new technologies, it involves large costs, both for initial painting and maintenance, and is limited by the available surface area, which is on the order of less than 1 percent of Earth's surface. All published estimates in the previous literature suggest that changing planetary albedo by whitening rooftops cannot compensate for a significant fraction of the forcing produced by present or future anthropogenic forcing by greenhouse gas emissions (e.g., GAO, 2011; The Royal Society, 2009).

---

[16] The L1 point is the point between Earth and the Sun where the gravitational attraction between the two bodies is equal, approximately 1.5 million km from Earth toward the Sun.

Bright crops. It has been proposed that specific choices for crop varieties (Ridgwell et al., 2009) or grassland, shrubland, or savannah species could increase planetary albedo (Hamwey, 2007). There are associated risks to making large changes to ecosystems (The Royal Society, 2009) and, even if done on a large scale, current estimates suggest these approaches are limited in the maximum amount of cooling they could produce globally (GAO, 2011; Lenton and Vaughan, 2009). Such methods may produce significant regional cooling potential that could be used as part of local adaptive measures (Ridgwell et al., 2009).

Reflective materials on surfaces. Deserts cover large land areas and generally are found in areas that receive large amounts of incident sunlight. Reflective material placed over large deserted areas could increase the albedo substantially (from 0.4 to 0.8 according to Gaskill [2004]) and potentially have a large impact on the radiative budget of the planet. The costs of such an approach are likely to be very high (The Royal Society, 2009), and although the technology appears plausible, no demonstration of the technology has yet been reported as of the GAO (2011) report. There may be significant maintenance costs for keeping the reflective surfaces clean. There are also serious unanswered questions about how this would affect desert ecosystems as well as atmospheric circulation and precipitation patterns, including potential effects on monsoons (The Royal Society, 2009).

In addition, there has also been at least one proposal to counteract melting polar ice and thawing permafrost by spreading disks of light-colored material to increase the albedo of areas of open water or specific areas in danger of melting, but there are still significant uncertainties about the effectiveness of this approach (Olson, 2012).

Microbubbles. A 1965 President's Science Advisory Committee report (PSAC, 1965) discussed floating small reflective particles over large oceanic areas to change the amount of reflected sunlight from the surface. Most observers think that this would be difficult to do in practice for many reasons, among them convergence of ocean currents and possible biogeochemical effects. A more recent proposal has been put forward to create microbubbles just under the surface of the ocean that could last for long periods of time to increase the albedo of the ocean's surface (Seitz, 2011). Such a suspension of voids is referred to as a hydrosol. There is very little published research on this idea, but in theory this approach would have the benefits of being local in scale and easily reversible (Olson, 2012). Evaluating the potential effectiveness of microbubbles requires significant further research, particularly into overcoming and optimizing variable microbubble yields and lifetimes, as well as further understanding of risks to phytoplankton ecology and biogeochemical cycles (Seitz, 2011).

Cirrus Cloud Modification

Modification of cirrus clouds is an alternative to planetary albedo modification methods, the focus of this report. Found in the very cold upper half of the troposphere (typically above 440 hPa, varying with latitude), cirrus clouds are composed almost completely of ice crystals and have a thin wispy appearance. Cirrus clouds absorb a fraction of the long-wavelength radiation (wavelengths of 2 to 25 μm) flowing up from the surface and the lower atmosphere and emit this absorbed energy as long-wavelength radiation upward, lost to space, and downward, contributing to greenhouse warming. Cirrus clouds also contribute to the planetary albedo by reflecting a fraction of the incoming solar (short-wavelength) radiation. Overall, the greenhouse warming contribution (which operates continuously over the whole globe) dominates the albedo contribution from cirrus (which operates only on the half of the globe in sunlight) (Chen et al., 2000; Hartmann et al., 1992; Liou, 1986).

Recent studies have suggested it might be possible to cool the planet by decreasing the opacity, frequency of occurrence, areal extent, and/or duration of cirrus clouds, thus increasing the fraction of the long-wavelength radiation flowing up from the surface and lower atmosphere on to space. While albedo modification techniques would operate only during the day and would be most effective around the equator, cirrus thinning could continuously affect the whole globe (but research shows it is most effective at high latitudes [Storelvmo and Herger, 2014]). In essence, albedo modification decreases the rate of heating of the planet while cirrus modification increases its rate of cooling.

Mitchell and Finnegan (2009) have suggested that the highest and coldest cirrus could be targeted for thinning by introducing aerosols that act as ice nuclei, producing ice crystals that grow rapidly and deplete water vapor, suppressing nucleation and growth of ice crystals that form by other means (homogeneous nucleation). They suggest using bismuth tri-iodide (BiI_3) as the ice nuclei, which is nontoxic and relatively inexpensive (Pruppacher and Klett, 1997). Published estimates by Mitchell and Finnegan and most recently by Storelvmo et al. (2013) and Storelvmo and Herger (2014) suggest that small increases to long-wavelength radiation to space could offset the enhanced radiative forcing due to a CO_2 doubling.

As discussed by Cotton (2008), the possible adverse consequences of seeding cirrus clouds to increase the outgoing long-wavelength radiation from the lower atmosphere and surface are most likely impacts on the hydrological cycle. Cotton indicates the need for chemical, cloud-resolving, and global models to evaluate the feasibility of this approach and to estimate possible adverse consequences. He judges the feasibility of this approach in terms of implementation strategies as being comparable to seeding sulfates in the lower stratosphere and suggests the costs would be similar to Crutzen's estimates for stratospheric seeding (Crutzen, 2006).

In a more recent modeling study, Storelvmo et al. (2014) found that seeding of mid- and high-latitude cirrus clouds had the potential to cool the planet by about 1.4 K, and that this cooling is accompanied by only a modest reduction in global rainfall. Intriguingly, and suggestive of the complexity of such modifications, seeding of the 15 percent of the globe with the highest solar noon zenith angles at any given time resulted in the same global mean cooling as a seeding strategy that involved 45 percent of the globe. In either case, the cooling was found to be strongest at high latitudes and could therefore serve to prevent Arctic sea ice loss.

Scientists have only a limited understanding of the physical and dynamic processes influencing formation, maintenance, and dissipation of cirrus clouds. Perhaps most critical to current research, there are significant uncertainties associated with ice nucleation in cirrus clouds and its proper representation in numerical models. Further research is required to be able to assess the potential viability of cirrus cloud modification as a response to climate impacts (Storelvmo et al., 2014). This includes improving the understanding of cirrus clouds through observations, better modeling to understand the role of cirrus clouds in the climate system and expected regional temperature changes from cirrus cloud dissipation, and determining whether cirrus cloud modification is feasible and effective as a climate intervention method with fewer negative consequences than other approaches. Research supporting possible cirrus cloud modification will also be relevant to better understanding the effects of stratospheric aerosol injection—either from volcanic eruptions or from stratospheric albedo modification efforts—because these aerosols will eventually settle out of the stratosphere into the upper troposphere where cirrus clouds reside (Cirisan et al., 2013; Kuebbeler et al., 2012). If deployment were to be evaluated, then development and testing of tailored seeding agents and delivery systems to optimize the dissipation of the cirrus cloud, including addressing the suitability for agents for multiple types of cirrus and understanding of the fate and impacts of seeding agents (evaporation versus falling out), would need to be undertaken.

Social and political challenges to cirrus modification research or eventual deployment are likely to be similar to those faced by proposed albedo modification techniques. These may come from some in the environmental community but also from the many individuals who believe the persistent chemtrail myth which says that long-lasting contrails produced by high-flying aircraft contain chemical or biological agents (see Box C.1 in Appendix C).

Observational Issues for Albedo Modification

The success of society in the face of a changing environment relies heavily on an effective observational capability to document and understand change, as well as to inform strategies to address change. The need for a robust observing capability becomes significantly amplified with the implementation of or experimentation with albedo modification methods, given that the indirect effects could be of greater impact than the direct effects, and they may well be unanticipated. The use of an engineered increase in albedo to offset the effects of anthropogenic CO_2 increase is fraught with uncertain outcomes that could potentially be much worse than the problem it seeks to address. As a result it is critical that any such undertaking requires a monitoring plan that provides a continually updated assessment of whether the benefits are likely to be greater than the adverse effects. The successful observational strategy would require four elements: (1) monitoring large-scale direct effects, (2) monitoring large-scale indirect effects, (3) intense local process observations to inform models, and (4) capability to detect unilateral and uncoordinated deployment.

Satellite Monitoring of Large-Scale Direct Effects of Albedo Modification

A minimal requirement for controlled deployment of a climate intervention involving albedo modification is that one be able to detect and characterize the actual change in albedo achieved by the intervention. This is crucial, because the chain of physical processes linking the controlled injection of a substance into the atmosphere to the resulting change in albedo is so complex, and involves so many stacked uncertainties, that it is unlikely to prove possible to accurately compute the albedo change a priori. It would be incumbent upon those who deploy an albedo modification technique to assess how well the target value is met. Accurate albedo monitoring is also a requirement for a broad class of field experiments aimed at testing albedo modification technologies, though there may also be experiments that yield useful scientific payback without producing a detectable change in albedo.

Satellites are the preferred platform for observation of large-scale albedo changes, because of their near-global coverage, but albedo observations from space pose a considerable challenge. These include converting observations from a single or limited number of viewing angles to total reflected energy using complex empirically tuned assumptions about the angular distribution of reflected radiation (Loeb et al., 2012); determining the full diurnal cycle based on incomplete sampling by satellites of diurnal variability; maintaining accurate calibrations to account for instrument degradation over time; and merging and intercalibrating observations from different satellites with different orbits at different times, in order to achieve the long-term records necessary do quantify and understand trends.

Any albedo modification, if deployed, should start with an intervention of small magnitude—with a target of perhaps −1 W/m^2—in order to gain experience with the consequences of a more modest intervention and its impacts on both to the short-wavelength energy balance and to other aspects of the system before making a decision as to whether the risks involved in scaling to larger values are tolerable; this is the "gradualist" scenario described in Chapter 2 (section on scenarios). In order to provide useful information as to how closely a −1 W/m^2 target is achieved, the accuracy of the albedo measurement needs to be significantly better than that, at least 0.25 W/m^2. Bender et al. (2006) concluded that albedo monitoring capabilities would have to be roughly an order of magnitude more accurate than they are today in order to assess their importance in the context of anthropogenic climate change. Since that finding is made in the context of an approximate 2.4 W/m^2 of radiative forcing by anthropogenic greenhouse gases, it is clear that the current monitoring capabilities fall far short of what would needed in the −1 W/m^2 gradualist scenario, let alone smaller-scale field trials, and would be of questionable adequacy even for a full-scale deployment.

Currently, monitoring of Earth's top-of-atmosphere radiation budget relies primarily on the CERES instrument, which has flown on a series of satellites and is still operational on NASA's Aqua and Terra satellites and the Suomi NPP satellite at the time of writing. The excess of the top-of-atmosphere mean energy imbalance relative to what can be justified on the basis of ocean heat uptake measurements provided an indication of the intrinsic error in the observation. For the CERES observations, this error (estimated from the excess imbalance) is approximately 5.7 W/m^2 (Loeb et al., 2009). The ocean heat uptake has been estimated to be 0.5 ± 0.43 W/m^2 at the 90 percent confidence level (Loeb et al., 2012). The order-of-magnitude difference between ocean heat uptake and the satellite-measured imbalance is attributable to some mix of errors in the infrared measurement and the albedo measurement, which results from uncertainties in calibration, measurement of the incident solar flux, instrument spectral response, and angular distribution models. The total uncertainty raises serious questions about the ability of CERES-type instruments to characterize a significant deployment of albedo modification. More work needs to be done on the validity of the data-processing assumptions when it comes to long-term albedo monitoring, and it would certainly be desirable to develop instrument suites that did not require such extensive corrections.

Measurement error is not the only, or even the dominant, challenge confronting albedo monitoring. Natural variability of albedo is considerable, and it imposes a barrier on the minimum magnitude of induced albedo change that can be detected with a limited-term observation. Considering natural variability limits alone, Seidel et al. (2014) concluded that detection of an abrupt 0.7 W/m^2 change in reflected sunlight would be unlikely within a year, even give 5 years of baseline data. They further concluded that detection (let alone characterization) of a 3-month experiment limited to the equatorial zone would require an albedo change three times larger than that produced by the Pinatubo eruption. These conclusions underscore the likelihood that any field experiment aimed at producing a measurable albedo change would need to be large enough to count as full deployment.

Measurement of albedo alone will not generally be sufficient to discriminate between albedo changes due to a climate intervention and those arising from other components of the climate system, such as volcanic aerosols, sea ice, or cloud changes. Isolating the direct effect of a climate intervention would be greatly facilitated by development of a hyperspectral short-wavelength monitoring capability. Beyond quantifying the bulk reflectivity of the surface and/or atmosphere, such observations would characterize reflectivity as a function of wavelength. Such information would provide fundamental insights into the nature of the atmospheric reflectors (i.e., cloud type, water content, optical characteristics, and aerosol radiative forcing) as well as the reflective characteristics of the underlying surface. These spectral signatures, when combined with top-of-atmosphere (TOA) solar irradiance measurements, would provide a detailed understanding of the strengths and limitations of the albedo modification techniques. Hyperspectral imagers can provide additional information on the nature of clouds (e.g., thin cirrus) due to the unique spectral signature of various cloud types and, in the case of snow- or ice-covered surfaces, will allow discrimination of clouds from the spectrally similar (but not identical) underlying snow and ice cover. Information of this type would be valuable in assessing the changes in cloud albedo achieved by boundary layer cloud-brightening schemes, as well as for characterizing unintended effects of stratospheric aerosol injection on upper tropospheric clouds.

Additional insights would be gained from multiangular observations for bulk assessment of cloud vertical structure, and lidar measurements (similar to the CALIPSO mission) for sampling of precise vertical structure of clouds and aerosols.

The capabilities established for monitoring these direct effects would have the added benefit of facilitating detection of deployment by unilateral actors, by detecting albedo anomalies against a climatological background. To detect such anomalies, however, such capabilities would need to be sustained.

Finally, since the ultimate objective of albedo modification interventions is to lower temperatures at or near Earth's surface, sustained monitoring of surface temperature would be required. There is a multidecadal history of global and regional surface temperature monitoring from satellites, which complements a distributed ground network. Current global-coverage sensors on polar-orbiting spacecraft include MODIS on Terra and Aqua and the Visible Infrared Imaging Radiometer Suite (VIIRS) on Suomi NPP, all of which build on and improve upon the heritage of the AVHRR system first launched in 1978. Continuity of VIIRS is planned through 2025 on the Joint Polar Satellite System (JPSS) series, and a sustained surface temperature measurement capability into the foreseeable future is essential for understanding the temperature evolution of the Earth system. The importance of such a system would be significantly increased if an albedo modification strategy were to be implemented, as it would be essential for assessing the temperature response at Earth's surface.

Satellite Monitoring of Large-Scale Indirect Effects of Albedo Modification

Monitoring albedo determines the proximate cause of the climate change induced by an engineered modification of albedo, but understanding how the climate system responds to this forcing requires additional observations. Albedo feedbacks arising from changes in clouds and sea ice are addressed by the measurements described in the previous section, but beyond that it is necessary to monitor the outgoing infrared radiation, which determines the rate at which Earth loses energy to space. The outgoing infrared flux is affected by the response of clouds, water vapor, and temperature of both the surface and the atmosphere, and accurate monitoring is a crucial part of determining the way a climate intervention has altered Earth's energy budget. Outgoing infrared observations are provided by CERES and similar space-borne instrument packages aimed at monitoring Earth's radiation budget.

Because the ocean has enormous heat capacity and is out of equilibrium with the warming atmosphere, closing Earth's energy budget requires monitoring of ocean heat uptake as well (Hansen et al., 2005). This monitoring is supported by a diverse range of observations of subsurface ocean temperature, but in recent years the Argo float network[17] has produced a major improvement in our ability to monitor ocean heat uptake.

---

[17] See http://www.argo.ucsd.edu/.

Comprehensive monitoring of indirect effects is complicated, because it involves a wide range of climatological processes whose importance may or may not be anticipated. Such processes span a wide range of atmospheric, hydrological, ecological, and other responses. Consequently it is necessary to have a system that observes such parameters as ecosystem health (stress) and dynamics, soil moisture, precipitation, oceanic thermodynamic and dynamic response to a modified energy balance, and other variables. The robustness of the system depends on the risk posture the international community is willing to take. The capabilities necessary to develop an effective system exist today and have largely been deployed, such as the Landsat series of observations, the upcoming soil moisture active and passive (SMAP) mission, microwave radiometers, ocean salinity measurements (e.g., Aquarius), and wind sensors (scatterometers). While this sounds like a call for continued deployment of all the capabilities that have been developed thus to date, it really is a recognition of the fact that avoiding surprises requires vigilance, and the monitoring that ought to accompany the deployment of this global-scale experiment is a commitment to a sustained system that observes all of these critical aspects of the Earth system.

Attributing a credible cause-and-effect relationship requires that scientists have a sufficiently long observation period to distinguish signal from noise and build credible relational statistics, and it also requires that we can develop physics-based linkages between the causes and what we believe are the effects. For this reason, the above observations would need to be sustained for more than a decade, but, more appropriately, through the life of the deployment, since the observed responses will likely be a result of multiple factors and not be stationary in nature. Moreover, because observations only provide information during or after the realization of an outcome, and the real world provides only one realization of a range of possible outcomes, it is critical that process models that capture the physical relationships between the deployment and the response be developed. These models are necessary to provide the insights into the physics that drives direct and indirect responses the forcings. Such insights are necessary in order to characterize and understand the behavior of the climate system response to the albedo modifications, to quantify risks, and to make credible projections. The more quickly and reliably such models can be developed, the sooner the observing system can be scaled back from a comprehensive monitoring system to a more strategic monitoring system targeted at verifying and improving our models. The fact would remain, however, that the better the observing system, the better equipped we will be to understand the implications of our actions.

In Situ Process Observations

Detailed understanding of the physics that produces the direct and indirect changes requires detailed process studies that in turn inform diagnostic and predictive models. As a result there is a need, over both land and sea, for a combined in situ and airborne suite of detailed observations on local and—to the extent possible—regional scales. These would complement the large-scale satellite observations described above. One goal of making such observations would be to quantify the forcing agents (e.g., the amount of sulfur dioxide and aerosols in the stratosphere or troposphere) and their evolution and transport over time. Another goal would be to characterize and quantify the response (e.g., the optical characteristics of the resulting clouds, an assessment of the direct and indirect radiative cooling associated with these processes). The specifics of the process observing system would be derived from the modeling objectives. The end goal is to improve model representation of the physics associated with the deployment, such that the secondary effects can be sufficiently characterized and predicted, in order to minimize any adverse effects.

Detecting a Unilateral and Uncoordinated Deployment

Observing capabilities for detecting unilateral and uncoordinated deployment of albedo modification activities would be relatively straightforward, since the act would be directly measurable. For more insight into the methods used to create the albedo modification and the associated implications, at a minimum, the observational capability identified in the first part of this section above ("Satellite Monitoring of Large-Scale Direct Effects of Albedo Modification") would be appropriate. For a more comprehensive insight into the effects, the observational needs would be similar to those identified in the second part of this section above ("Satellite Monitoring of Large-Scale Indirect Effects of Albedo Modification").

Other methods for detecting unilateral deployment, particularly prior to the actual deployment, involve the gathering of intelligence on the movement or use of albedo modification agents (e.g., chemical feedstock transport, manufacturing, and injection facilities).

Current Observational Capabilities and Needs for Future Continuity of Observations

Monitoring of Earth's TOA energy budget is at present provided primarily by the CERES suite of instruments, flying on NASA's Terra and Aqua satellites and the Suomi NPP satellite. The Terra and Aqua missions are well past their design lives, while Suomi NPP is 3 years into its 5-year design life. With the next CERES instrument planned for launch on the NOAA JPSS platform in 2017, there may be some risk to measurement continuity, which is a very high priority. A number of other Earth radiation budget monitoring projects are anticipated, but maintaining continuity with the CERES record of the past decade is necessary to provide reliable long-term baseline data (Riley Duren, personal communication).

Monitoring of ocean heat uptake at present relies heavily on the Argo float network. This network is supported by a diverse range of international funding sources, but the funding has not been structured to support an operational, as opposed to research-mode, system.[18] Hence, continuity of these crucial measurements into the future is far from ensured.

Some of the most uncertain aspects of climate science have to do with understanding the radiative forcing associated with aerosols. The failure of the current observing capability to quantify the radiative forcing associated with anthropogenic emissions is consistent with the conclusion that the current observational capability to observe and understand climate forcing associated with albedo modification strategies is lacking (see also Robock, 2014). Also lacking is an ability to monitor some of the indirect effects associated with injections: changes to stratospheric chemistry as well as heating near the tropopause and H_2O within the stratosphere, for stratospheric injection and changes to cloud optical depth and cloud effective radius associated with tropospheric injection. For example, the MODIS instrument, when combined with observations from the CALIPSO mission, is able to measure cirrus particle sizes which might change as a result of stratospheric injections, but more study is needed to understand whether these current capabilities (in conjunction with current modeling capabilities) are sufficient to attribute an observed change with a stratospheric aerosol injection.

The Pre-Aerosol, Clouds, and ocean Ecosystem (PACE) mission could provide the capability to monitor tropospheric aerosols as well as aerosol-cloud interactions if it were deployed as originally envisioned—with coincident hyperspectral imaging and multiangle polarimetry with spatial resolution of 250×250 m^2 for selected bands. In addition, such a configuration should allow the retrieval of aerosol heights. However, budget constraints and mission costs are such that the current plans for PACE (still in the definition phase) do not include the polarimeter, and the hyperspectral capability is expected to be scaled back (particularly given the fact that the mission is cost capped). Moreover, the mission is not is not expected to launch until 2019 or

---

[18] See http://www.argo.ucsd.edu/.

later (Steve Platnick, private communication). If the mission were launched with this combined capability and could achieve an accuracy of the maximum of either 10% or 0.002 optical depth units, much of the albedo forcing and response agents could be well understood.

The SAGE III instrument to be launched on ISS in 2014 is capable of limb-scanning measurements of aerosol optical depth and so will be able to measure the vertical profile of aerosol optical depth at latitudes up to to 51°. At low latitudes the spacing between profiles may be large, so initial detection of an injection may be missed, but once spread zonally should be detectable. The accuracy and precision of the stratospheric integrated column is wavelength dependent, ranging from a few percent at wavelengths ≥676 nm, to ~10% at 525 and 449 nm and perhaps 20% at 386 nm. Three versions of SAGE III were built at the same time, and the SAGE III ISS is the last of the three to be launched.

Benefits of Multiple-Use Observational Capability

The observing systems needed to support albedo modification research and controlled deployment are essentially the same as those needed to address fundamental questions concerning the climate system, including estimates of climate sensitivity, characterization of cloud and water vapor feedbacks, aerosol radiative forcing, and response of sea ice and snow cover, all of which occur against the backdrop of natural climate variability. Investment in maintaining continuity of current capabilities, and ultimately improving on their accuracy, is a prime opportunity of a multiple-benefit program that would not only contribute to a better understanding of the consequences of deploying albedo modification interventions, it will also provide fundamental new knowledge about the climate system, which will be essential for meeting the challenges of climate change. It is a no-regrets policy that will be valuable even if albedo modification is never deployed.

SUMMARY AND RESEARCH NEEDS FOR ALBEDO MODIFICATION

This chapter has focused on two anthropogenic actions that are considered to be potentially feasible that could cause Earth to start cooling within a year or two of the initiation of an intervention: (1) introduction of stratospheric aerosols and (2) increasing the reflectivity of low clouds (marine cloud brightening).

It may be technically possible to produce significant changes to the radiative balance of Earth (order 1 W/m^2 or larger) via either of these technologies without the need for major technological innovations. However, albedo modification strategies may introduce major and rapid perturbations to the planet with secondary and tertiary effects on environmental, social, political, and economic systems that are very difficult to predict currently and with effects that could be severely negative. Without further information on these risks, the low initiation costs of albedo modification cannot be balanced against other potential costs and risks of not deploying albedo modification methods.

Looking across the technologies described in this chapter, the committee has identified the following research needs in order to better observe some basic properties associated with Earth's albedo. Most of these research needs relate to observational capabilities for monitoring Earth's energy budget that are of a multiple-use nature, address pressing needs in a broad range of climate science besides analysis of albedo modification effects, and do not require any large-scale albedo modification experimentation to yield useful results. Wherever possible, the focus should be placed on "multiple-benefit" research, that is, research that contributes to albedo modification capabilities while contributing to the understanding of climate change and other basic research topics assuming albedo modification is never deployed. Research and observational programs in this category include improved monitoring of Earth's radiation budget and improved understanding of aerosols and their effect on clouds. An extensive set of recommendations describing modeling and field studies that can be used to improve understanding of relevant processes, and potential consequences from albedo modification, can be found in the earlier sections titled "Summary and Statement of Research Needs for SAAM" and "Summary and Statement of Research Needs for Marine Cloud Brightening" and in Box 5.1 of Chapter 5.

- Because CERES is the prime tool for understanding the top-of-atmosphere radiation budget, a high priority should be assigned to maintaining the continuity of measurement with the CERES instrument package, or with an improved package that can be accurately intercalibrated with CERES during a period of overlapping observations. Since, ultimately, the warming experienced by current and future generations is a direct result of this energy imbalance, sustained monitoring is essential for understanding the evolution of the climate system whether in response to greenhouse forcing or climate intervention. More research is also needed to determine the long-term accuracy of recalibrated and bias-corrected measurements.
- Research is needed on development of a new generation of short-wavelength (albedo) and long-wavelength (outgoing infrared) space-borne instruments that do not require the large bias corrections of current instruments. Development of instruments that could in addition provide spectrally resolved

measurements ("hyperspectral imagers") would provide an improved basis for discriminating the processes leading to changes in the radiation budget. For support of albedo modification research, hyperspectral short-wavelength measurements are particularly important, but hyperspectral long-wavelength measurements can help discriminate cloud changes and may also be useful in monitoring stratospheric heating due to aerosols.

- Maintaining continuity of the existing Argo float system for continued and sustained monitoring of ocean heat uptake is a crucial part of monitoring the energy budget, as it is the prime source of information about heat exchange between the atmosphere and ocean. Opportunities to expand the system and improve its accuracy should be sought, as well as other opportunities to improve monitoring of ocean heat uptake and storage. Because this heat uptake and storage play a key role in modulating the magnitude and timing of surface temperature change, accurately monitoring these energy exchanges is essential for understanding the response of the climate system to current greenhouse forcing. This need becomes even greater under conditions of climate intervention.
- The observations associated with an intervention, such as hyperspectral measurements, polarimetry, and so on, would provide new data sources, and realizing their full value will require new assimilation and analysis approaches.
- To make use of these types of observations, research is needed on data assimilation and data analysis to improve methods for making optimal use of observations in detecting and attributing the albedo and climate response to deliberate albedo modification.
- Abrupt termination of albedo modification in a high-CO_2 world would lead to rapid warming and a host of other rapid changes in climate. There is a need for more research on the impacts of abrupt termination of albedo modification on natural ecosystems and human society. Specifically, it is important to understand what the rates and magnitudes of post-termination warming would be both globally and regionally, what the associated impacts to the hydrological cycle would be, and what the ecosystem responses would likely be. Moreover, research into the relative impacts of a nonintervention scenario and an abruptly terminated intervention scenario, and even a slowly terminated intervention scenario, is needed.
- Finally, if climate-altering deployment of any type of albedo modification strategy were to occur, it would require technology experiments (e.g., tests of delivery systems for aerosols). Because these would be explicitly for the purpose of deployment and experimentation, they might not rise to the level of multiple-benefit research (even though they may produce some improved

> understanding of aerosol microphysics). Nonetheless, research in this area would be required in order to responsibly carry out any kind of test or deployment. Development of engineering capabilities required for deployment rather than research should only be developed in the context of a reviewed plan for engineering scale-up of a proposed technique, so that potential "show-stoppers" are evaluated before more tractable but less important ones.

Table 3.4 provides a quick summary overview of the committee's judgments on aspects such as effectiveness, technical readiness, ramp-up time, duration of effects, cost, ability to detect and monitor, and various risks of the albedo modification strategies presented in this chapter. In each category, the committee has provided an estimate of not only the magnitude of the effect (e.g., high, medium, low, and what those categories mean for that table entry) but also the committee's confidence in that categorization. The entries on the tables are the product of committee deliberation based on an understanding of the available literature. The table goes into detail for the two strategies that were discussed in detail: stratospheric sulfate aerosol injection and marine cloud brightening.

TABLE 3.4 Table Summarizing the Committee's Judgments on Various Aspects of the Two Major Albedo Modification Techniques Presented in this Chapter

Committee Confidence:
● High ◍ Medium ○ Low

	Stratospheric Aerosol Albedo Modification	Marine Cloud Brightening
Ability to mask some consequences of greenhouse gas warming, i.e., ability to produce substantial cooling of global mean temperature		
High: technique could achieve substantial cooling by itself, i.e., a radiative forcing equivalent to a doubling of CO_2	◍	
Medium: technique could be a substantial contributor		◍
Low: technique could be helpful but cooling effect is in noise		
Technological readiness (systems level maturity), technical risk		
Mature technology (ready to deploy quickly, low technical risk): technology exists at scale		
Intermediate-maturity technology: prototypes exists, not to scale		
Immature technology (not ready to deploy quickly, high technical risk): needs prototyping	●	●
Technological readiness (device level maturity), technical risk		
Mature technology (ready to deploy quickly, low technical risk): technology exists at scale		
Intermediate-maturity technology: prototypes exists, not to scale	◍	◍
Immature technology (not ready to deploy quickly, high technical risk): needs prototyping		
Time required to scale to maximum ("irresponsible/uninformed") deployment with major effort[a,b]		
Fast: years (i.e., <10 years)	●	●
Medium: decades (i.e., 10 < x < 100 years)		
Slow: centuries (i.e., >100 years)		

continued

TABLE 3.4 Continued

	Stratospheric Aerosol Albedo Modification	Marine Cloud Brightening
If decision made to deploy, time required to develop informed, well-planned, and controlled maximum deployment with major effort[a,b]		
Fast: years (i.e., <10 years)		
Medium: decades (i.e., 10 < x < 100 years)	◍	◍
Slow: centuries (i.e., >100 years)		
Time for direct radiative effects to dissipate if albedo modification activity is suddenly stopped[c]		
Slow: 1-5 years	●	
Medium: 1-5 months		
Fast: 1-5 days		●
Relative costs of an albedo modification device[d] (orders of magnitude; when building at scale)		
Low cost: order \$1 billion per year per 1 W/m^2 (i.e., >0.3 W/m^2 per billion\$/yr)	●	●
Medium cost: order \$10 billion per year per 1 W/m^2 (i.e., 0.03 < x < 0.3 W/m^2 per billion\$/yr)		
High: order \$100 billion per year per 1 W/m^2 (i.e., <0.03 W/m^2 per billion\$/yr)		
Relative costs of an albedo modification system[e] (orders of magnitude; when building at scale)		
Low cost: order \$1 billion per year per 1 W/m^2 (i.e., >0.3 W/m^2 per billion\$/yr)		
Medium cost: order \$10 billion per year per 1 W/m^2 (i.e., 0.03 < x < 0.3 W/m^2 per billion\$/yr)	○	○
High cost: order \$100 billion per year per 1 W/m^2 (i.e., <0.03 W/m^2 per billion\$/yr)		

continued

TABLE 3.4 Continued

	Stratospheric Aerosol Albedo Modification	Marine Cloud Brightening
Ability to detect unsanctioned albedo modification at scale[f]		
Easily verifiable: existing and planned observation systems can verify without retasking	●	●
Moderately easy to verify: existing observation systems would need retasking or known technology would need to be deployed		
Difficult to verify: new technology/methods would need to be developed/deployed		
Ability to measure the radiative forcing of a large-scale, decade-long albedo modification deployment with sufficient accuracy		
Easily verifiable: existing and planned observation systems can verify without retasking		
Moderately easy to verify: existing observation systems would need retasking or known technology would need to be deployed; using substantial additional resources employing existing technology	●	●
Difficult to verify: new technology/methods would need to be developed/deployed		
Ability to monitor and attribute the climate response of a large-scale, decade-long albedo modification deployment with sufficient accuracy		
Easily verifiable: existing and planned observation systems can verify without retasking		
Moderately easy to verify: existing observation systems would need retasking or known technology would need to be deployed; using substantial additional resources employing existing technology		
Difficult to verify: new technology/methods would need to be developed/deployed	◍	◍

continued

TABLE 3.4 Continued

	Stratospheric Aerosol Albedo Modification	Marine Cloud Brightening
Environmental consequences and risks (geographic extent of impact, adverse consequences, co-benefits)[g,h]		
Local-scale consequences		
Regional-scale consequences		●
Global-scale consequences	●	
Addresses nonwarming effects of CO_2 (e.g., ocean acidification, CO_2 fertilization)		
Yes		
Somewhat		
No	●	●
Sociopolitical consequences and risks (include national security)[h]		
None / only national issues		
Binational issues (e.g., one border involved such as United States–Canada)		●
Multinational issues	●	
Governance challenges for deployment at scale[h]		
No novel governance challenges		
Governance challenges likely to be primarily territorial, but with some legitimate interest by other states		●
Potential for substantial adverse effects across international borders or to an international commons	●	
How many potential unilateral and uncoordinated actors could have both the technology and resources to deploy at scale		
Few actors, order 1		
Medium order, 10		
High order, 100	○	○

continued

TABLE 3.4 Continued

NOTE: In each category, the committee has provided an estimate of not only the magnitude of the effect (e.g., high, medium, low, and what those categories mean for that table entry), but also the committee's confidence in that categorization. The entries on the tables are the product of committee deliberation based on an understanding of the available literature.

[a] A "major effort" denotes something on the scale of the Manhattan Project.

[b] Refers to time from when a decision would be made, but assumes the use of current technologies.

[c] Does not include secondary effects in climate system, such as changes in precipitation patterns.

[d] Device refers to a method for deploying some particular albedo modification technique.

[e] System refers to a device or set of devices capable of altering the radiative energy balance in a measurable way and the associated observing and modeling capabilities for assessing their radiative impact.

[f] This is likely not a climate signal, but would rather be a logistical signal (i.e., deployment of large numbers of planes to the stratosphere or large numbers of ships) and the resulting stratospheric aerosol cloud (with lidar) and lines in the clouds.

[g] See sections "Environmental Consequences of SAAM" and "Environmental Consequences of MCB" above.

[h] Instances where the committee felt the table entries were between values are represented by a symbol that spans both values.

CHAPTER FOUR

Governance of Research and Other Sociopolitical Considerations

GOVERNANCE CONSIDERATIONS FOR ALBEDO MODIFICATION RESEARCH

The focus of this chapter is on the issue of governing research, because research is the only albedo modification-related activity that the committee believes should be considered at this time. Such research encompasses a range of activities from the innocuous, such as modeling, to the more invasive, such as controlled small-scale test deployments for experimentation purposes. The degree and nature of governance should vary with the activity, and the associated risks. The committee begins by reviewing previous discussions on the governance of albedo modification research before briefly identifying some of the issues related to the governance of albedo modification deployment, and then discusses a path forward. The committee believes it is premature to engage in a larger discussion of governance of deployment given the large uncertainties about albedo modification.

It is important to give careful thought to the mechanisms for governing research on albedo modification, since they may later form part of the basis for a mechanism for governing sanctioned or unsanctioned deployment should a choice ever be made to proceed to that stage. Albedo modification will test international relationships in unprecedented ways. Although coordinated international efforts to deal with global-scale threats have been successful in the past, such as the Montreal Protocol, no similar international effort has been undertaken to address the sort of deliberate global alteration that would be involved in albedo modification.

Questions that will likely need to be addressed in any future international agreement governing albedo modification include the following:

1. How is it decided when the benefit to albedo modification will outweigh the harm? What metric should be used?

2. What obligation do the acting parties have to compensate others for damages, anticipated or otherwise, caused by albedo modification? Who decides causality and how is it determined?
3. Who decides what is benefit versus harm, and on what time and space scales are such determinations made?

Pidgeon et al. (2013) argue that public surveys show that "international governance and regulatory structures should be under development now to help shape geoengineering research." Parson and Ernst (2013) argue that research will "require international governance as the scale of interventions grows beyond a single nation's territory—or as other nations assert claims to participate due to the international significance of the research, even if physical trans-boundary effects are small." They go on to suggest that

> . . . there will not be a clean boundary between an early period of "scientific" [climate engineering] governance and some later period of "operational" governance. Rather, future decisions about [climate engineering] interventions will continue to depend on uncertain scientific judgments synthesized from prior research—judgments about projected effectiveness and risks of proposed interventions, about attribution of consequences to interventions underway, and about appropriate monitoring and adaptation strategies—even as they also seek to advance operational risk-management objectives.

Hulme (2014) explores three possible models for governance: a multilateral process operated through the United Nations, a consortium of several nations, and deployment by a single nation. He argues that none of these will result in adequate risk governance: that research on albedo modification will inevitably lead to deployment and, hence, "if the deployment of the technology cannot conceivably be adequately governed, then the technology itself should not be researched." The committee's view is that ignoring the need to control albedo modification risk through research and governance does not ensure that albedo modification will never be deployed, and in fact it increases the likelihood that any deployment would be less successful and have more undesirable side effects.

A single nation, or even a very wealthy individual, could have the physical and economic capability to deploy albedo modification with the intention of unilateral action to address climate change in a geographic region. Establishing strong international norms regarding the conditions under which deployment of albedo modification might be warranted could help dissuade such unilateral and uncoordinated action. Establishing such norms will only occur with the deliberate initiation of an international conversation on what is known and not known about the potential risks and benefits of albedo modification. Such conversations are best initiated through consideration of research results that allow for constructive conversations based on effectively circumscribed information. Research that is aimed at understanding the impacts of responsible deployment of albedo modification will also provide important insights into the effects of irresponsible deployment, better equipping nations to deal with such threats more effectively.

While the issues of potential linkage, precedent, and political and institutional lock-in between research and deployment are important, they need to be addressed through a broad civil society conversation as part of establishing a research governance strategy (Recommendation 6). These topics are beyond the scope of this report and the charge to the committee.

Previous Discussions of Governance of Albedo Modification Research

Several authors have discussed the governance arrangements that they believe are needed to manage research related to albedo modification. One of the first public calls for research on climate intervention came in the early 1990s. Writing in *EOS,* Keith and Dowlatabadi (1992) argued that research should focus on "answering questions with the greatest product of uncertainty and importance." They summarized a set of issues related to risk, politics, and ethics that they believed should inform such priority setting and focused in particular on issues of sovereignty, equity, liability, and security, calling for greater attention to "non-technical issues and risks." Schelling (1996) was one of the first to consider how existing international institutions might handle the governance of both albedo modification and carbon dioxide removal techniques.

Over the course of the next decade and a half, albedo modification generally grew to be more openly discussed, including at two international workshops run in Washington, DC, and Lisbon, Portugal, in the late 2000s. Building on views expressed by participants of those workshops, Victor et al. (2009) wrote the following:

> The scientific academies in the leading industrialized and emerging countries—which often control the purse strings for major research grants—must orchestrate a serious and transparent international research effort funded by their governments. Although some work is already under way, a more comprehensive understanding of geoengineering options and of risk-assessment procedures would make countries less trigger-happy and more inclined to consider deploying geoengineering systems in concert rather than on their own. (The International Council for Science, which has a long and successful history of coordinating scientific assessments of technical topics,

> could also lend a helping hand.) Eventually, a dedicated international entity overseen by the leading academies, provided with a large budget, and suffused with the norms of transparency and peer review will be necessary. In time, international institutions such as the Intergovernmental Panel on Climate Change could be expected to synthesize the findings from the published research. . . .
>
> Although the international scientific community should take the lead in developing a research agenda, social scientists, international lawyers, and foreign policy experts will also have to play a role. Eventually, there will have to be international laws to ensure that globally credible and legitimate rules govern the deployment of geoengineering systems. But effective legal norms cannot be imperiously declared. They must be carefully developed by informed consensus in order to avoid encouraging the rogue forms of geoengineering they are intended to prevent.

Early discussions on albedo modification research focused on the so-called "double moral hazard" issue—that on one hand research into these proposed techniques could lead to policy makers deciding to lose focus and/or urgency for reducing emissions, while on the other hand, not researching albedo modification techniques could allow for a situation where an albedo modification approach is deployed without a full understanding of its consequences (either a sanctioned or unsanctioned approach; see further discussion in the "Ethical and Sociopolitical Issues" section below). Concerns over the first part of this "moral hazard" have led to proposals that an international prohibition be implemented with respect to all research related to albedo modification (see description of the Convention on Biological Diversity later in this chapter). In response to this, Victor et al. (2009) argued the following:

> Those who worry that such research will cause governments to abandon their efforts to control emissions, including much of the environmental community, are prone to seek a categorical prohibition against geoengineering. But a taboo would interfere with much-needed scientific research on an option that might be better for humanity and the world's ecosystems than allowing unchecked climate change or reckless unilateral geoengineering. Formal prohibition is unlikely to stop determined rogues, but a smart and scientifically sanctioned research program could gather data essential to understanding the risks of geoengineering strategies and to establishing responsible criteria for their testing and deployment.

The Royal Society's report on geoengineering (Shepherd et al., 2009) further elaborated this same theme, arguing the following:

> An obvious drawback of a moratorium is that it inhibits research. . . . In the context of geoengineering, it would make it almost impossible to accumulate the informa-

> tion necessary to make informed judgments about the feasibility or acceptability of the proposed technology. Furthermore, it is likely to deter only those countries, firms and individuals who would be most likely to develop the technology in a responsible fashion, while failing to discourage potentially dangerous experimentation by less responsible parties. To overcome this problem, some commentators have suggested forming an international consortium to explore the safest and most effective options, while also building a community of responsible geoengineering researchers, along the lines of other international scientific collaborations, such as the European Organization for Nuclear Research (CERN) and the Human Genome Project (Broecker and Kunzig, 2008; Victor et al., 2009).

The Royal Society report (Shepherd et al., 2009) also discussed some of the considerations that should go into the governance of albedo modification research. They argued that when assessing alternative strategies, discussions of governance should

> . . . include the reversibility of society's commitment to a technology, and the ease of remediation if problems arise. Indicators of a technology's relative 'inflexibility' include: long lead times from idea to application; capital intensity; large scale of production units; major infrastructure requirements; closure or resistance to criticism; and hype about performance and benefits (RCEP, 2008). As a general guide, the more of these factors that are present, the more caution should be exercised in committing to the adoption of a particular technology.

A year after the publication of the Royal Society report, the Asilomar International Conference on Climate Intervention Technologies was held at the Asilomar Conference Center in California in March 2010. This conference brought together more than 100 leading researchers and thinkers to discuss a wide range of scientific and research governance issues. In their final report (ASOC, 2010) the conference organizing committee reported that conference deliberations resulted in five recommendations for the governance of research:

> (1) climate engineering research should be aimed at promoting the collective benefit of humankind and the environment; (2) governments must clarify responsibilities for, and, when necessary, create new mechanisms for the governance and oversight of large-scale climate engineering research activities; (3) climate-engineering research should be conducted openly and cooperatively, preferably within a framework that has broad international support; (4) iterative, independent technical assessments of research progress will be required to inform the public and policymakers; and (5) public participation and consultation in research planning and oversight, assessments, and development of decision-making mechanisms and processes must be provided. The conferees concluded that expanding and continuing the discussion with an even

> broader set of participants will be an essential step in moving forward to explore the potential benefits, impacts, and implications of climate engineering. (ASOC, 2010)

Four months before the Asilomar conference a group of academics in the United Kingdom submitted a set of principles to a House of Commons Science and Technology Select Committee on "The Regulation of Geoengineering" (House of Commons Science and Technology Committee, 2010; Rayner et al., 2013). The five principles, which were subsequently discussed at the Asilomar conference, read as follows:

1. *Geoengineering to be regulated as a public good.* While the involvement of the private sector in the delivery of a geoengineering technique should not be prohibited, and may indeed be encouraged to ensure that deployment of a suitable technique can be effected in a timely and efficient manner, regulation of such techniques should be undertaken in the public interest by the appropriate bodies at the state and/or international levels.
2. *Public participation in geoengineering decision making.* Wherever possible, those conducting geoengineering research should be required to notify, consult, and ideally obtain the prior informed consent of those affected by the research activities. The identity of affected parties will be dependent on the specific technique which is being researched—for example, a technique which captures carbon dioxide from the air and geologically sequesters it within the territory of a single state will likely require consultation and agreement only at the national or local level, while a technique which involves changing the albedo of the planet by injecting aerosols into the stratosphere will likely require global agreement.
3. *Disclosure of geoengineering research and open publication of results.* There should be complete disclosure of research plans and open publication of results in order to facilitate better understanding of the risks and to reassure the public as to the integrity of the process. It is essential that the results of all research, including negative results, be made publicly available.
4. *Independent assessment of impacts.* An assessment of the impacts of geoengineering research should be conducted by a body independent of those undertaking the research; where techniques are likely to have transboundary impact, such assessment should be carried out through the appropriate regional and/or international bodies. Assessments should address both the environmental and socioeconomic impacts of research, including mitigating the risks of lock-in to particular technologies or vested interests.
5. *Governance before deployment.* Any decisions with respect to deployment should only be taken with robust governance structures already in place, using existing rules and institutions wherever possible.

In parallel with the deliberations by the committee of the House of Commons, under the Chairmanship of Congressman Bart Gordon the U.S. House of Representative's Committee on Science, Space, and Technology held three hearings on geoengineering (U.S. Congress, 2010). The final hearing included testimony via a video conference link with Mr. Phil Willis who chaired the Committee of the House of Commons.

In testimony presented to the third hearing (March 18, 2010) of the House Science Committee, Morgan introduced the concept of an "allowed zone," arguing that, governed only by national environmental and other regulations, scientists should be able to conduct small-scale field studies in the stratosphere within some tightly constrained bounds defined in terms of variables such as very low impact on radiative forcing, short lifetime, and very limited impact on ozone depletion (U.S. Congress, 2010). Morgan and Ricke (2010) (also see Parson and Keith, 2013) subsequently elaborated these ideas in a report published by the International Risk Governance Council in which they argued that, while laboratory and computer modeling studies should come first,

> because there are many important questions about these technologies that can only be answered by observing the real world, within a few years it will likely be necessary to also conduct modest low-level field testing in a way that is transparent and coordinated informally within the international scientific community.

After outlining a number of scientific questions that such studies might address, Morgan and Ricke (2010) argued that[1]

> [s]o long as modest low-level field studies designed to answer these questions are done in an open and transparent manner, we believe they should not be subject to any formal international process of vetting and approval. Countries and firms routinely fly various aircraft in the stratosphere, or send rockets through the stratosphere into space. These activities release significant quantities of particles and gases. A requirement for formal prior approval of small field studies, just because they are directed at learning about SRM and its limitations, is probably unenforceable because judging intent is often impossible. Such a regulation would, at best, make conducting modest low-level SRM research extremely difficult and, at worst, impossible.
>
> That said, clearly one of the first objectives of an SRM research programme should be to give more precise meaning to the phrase "modest low-level." This definition is important both to begin to create clear norms within the international scientific

---

[1] "SRM" in this text refers to "solar radiation management," where the committee prefers to use the term "albedo modification" instead.

> community, and also to provide technical input to the diplomatic and foreign policy community as it begins to think about how it might best regulate larger-scale experimental activities or proposals for actual implementation.
>
> One possible approach would be to define, based on research, an "allowed zone." Once a proposal for such a zone has been developed through research, it would need to be informally vetted within the international research community (for example, through a process such as the one the Royal Society is initiating, through the IAC [Inter Academy Council of the world's science academies], through ICSU [International Council for Science], or through some similar group). After vetting, while experiments may still be subject to any number of regulatory requirements within the country funding or hosting them, scientists should be able to proceed with studies that fall inside this zone without formal international approval, subject only to the requirements that their studies are publicly announced and all results are made public. They should also be informally assessed and coordinated within the scientific community. Once an "allowed zone" has been defined, a norm should be created that the further an experiment ventures outside such a zone, the more extensive the international vetting should be before it is conducted. In the future, such a boundary of allowed activities might be formally incorporated in an international treaty or other agreement.

Seven months after the completion of the series of three hearings by the House Science Committee, the U.S. Government Accountability Office (GAO, 2010) published a report recommending the following:

> The appropriate entities within the Executive Office of the President (EOP), such as the Office of Science and Technology Policy (OSTP), in consultation with relevant federal agencies, should develop a clear, defined, and coordinated approach to geoengineering research in the context of a federal strategy to address climate change that (1) defines geoengineering for federal agencies; (2) leverages existing resources by having federal agencies collect information and coordinate federal research related to geoengineering in a transparent manner; and if the administration decides to establish a formal geoengineering research program, (3) sets clear research priorities to inform decision-making and future governance efforts.

As a follow-on activity to its major study on geoengineering, The Royal Society teamed with the Environmental Defense Fund and The World Academy of Sciences in a project called the Solar Radiation Management Governance Initiative (SRMGI). This effort established "an expert working group and large network of stakeholder partner organizations," ran a conference at The Royal Society's Kavli International Centre in the United Kingdom in March 2011, and subsequently organized sessions on governance in Pakistan, India, China and Senegal, South Africa, and Ethiopia (SRMGI, 2013b).

In preparation for the SRMGI conference Shepherd and Morgan (2011) prepared a background paper that outlined a series of thresholds and categories and then suggested a set of choices that must be made in deciding whether and how to govern albedo modification research:

> **CHOICE 1:** Establish a formal international ban or "taboo" on all forms of SRM research, similar to that which has been developed for chemical and biological weapons.
>
> **CHOICE 2:** In addition to any national regulations that may apply, subject all computer modeling and laboratory studies of SRM to some form of formal international regulatory oversight and/or approval.
>
> **CHOICE 3:** In addition to any national regulations that may apply, even small-scale experimental studies with negligible impact that are conducted outside of the laboratory should be subjected to international regulatory oversight, review and approval.
>
> **CHOICE 4:** In defining an "allowed zone" in which field studies can be conducted, subject only to professional norms of good scientific conduct and national (as opposed to international) regulations, physical and biological impacts should be considered, but more subjective issues of public risk perception should not considered in defining this zone.
>
> **CHOICE 5:** Experimental field studies that push out beyond the boundaries of an "allowed zone" (however defined) should be subjected to international regulatory oversight, review and approval.[2]

In its report *Solar Radiation Management: The Governance of Research* (2013a) the SRMGI project reported a set of nine general conclusions:

1. Nothing now known about SRM provides justification for reducing efforts to mitigate climate change through reduced GHG emissions, or efforts to adapt to its effects. The evidence to date indicates that it could be very risky to deploy SRM in the absence of strong mitigation or sustainable CDR methods.
2. Research into SRM methods for responding to climate change presents some special potential risks. Governance arrangements for managing these risks are mostly lacking and will need to be developed if research continues.

---

[2] Further information is available at http://www.srmgi.org/files/2011/09/SRMGI-background-paper-Thresholds.pdf.

3. There are many uncertainties concerning the feasibility, advantages and disadvantages of SRM methods, and without research it will be very hard to assess these.
4. Research may generate its own momentum and create a constituency in favour of large-scale research and even deployment. On the other hand, ignorance about SRM technology may not diminish the likelihood of its use, and in fact might increase it.
5. A moratorium on all SRM-related research would be difficult if not impossible to enforce.
6. Some medium and large-scale research may be risky, and is likely to need appropriate regulation.
7. Considering deployment of SRM techniques would be inappropriate without, among other things, adequate resolution of uncertainties concerning the feasibility, advantages and disadvantages. Opinion varied on whether a moratorium on deployment of SRM methods would be appropriate at this stage.
8. The development of effective governance arrangements for potentially risky research (including that on SRM) which are perceived as legitimate and equitable requires wide debate and deliberation. SRMGI has begun, and will continue to foster, such discussion.
9. International conversations about the governance of SRM should be continued and progressively broadened to include representatives of more countries and more sectors of society. Appropriate international organizations should also be encouraged to consider the scientific, practical, and governance issues raised by the research of SRM methods.

The report of the Bipartisan Policy Center's (BPC's) Task Force on Climate Remediation Research published in October of 2011 argued that the United States should undertake a serious program of research on carbon dioxide removal (CDR) and albedo modification, under the coordination of the White House OSTP. It called for the White House to establish a new advisory commission that would be charged with helping to guide this research. The BPC task force—composed of 18 leading experts in the field of climate intervention science and governance[3]—argued that

> The federal government should develop transparency protocols for all potentially risky forms of climate remediation research. Those protocols should be appropriate for the magnitude and extent of potential impacts for the specific experiment under con-

---

[3] Note that several members of this task force are also members of the committee that authored this report.

> sideration—that is, protocols should be based not only on the risks posed by related research, but also on the risks that would be posed by deployment.

It also argued that

> Effective research programs must examine more than just the potential impacts, effectiveness, and risks of CDR and SRM technologies. They must also help develop appropriate governance structures for research into those technologies, domestically and internationally.

In a paper titled "Vested Interests and Geoenginering Research," Long and Scott (2013) identify what they term "the four Fs": factors that they argue should be considered in making choices about the design and conduct of research. These are

> *Fortune* – the fact that there are powerful vested interests, such as those who want to sustain the fossil fuel industry, or develop and sell carbon credits.
>
> *Fear* – both appropriate fear of causing serious harm to the Earth system and also various types of "inappropriate fear" such as reputational fears on the part of investigators.
>
> *Fame* – the risk that investigators may become carried away by publicity and notoriety.
>
> *Fanaticism* – the risks that "reasonable ideological position [could] drift into fanaticism when it hardens into a rigid devotion."

Long and Scott (2013) argue that the best way to counteract the risks posed by their "four Fs" is to devise a risk governance system that ensures transparency, institutional designs that "foster standards of [good] practice," an approach to research management that is more collaborative and mission driven, and adequate public deliberation. They conclude that "it is not too early to begin the conversation about the human weaknesses, vested interests, and frightening possibilities of mismanaging geoengineering" and argue that the approaches they have outlined can be used to mitigate these risks.

Morgan et al. (2013) have argued that in undertaking a program of research it will be essential to develop "a code of best SRM research practice" that has three components:

1. Guidelines for making research results available to decision makers and the public (what we call "open access to SRM knowledge");

2. Delineation of categories of field experiments that are unlikely to have adverse impacts on health, safety, or the environment (i.e., experiments conducted within what Morgan and Ricke have previously termed an "allowed zone" of minimal forcing, minimal duration, and minimal impact on stratospheric ozone); and
3. Agreement that any field research to be conducted outside the "allowed zone" will not be undertaken before a clear national and international governance framework has been developed.

After outlining how such a code of practice might be developed, they lay out a strategy under which the United States would take the lead in creating a formal set of norms. Since most albedo modification–related research will likely be funded by the government, they outline a strategy by which federal funding agencies could ensure that the attributes of best practice would be adopted in all the research they support. They argue, "Once developed and implemented, it should be possible to persuade others across the international research community to adopt similar norms. Organizations such as the International Council of Scientific Unions (ICSU), and the world's National Academies of Science, are well positioned to promote such adoption."

Most recently, two workshops held in the spring of 2014 moved the discourse on research governance beyond more abstract discussion to focus on specific cases. At a workshop in March of 2014 organized at Harvard by David Keith, Riley Duran, and Douglas MacMartin (Keith et al., 2014), 28 experts spent 2 days, developing the first reasonably detailed descriptions of a list of eight field experiments that might be run as part of a first round of albedo modification–related experimental studies, and then conducted preliminary reviews of those ideas. The experiments considered are summarized in Table 4.1.

Approximately a month later, a similarly sized second workshop was convened by Jane Long and others (Long et al., 2015) in San Francisco to examine in detail the research governance needs of the eight proposed field projects that had been presented at the Harvard workshop.[4] Although these proposed studies by no means included all of the possible albedo modification field experiments that one might see in an initial set of studies, participants argued that they did span a wide enough space to provide a basis for developing a reasonably detailed assessment of research governance needs.

---

[4] The San Francisco workshop was co-sponsored by the Bipartisan Policy Center, the Environmental Defense Fund, the Center for Climate and Energy Decision Making at Carnegie Mellon University, and the University of California, Berkeley.

TABLE 4.1 Summary of the Field Test Experiments Proposed and Critiques at the March 2014 Harvard Workshop that Then Formed the Basis for Discussion of Research Governance at the San Francisco Workshop a Month Later

Exp#	Informal Title	Category Type(s)	Cost ($M)	Local Forcing, Area, Duration, and Equivalent Energy	Material and Mass	Synopsis
1	SCoPEx	Process study	10	$\Delta RF = 0.01\text{-}0.1\ W/m^2$ $A = 10^1\ km^2$ T = 1 week N = 4 $E = 2.4 \times 10^{12}\ J$	10^3 g of S and <10^5 g of H_2O	Stratospheric propelled balloon to test chemistry response to H_2SO_4 and H_2O and to test aerosol microphysical models
2	Cirrus cloud seeding	Process study	0.5	$\Delta RF = 1\text{-}10\ W/m^2$ $A = 10^2\ km^2$ T = 1 week N = 4 $E = 2.4 \times 10^{15}\ J$	3 × 10 g of BiI_3	Ice nucleation seeding from aircraft in upper troposphere to test cirrus dispersal mechanisms
3	MCB Phase 1-2	Technology development, Process study	1	$\Delta RF = 0.1\text{-}5\ W/m^2$ $A = 1 \times 10^2\ km^2$ T = 2 weeks N = 4 $E = 2.4 \times 10^{15}\ J$	Sea salt	Marine cloud brightening: (1) boundary layer injection of sea salt from coastal site to test sprayer technology; (2) coastal test of cloud brightening

continued

TABLE 4.1 Continued

Exp#	Informal Title	Category Type(s)	Cost ($M)	Local Forcing, Area, Duration, and Equivalent Energy	Material and Mass	Synopsis
4	MCB Phase 3	Process study, scaling test	2	$\Delta RF = 5\text{-}50\ W/m^2$ $A = 1 \times 10^2\ km^2$ $T = 4$ weeks $N = 4$ $E = 4.8 \times 10^{16}\ J$	Sea salt	Ocean test of marine cloud brightening (sea salt injection into boundary layer from single ship; e.g., single enhanced ship track)
5	MSGX	Scaling test, technology development	100	$\Delta RF = 0.2\ W/m^2$ $A = 1 \times 10^6\ km^2$ $T = 6$ months $N = 1$ $E = 1.3 \times 10^{19}\ J$	5×10^8 g of S	Sustained stratospheric injection of H_2SO_4 from aircraft, observe mesoscale effects from satellites and aircraft
6	Climate response test	Climate response test	>1,000	$\Delta RF = 0.5\ W/m^2$ $A = 5 \times 10^8\ km^2$ $T = 10$ years $N = 1$ $E = 8 \times 10^{22}\ J$	1×10^{12} g of S per year	Test global climate response to large-scale modulated input (either stratospheric sulfate or marine cloud brightening)

continued

TABLE 4.1 Continued

Exp#	Informal Title	Category Type(s)	Cost ($M)	Local Forcing, Area, Duration, and Equivalent Energy	Material and Mass	Synopsis
7	MOCX	Scaling test, technology development	10	$\Delta RF = 50\text{-}100\ W/m^2$ $A = 4 \times 10^4\ km^2$ T = 4 weeks N = 4 $E = 7.7 \times 10^{19}\ J$	Sea salt	Mesoscale Ocean Cloud Experiment. Large-scale test of marine cloud brightening in open ocean with multiple, coordinated ships
8	SPICE-2	Technology development	0.5	ΔRF = none $A = 1 \times 10^1\ km^2$ T = 2 weeks E = none	10^3 g of H_2O	Test 1-km-scale balloon injection approach
9	Volcanogenic particles	Process study	2	ΔRF = none A = TBD km^2 T = TBD days E = TBD	Small amounts of H_2S, SO_2, SO_4^{2-}, SiO_2	Observe physical/chemical fate of candidate particles from (i) volcano and (ii) aircraft injection (S-bearing species and SiO_2)

NOTE: MCB, marine cloud brightening. The portfolio spans three primary categories of albedo modification: stratospheric aerosol injection, cirrus cloud seeding (strictly speaking this is long-wavelength not "albedo modification"), and marine cloud brightening, degree of local perturbation (change in local peak radiative forcing, ΔRF), area of the experiment domain (A), individual test duration (T), number of tests in an experiment (N), equivalent energy ($E = \Delta RF \times A \times T \times N$), the primary composition and mass of materials injected into the atmosphere, and the type of experiment. Experiment costs are very uncertain. In each case, experiment duration is limited to the active period of injection (in some but not all cases, continuous) and does not indicate months of preparatory efforts or data analysis. ΔRF represents the quasi-instantaneous change in radiative forcing over the domain indicated in response to a given experiment (assuming the experiment is operating at "steady state"); it does not account for natural variability or startup. In some cases the relative perturbations of the different experiments are somewhat arbitrarily chosen to explore the phase space (e.g., this is not meant to imply that MCB produces an inherently larger impact than cirrus cloud seeding).
SOURCE: Keith et al., 2014.

A summary of results from these two workshops was presented at a briefing conducted at the Bipartisan Policy Center (BPC) on June 5, 2014. Box 4.1 reproduces the answers to two questions considered in detail by participants in the San Francisco workshop:

> Question 1. If a program manager gets a proposal for an outdoor climate-engineering experiment (involving controlled emissions), what should they do?
>
> Question 2: If the government decides at some point to organize a strategic research program (including controlled emissions experiments) on climate engineering, what advice do we have?

BOX 4.1 RESPONSES TO KEY GOVERNANCE QUESTIONS IDENTIFIED IN PREVIOUS WORKSHOPS

Below are responses to two general questions about albedo modification research governance developed by participants in a workshop held in San Francisco (March 31 to April 2, 2014) in which participants examined eight field studies that had been proposed in a workshop at Harvard in early March.

Question 1. If a program manager gets a proposal for an outdoor climate engineering experiment (involving controlled emissions), what should they do?

1. **Start with a few good test cases.** The first time a governance issue arises it can be very helpful if there are specific cases, not a broad class of projects that have been thoroughly explored. By focusing on a specific case, the discussion can be bounded and thus avoid making issues bigger than they need to be. This can help to establish a track record in dealing with a controversial subject and developing a process for assigning appropriate scrutiny and outreach. Program managers who get investigator-driven SRM research proposals should consider whether they have the attributes to make them a good test case.
2. **Seek independent and broad-based advice.** Even for low-risk, small-scale experiments, the intent of the research will be controversial. Obtaining broad-based advice early will aid in addressing any controversies and providing guidance about a wide spectrum of physical and social risks and as well as the benefits of increased understanding that are posed by the proposed experiment. Securing independent advice can provide support for moving forward, or holding back depending on how the benefits compare to the risks. This process can be very useful as "training wheels" for constructing a formal broad-based advisory body should the U.S. government decide to establish a climate-engineering research program.
3. **Clearly identify the research as climate-engineering research.** Obfuscation could easily lead to research being seen as violating the public trust. Equally important, early outdoor research (involving controlled emissions) of low risk provides an important

continued

BOX 4.1 CONTINUED

opportunity to develop governance practices and ensure public engagement early enough in the process to engage diverse stakeholders without engendering fixed positions on how to proceed.

4. **Require strong scientific justifications.** Early research should be scientifically important, effectively addressing critical unknowns. The purpose and outcomes of this research should be highly compelling.
5. **Require careful preparation.** Address safety and social concerns with more review and contingency planning than is the norm. Require effective public outreach and engagement, as opposed to just education. Rigorously ensure all regulatory requirements are thoroughly satisfied.
6. **Consider co-benefits for climate science.** At the same time that climate-engineering research should not be hidden behind a climate science front, much of climate-engineering research will inspire investigators to address significant and difficult problems in climate science. U.S. research programs should emphasize this societal benefit. Research designed only to address climate-engineering issues should be considered for funding.
7. **Develop a narrative.** Climate-engineering research should be seen in the context of the range of approaches being considered for dealing with the climate problem.
8. **Assess the early research and make a decision if and how to continue research.** Starting with a small number of limited experiments provides an opportunity to learn and engage in adaptive management.

Question 2. If the government decides at some point to organize a strategic research program on climate engineering, what advice do we have?

1. **Use the experience of small-scale investigator-driven research to help plan the program.** Start with small projects, and while learning through those efforts begin the process of setting a broad agenda.
2. **Make sure there is an independent advisory group.** Establishing an advisory board early will provide an opportunity for the advisory function to gain experience by examining research that is relatively uncontroversial. If research moves into a mission-driven approach, the board will be better prepared to handle the more complex issues associated with vested interests, public deliberation and outreach, and interactions with the international community.
3. **Declare a moratorium on larger-scale interventions.** Establish an upper limit on the duration, spatial scale, and forcing allowed for research and promote the adoption of a global moratorium of research beyond those limits.
4. **Treat climate engineering as a systems problem and design the research program accordingly.** Bring scientists together to identify gaps with an understanding of the larger set of problems being addressed. Because the risks of climate-engineering research go beyond the physical realm, the process of shaping the science agenda should include

continued

BOX 4.1 CONTINUED

more than natural scientists and should include the human systems that would interact with any climate-engineering program.

5. **Make the research strategy for climate engineering part of a larger climate research strategy.** We need to understand the implications of diverse options in terms of what outcomes they might provide for climate, humanity, and ecosystems.. Quoting one participant: "Only a fool would start on SRM if there was no strategy for mitigation." Make sure the critical importance of this coupling is communicated successfully.
6. **Seek international involvement.** As research becomes programmatic in nature, there will be concerns about issues such as the possibility that nations are weaponizing climate-engineering technologies or that there might be impacts on other nations from poorly understood connections. Ensuring that research is both transparent and unclassified, as well as involving international collaborations, will help, but not prevent, the possibility that climate engineering will become politicized. Establishing an international advisory group whose first job is to evaluate whether proposed research has international impact may also be helpful.
7. **Explore the human institutions that will be needed if we go beyond investigator-driven research.** Investigator-driven research might (or might not) move to programmatic research, and from there to preparation for deployment and possibly deployment. It may become clear that climate engineering should never be deployed, but if it is, institutions will be needed to develop and deploy the methods. Go slow.

In addition to the workshop in San Francisco that built on the field experiments that were outlined at the Harvard workshop, a third workshop, "Understanding Process Mechanisms for the Governance of SRM Field Experiments," was held on April 16 and 17, 2014, at the Institute for Advanced Sustainability Studies (IASS) in Potsdam that also used the Harvard workshop as a starting point. Organizers Stefan Schaefer and Nigel Moore of IASS write (IASS, 2014),

> While the outcomes of the workshop are still being formed through follow-up activities, patterns emerged in the discussions throughout the workshop. Some of these initial findings are listed below:
>
> - Aside from the largest of the proposed experiments (which might better be characterized as deployment than research), the experiments mostly seem to have low or negligible direct physical risks, whether to humans or the environment.
>
> - The risks that came up as most worthy of near-term governance were not physical but rather social in nature. These tended to concern the risk that without reflexive

and accountable systems of control or information sharing, outdoors research might make it more likely that society proceeds uncritically toward deployment. These risks were difficult to delineate on an experiment-by-experiment basis and therefore it was often more productive to discuss the experiments as a group than individually.

While [environmental impact assessment] and disclosure mechanisms were seen as necessary components of a governance regime for SRM, they may not be sufficient in and of themselves. Current examples of these mechanisms from other areas of environmental and technology policy would likely need to be adapted to suit the unique context of SRM research. Many participants suggested that they should be used as tools for making research processes more transparent (including the results and risks of individual projects and the purpose of larger research programs).

Transparency in this case is also seen as a first step towards the integration of non-scientific perspectives into the design of research activities.

- Some participants were particularly concerned that devising governance for SRM—especially if the control mechanisms arise in direct response to existing research plans—may provide an enabling context for such activities to proceed, thus legitimizing SRM development and use in the absence of a broad societal consensus. Again, this concern was not one that applies to a single type of experiment, but may be more broadly applicable to SRM research as a whole. Reacting to this, other participants at the meeting suggested that efforts toward establishing societal consensus would have to take place through a different, though perhaps parallel, process as that of the regulation of single experiments so as to avoid the creation of a regulatory environment where every proposed experiment becomes a referendum on the entire field of research.

ETHICAL AND SOCIOPOLITICAL ISSUES

There are a number of ethical issues that accompany albedo modification, both in relation to research on albedo modification and in relation to its potential deployment (Burns and Strauss, 2013; Corner and Pidgeon, 2010; Preston, 2012). Research into proposed albedo modification techniques faces a so-called "double moral hazard" (see explanation in "Previous Discussions of Governance of Albedo Modification Research" section above). The idea of the moral hazard in relation to albedo modification is the subject of ongoing analysis and debate (Hale, 2012; Hamilton, 2013). There have been a number of articles discussing the moral and ethical responsibilities surrounding research into albedo modification (e.g., Bunzl, 2009; Jamieson, 1996; Schneider, 1996), including discussion of the argument that research in the near term is morally and ethically good in order to "arm the future" should future generations face a dire enough situation that they would consider deploying an albedo modification technology (e.g., Betz, 2012; Gardiner, 2010). Others have further argued that indoor research on albedo modification (e.g., computer modeling simulations) is ethical insofar as it provides information for policy makers and the public to make more informed choices, and that outdoor research (e.g., field experiments with controlled emissions) is "not ethical unless subject to governance that protects society from potential environmental dangers" (Robock, 2012).

The ethical issues related to the potential deployment of albedo modification include debates over the morality of deliberately taking control of the planet's temperature, as well as discussion of the potential psychological effects of living in such a world (see Preston [2012] and essays within). Furthermore, there are additional ethics issues that arise from the potential imposition of any actions by those deploying such measures on those who have no say or who may not favor such deployment, that is, marginalized, vulnerable, and voiceless populations. Nations with the means to deploy albedo modification techniques are more likely to have the means to adapt to the secondary effects of such deployments. Potential intergenerational implications compound the ethical issues regarding who has authority, whether legal or moral, to enter into deliberate actions that might precipitate profound effects or place obligations on future generations. Key questions have to be answered prior to undertaking large-scale research or any responsible deployment of albedo modification:

- Who decides if the benefits of albedo modification outweigh the risks, and what are the criteria?
- Who gets to decide when and in what way albedo modification will be undertaken?
- Would society ever know enough to responsibly decide to deploy albedo modification?

It is clear that further research on these ethical questions is required. Research on the social implications and ecological and economic ramifications of deployment could better define if it is possible to mitigate societal concerns and if so what would be required. The secondary physical effects of albedo modification, those not directly defined by the change in net radiative forcing, will potentially cause very large perturbations to biophysical systems with complex interactions at a diversity of scales ranging from the individual to the national. Moreover, international attitudes toward deployment of albedo modification strategies would have important implications for how any deploying nation or group of people is perceived. Action with even the best intentions can be perceived negatively if those intentions are not clear and based on demonstrably credible research that supports that such actions would be overwhelmingly positive for humanity. Thus, the factors that affect perceptions, and the factors that affect social response to the outcomes of albedo modification, need to be extensively studied in order to strengthen—or at least minimize—the damage to international relationships prior to, during, and after any potential deployment.

RELEVANT U.S. LAWS AND INTERNATIONAL TREATIES

A number of domestic and international legal questions could arise from research on albedo modification or the deployment of albedo modification techniques. National governments are likely to grapple with these questions first, because they are likely to be the source of initial funding for albedo modification research. In the United States, for example, such research would be funded and/or conducted by federal agencies, such as the National Aeronautics and Space Administration, the U.S. Department of Energy, the National Science Foundation, and the National Oceanic and Atmospheric Administration (NOAA), who would have to consider statutory limits on the scope of their work and what permissions would be required before the albedo modification research is conducted. A recent Congressional Research Service report (Bracmort and Lattanzio, 2013) lists federal agencies that have legislative authority to fund, conduct research, monitor projects, and promulgate or enforce regulations on albedo modification.

Although no legal mechanism has been created at either the national or international level specifically to address albedo modification research or deployment, there are a number of U.S. laws and international treaties that may apply and would have to be considered. At the federal level, this includes the Weather Modification Reporting Act, the National Weather Modification Policy Act, the Clean Air Act, and the National Environmental Policy Act (NEPA). Relevant international treaties include the United Nations Framework Convention on Climate Change (UNFCCC), the Convention on Biological Diversity (CBD), the Vienna Convention for the Protection of the Ozone Layer and its subsequent Montreal Protocol, the Convention on Long-Range Transboundary Air Pollution (CLRTAP), the Convention on the Prohibition of Military or Any Other Hostile Use of Environmental Modification Techniques (ENMOD), and the Outer Space Treaty. There may be other local, state, and federal laws, as well as other international treaties, that are relevant to albedo modification research or deployment; more information can be found elsewhere (Hester, 2013; Lin, 2013a; SRMGI, 2013a).

Relevant U.S. Laws

The Weather Modification Reporting Act of 1972 and the National Weather Modification Policy Act of 1976 gave NOAA authority to require reporting of all weather modification activities in the United States. "Weather modification" is defined as "any activity performed with the intention of producing artificial changes in the composition, behavior, or dynamics of the atmosphere." According to Morgan et al. (2013), "the U.S. National Weather Modification Reporting Act provides a statutory framework for making an SRM [solar radiation management] open-access research policy mandatory in the United States, at least insofar as the research entails field experiments that are conducted domestically and are of such a scale that they could actually affect climate or weather."

Title VI of the 1990 Amendments to the Clean Air Act gave the U.S. Environmental Protection Agency (EPA) the authority to require the phase-out of the production and consumption of ozone-depleting substances in accord with the Montreal Protocol and its amendments. The EPA is required to add any substance with an ozone depletion potential of 0.2 or greater to the list of Class I substances and to set a phase-out schedule of no more than 7 years, and to add any substance that "is known or may reasonably be anticipated to cause or contribute to harmful effects on the stratospheric ozone layer" to the list of Class II substances and set a phase-out schedule of no more than 10 years. Thus, albedo modification techniques involving the injection of sulfur dioxide or other substances from U.S. territory into the stratosphere could be subject to Title VI if they are judged to deplete or cause "harmful effects" on stratospheric ozone.

The relevance of other provisions of the Clean Air Act to albedo modification is not clear. An expansive view of the Clean Air Act (Pub. L. 88-206, 42 U.S.C. §7401 et seq.) could include the authority to regulate albedo modification research activities, particularly those involving release of criterion pollutants such as sulfur dioxide (Bracmort and Lattanzio, 2013; GAO, 2010; Hester, 2013). Such an interpretation could be undertaken administratively without necessarily involving new legislation, but it is likely it would have to pass muster in the courts, as did the establishment of EPA's authority to regulate greenhouse gas emissions.

The National Environmental Policy Act of 1970 requires all federal agencies to take environmental protection into account in decision making. The NEPA requirements are procedural; it requires agencies to consider environmental impacts but it does not prevent or preclude action. If a proposal is deemed a major federal action significantly affecting environmental quality, it can trigger a requirement to prepare an environmental impact statement (EIS). In the case of a broad policy or program, a programmatic EIS might be required in addition to an EIS for each project. "In the case of research involving field experiments, the National Environmental Policy Act may require an Environmental Impact Assessment, unless the proposed project fits into a category excused from such assessment. If an assessment is required and prepared, the public will have ample notice and opportunity for comment" (Morgan et al., 2013).

Governance of local, state, or privately funded albedo modification activities is not straightforward. It may not be clear how this would happen, however, and may be more effectively addressed in the short term through norms within the scientific community. Ultimately if there was concern that such soft approaches were not sufficient it may require a legislative solution, which would be challenging given the lack of clarity of the risks and even the types of research that might be proposed.

Relevant International Treaties

Under the 1992 UNFCCC, parties commit to collect and share data on greenhouse gas (GHG) emissions and to develop national policies to address GHG emissions, to achieve the ultimate objective of "stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system . . . within a time-frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened and to enable economic development to proceed in a sustainable manner" (UNFCCC, 1992a). The focus of the Convention and subsequent protocols and agreements is on stabilizing GHG concentrations by reducing emissions and enhancing sinks, and facilitating adaptation to climate change. Although the possibility of reducing the climate impacts of increased GHG concentrations (e.g., through albedo modification) is not addressed in the Convention, there are provisions that may be considered applicable to albedo modification, including the requirement to "take precautionary measures to anticipate, prevent or minimize" the effects of climate change and to consider "the adverse effects of . . . the implementation of response measures" (UNFCCC, 1992b).

The objective of the 1992 Convention on Biological Diversity is to promote the conservation and sustainable use of biological diversity and the fair and equitable sharing of benefits arising from genetic resources. The key principle of the Convention is the sovereign right of parties to exploit their own resources pursuant to their own environmental policies, while ensuring that their activities do not damage the environment of areas beyond the limit of their national jurisdiction. The United States signed but is not a party to the CBD. In October 2010, the CBD's Conference of Parties issued

Decision X/33, which addressed climate engineering. The decision "invites Parties and other governments, according to national circumstances and priorities, as well as relevant organizations and processes," to ensure that "no climate-related geo-engineering 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, with the exception of small scale scientific research studies that would be conducted in a controlled setting," and then "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." Thus, the CBD recognizes an exception for controlled scientific research for which there is an adequate scientific basis and where adequate consideration is given to the associated risks. Due to its hortatory language, Decision X/33 is generally not considered to be legally binding on parties to the CBD but is notable for being the first UN-body decision to address "climate related geoengineering" research writ large.

In the 1985 Vienna Convention, together with the 1987 Montreal Protocol and subsequent amendments, parties agree to adopt measures to reduce or prevent human activities that have or are likely to have adverse effects resulting from modification of the ozone layer. This has primarily involved agreements to phase out the production and consumption of ozone-depleting substances, but albedo modification techniques that involve injection of aerosols into the stratosphere also might be considered activities that may have adverse effects on ozone, and could therefore be subject to the Convention as more information becomes available.

The 1979 Convention on Long-Range Transboundary Air Pollution defines "air pollution" as substances that "endanger human health, harm living resources and ecosystems and material property and impair or interfere with amenities and other uses of the environment," and "long-range transboundary air pollution" as air pollution "which has adverse effects in the area under the jurisdiction of another State at such a distance that it is not generally possible to distinguish the contribution of individual emission sources or groups of sources." Eight protocols to CLRTAP detail reduction commitments for specific pollutants, including sulfur, nitrogen oxides, volatile organic compounds, and heavy metals. It is unclear if or how CLRTAP would apply to albedo modification activities. For example, small-scale experiments involving injection of sulfate aerosols into the stratosphere would not endanger human or environmental health, and even full-scale deployment is likely to have a negligible effect on rates of sulfate deposition and compliance with the CLRTAP protocol on sulfur emissions.

The 1977 Convention on the Prohibition of Military or Any Other Hostile Use of Environmental Modification Techniques prohibits "military or any other hostile use of environmental modification techniques having widespread, long-lasting or severe effects as the means of destruction, damage or injury to any other State Party." The Convention defines "environmental modification techniques" as "any technique for changing—through the deliberate manipulation of natural processes—the dynamics, composition or structure of the Earth, including its biota, lithosphere, hydrosphere and atmosphere, or of outer space." Although albedo modification would be considered an "environmental modification technique" as defined by the Convention, Article III states "this Convention shall not hinder the use of environmental modification techniques for peaceful purposes and shall be without prejudice to the generally recognized principles and applicable rules of international law concerning such use." Thus, ENMOD would appear to apply to albedo modification techniques only if they were applied in a hostile manner with the intent to cause damage to another party to the Convention, where the United Nations Security Council would be responsible for determining intent.

Finally, the 1967 Outer Space Treaty would apply to space-based albedo modification techniques, such as mirrors or shades orbiting the Earth or Sun. The Treaty provides that the "use of outer space . . . shall be carried out for the benefit and in the interests of all countries," that parties "shall bear international responsibility for national activities in outer space," and that a party that places an object into space "is internationally liable for damage to another State Party to the Treaty or to its natural or juridical persons by such object."

There is ongoing scholarship in this area, and further research on these legal questions would be helpful in understanding the existing national and international constraints on albedo modification research and deployment.

INTELLECTUAL PROPERTY AND PRIVATE-SECTOR ENGAGEMENT

Finally, the committee wishes to acknowledge that there are and will continue to be important issues associated with intellectual property and the engagement of the private sector in albedo modification. In general, engaging the private sector in research has known benefits. Such involvement can spur innovation, attract capital investment, lead to the development of more effective and lower cost technologies at a faster rate, and produce commercial spin-offs that benefit the economy (Bracmort and Lattanzio, 2013). For example, the involvement of private industry contributing to space exploration has generally been viewed quite positively. However, there are potential shortcomings as well, such as the possibility of neglecting social, economic, and environmental risk assessments in favor of the pursuit of corporate profitability. Perhaps the greatest concern with private-sector involvement is that an industry with product lines targeted toward albedo modification would create a group with a vested financial interest in deployment.

Intellectual property issues are not just a theoretical consideration for the future but have already emerged in at least one climate intervention experiment. The Stratospheric Particle Injection for Climate Engineering (SPICE) experiment cancelled a field trial in 2012, partially on account of controversy over a patent application for the apparatus to deliver water mist to a 1-km altitude using a balloon and pipe. Many SPICE team members considered the patent submitted by another team member to be a conflict of interest and harmful to public perception of the project.

To this point, private-sector engagement in albedo modification has been modest. A substantial acceleration of albedo modification research would likely require additional incentives, such as public subsidies, GHG emission pricing, ownership models, intellectual property rights, and trade and transfer mechanisms for the dissemination of the technologies (Bracmort and Lattanzio, 2013). These incentives will determine not only whether but how the private sector engages with albedo modification. It would be preferable for the public to have substantial discussion as to what outcomes are desirable before determining what incentives to offer.

NEXT STEPS

As discussed above, there have been repeated calls for the formation of a governance mechanism that allows for research on some types of proposed albedo modification proposals to be pursued. One of the common themes that emerges from these previous discussions is that, whatever the governance mechanism for some types of albedo modification research, it should be transparent and done with input from a broad set of stakeholders to engender trust among the stakeholders, and to ensure all dimensions are appropriately considered. Another common theme is that the goal of the governance should be to ensure that the benefits of research are realized toward helping society understand the challenges and impacts of albedo modification while minimizing the risks associated with the conduct of such research. The committee emphasizes that "governance" is not synonymous with "regulation" and that appropriate governance of albedo modification research could take a wide variety of forms depending on the types and scale of the research undertaken.

There have also been previous calls for the United States to lead the development of standard practices or "norms" that would likely be followed by researchers and funding agencies in other countries (Victor, 2008). As described below, there are no domestic laws or international legal agreements that directly regulate albedo modification research, but this lack of statute should not limit efforts to establish self-governance within the scientific community or more formal governance structures based on the principle that both transparency and civil society engagement are critical to development of support for continuation of research, let alone getting support for public financing of the research.

Whether the governance of albedo modification research is most effectively achieved through an expansion of existing structures or development of a separate structure specifically for this purpose is not clear, and it is not the purview of the committee to make such a determination. But as a society we are currently at a point in which governance of albedo modification research could get out in front of the need for that governance; thus, being proactive rather than reactive could allow for the development of a thoughtful and effective structure that will be commensurate with the needs and risks. In an arena where conspiracy theories already abound (e.g., chemtrails; see Appendix C), public trust will be undermined if research, particularly if funded with public money, occurs outside of public view (e.g., who is working on what and why).

Moving forward, the committee recommends the initiation of a serious deliberative process to examine (a) what types of research governance, beyond those that already exist, will be needed for albedo modification research, and (b) the types of research that would require such governance, potentially based on the magnitude of their expected impact on radiative forcing, their potential for detrimental direct and indirect effects, and other considerations, including sociopolitical risks. This is described further in Chapter 5.

CHAPTER FIVE

Way Forward

Most discussions of the climate change challenge focus on addressing greenhouse gas emissions and their impacts: for example, the scale of infrastructure that would need to be rebuilt in order to curtail emissions in a meaningful way; the expense of carbon dioxide removal (CDR), carbon capture and sequestration (CCS), and other techniques; and the major social disruption of adaptation for a global population concentrated near sea level. Against that backdrop, the issues surrounding albedo modification stand in stark contrast. By comparison, increasing Earth's reflectance of global radiation, at least approximately, requires no major retooling of the energy infrastructure, is relatively easy to accomplish (e.g., could be undertaken by a subnational organization), and has lower direct costs when compared to either mitigation or adaptation. The committee therefore focused on what scientific knowledge would be needed to decide whether albedo modification could be deployed responsibly, safely, effectively, and with predictable and desirable outcomes.

There are both theoretical and observational reasons to believe that albedo modification has the potential to act rapidly to offset some of the consequences of global warming at a relatively low cost, albeit with high risks of unintended consequences. If less energy from the Sun is absorbed by the Earth system, the surface of Earth will cool on average. This is clearly demonstrated by the history of past volcanic eruptions. For example, the eruption of Mount Pinatubo in the Philippines in 1991 injected large amounts of sulfur dioxide into the stratosphere that increased Earth's albedo and decreased the amount of sunlight absorbed, causing the atmosphere to cool an estimated 0.3°C over a period of 3 years. Other eruptions, such as Tambora in 1815, caused global climatic anomalies that led to widespread crop failure and famine. Overall, it is difficult to compare the injection of an aerosol plume from a single volcanic eruption to repeated aerosol injections that result in a more sustained albedo modification.

Modeling studies have also shown that large amounts of cooling, equivalent in scale to the predicted warming due to doubling the CO_2 concentration in the atmosphere, can be produced by the introduction of tens of millions of tons of aerosols into the stratosphere. Increasing the reflectivity of low clouds is another strategy that could cool the planet within a year or two from the onset of the intervention. Although there are many reasons to be cautious in interpreting model results, climate simulations can extend scientific understanding of albedo modification to timescales beyond those observed with volcanic eruptions. Preliminary modeling results suggest that albedo modification may be able to counter many of the damaging effects of high greenhouse gas concentrations on temperature and the hydrological cycle and reduce some impacts to sea ice. Models also strongly suggest that the benefits and risks will not be uniformly distributed around the globe.

Feasibility studies suggest that it may be technically possible to introduce aerosols into the stratosphere that can produce significant cooling (on the order of 1 W/m^2 or larger) with little or no major technological innovations required. Direct costs of deployment of a stratospheric aerosol layer of sufficient magnitude to offset global mean radiative forcing of CO_2 have been estimated to be orders of magnitude less than the cost of decarbonizing the world's economy. Although these cost estimates do not include an appropriate monitoring system or indemnification for damages from albedo modification actions, they are small enough that decisions are likely to be based primarily on considerations of potential benefits and risks, and not primarily on the basis of direct cost.

Despite some initial research advances discussed in Chapter 3 of this report, much remains unknown about albedo modification. Proposed albedo modification approaches introduce environmental risks and political ramifications associated with intended and unintended consequences; these risks are not well understood and generally unquantified. These gaps in understanding present significant barriers and risks to deploying the range of albedo modification strategies under consideration. As such, the committee identifies a set of measured steps intended to improve our understanding of albedo modification, while underscoring that other efforts to mitigate climate change should remain the primary focus.

ALBEDO MODIFICATION WITHIN A PORTFOLIO OF CLIMATE RESPONSES

Avoiding greatly increased risk of damage from climate change will require a portfolio of response strategies. The deployment of any climate response strategy requires consideration of many factors: How effective is the strategy at achieving predictable and desirable outcomes? How much does the strategy cost to implement at a scale that matters? What are the risks for unintended consequences and opportunities for co-benefits? What governance mechanisms are in place to ensure safety, equity, and other ethical aspects are considered? The committee evaluated CDR and albedo modification within this broader portfolio of climate response.

Despite the growing recognition of these risks, global society has yet to adequately implement the well-known strategies for mitigating climate change (e.g., reducing GHG emissions by conserving energy and developing carbon-free energy sources).

The result may be circumstances in the future that are sufficiently adverse that intervention in the climate system to reverse or reduce these effects may be deemed necessary. Such climate intervention could be achieved through two classes of strategies—albedo modification and carbon dioxide removal. These strategies carry very different costs and risks (see Table 5.1).

TABLE 5.1 Overview of General Differences between Carbon Dioxide Removal Proposals and Albedo Modification Proposals

Carbon dioxide removal proposals…	**Albedo modification proposals…**
… address the cause of human-induced climate change (high atmospheric GHG concentrations).	… do not address cause of human-induced climate change (high atmospheric GHG concentrations).
… do not introduce novel global risks.	… introduce novel global risks.
… are currently expensive (or comparable to the cost of emission reduction).	… are inexpensive to deploy (relative to cost of emissions reduction).
… may produce only modest climate effects within decades.	… can produce substantial climate effects within years.
… raise fewer and less difficult issues with respect to global governance.	… raise difficult issues with respect to global governance.
… will be judged largely on questions related to cost.	… will be judged largely on questions related to risk.
… may be implemented incrementally with limited effects as society becomes more serious about reducing GHG concentrations or slowing their growth.	… could be implemented suddenly, with large-scale impacts before enough research is available to understand the risks relative to inaction.
… require cooperation by major carbon emitters to have a significant effect.	… could be done unilaterally.
… for likely future emissions scenarios, if abruptly terminated would have limited consequences	… for likely future emissions scenarios, if abruptly terminated would produce significant consequences.

NOTE: GHG stands for greenhouse gases released by human activities and natural processes and includes carbon dioxide, methane, nitrous oxide, chlorofluorocarbons, and others. The committee intends to limit discussion to proposals that raise the fewest problematic issues, thus excluding ocean iron fertilization from the CDR list. Each statement may not be true of some proposals within each category.

To be effective, carbon dioxide removal should be pursued collectively by a number of international participants. In contrast, albedo modification could be undertaken unilaterally. The environmental and climate system consequences of albedo modification are as yet poorly characterized, and the governance issues are complex as well. Some forms of carbon dioxide removal also involve environmental risk, for example from changes in ocean ecology or induced seismicity from underground injection of CO_2 or from the use of inappropriate reservoirs. The barriers to deployment of CDR approaches are largely related to high costs, slow implementation, limited capacity, and policy considerations. As is true for mitigation and adaptation, society must take advantage as soon as possible of CDR strategies that can help avoid the worst effects of warming. We will lose this opportunity if society delays in research and development to lower the technical barriers to efficacy and affordability of CDR for deployment.

One of the main findings is that albedo modification does not address in any way the fundamental cause of climate warming: excess greenhouse gases in the atmosphere. Thus, deployed in isolation, albedo modification has no exit strategy. Using the simple home heating analogy introduced in Chapter 1, if the blinds in the overinsulated house were made of some fragile substance that deteriorated over time, they would need to be frequently replaced and kept drawn indefinitely because albedo modification alone only masks the problem. If sulfate aerosols were injected into the stratosphere, interruption of the aerosol injection would return the planet rather rapidly to the state that it would have been in had there been no intervention, risking dramatic ecologic and agronomic impacts. In addition, albedo modification does nothing to address ocean acidification, another impact of greenhouse gas emissions that is predicted to have serious consequences for ocean ecosystems. For these reasons, albedo modification is no substitute for mitigation. Hence, in order to avoid serious longer-term problems, any future decision to embark on aerosol injection should be paired with efforts to mitigate greenhouse gas emissions, remove carbon dioxide from the atmosphere, or both. Indeed, the degree to which those mitigation and CDR strategies are successful would affect how aggressively and for how long albedo modification would need to be sustained.

A further risk involves the deployment of albedo modification without adequate development of emissions mitigation and carbon dioxide removal as viable exit strategies. If albedo modification were to be used to reduce peak warming significantly or to offset the effects of substantial additional CO_2 emissions, then there is no good exit strategy unless economically viable CDR technologies become available. For this reason development of CDR should go hand in hand with consideration of the scope of safe application of albedo modification techniques.

As discussed in Chapters 2 and 3, if albedo modification were to be deployed, the albedo-modified world would not constitute a return to the preindustrial low-CO_2 state. It would be an altered climate state that, like the unmodified high-CO_2 state, has no analogue within preindustrial times spanning the rise of human civilization. Models can help inform judgments about whether the albedo-modified state might be preferable to an unmodified high-CO_2 state. According to various simple statistics, it can be said that the albedo-modified state is in some sense "closer" (in terms of mean surface temperature and precipitation) to the preindustrial state than is the unmodified high-CO_2 state. But simple statistics are not necessarily the ones that will prove most salient to those who may face the need to make a decision about the amount of albedo modification to deploy, or to those affected by the decisions. How much albedo modification is considered optimal will vary from region to region, and trade-offs between regions will be difficult to make. How should disparities in wealth and ability to adapt to climate change be taken into account, or the dependence of some regions on critical circulations like monsoons? The subject of metrics for use in the decision process is an area that requires much further research. Although modeling results can help inform judgments of how much albedo modification to deploy, decisions will ultimately involve values and relative acceptability of various kinds of risks—factors that are outside the scope of science. But one thing is certain: the more albedo modification that is deployed, the greater the deviation of the modified state from the preindustrial state, and the greater the risks. This underscores a recurring theme in this report, that the potential availability of albedo modification in the portfolio of responses to global warming does not constitute a license for unbounded CO_2 emissions.

It is the committee's assessment that there is no substitute for dramatic reductions in emissions of CO_2 and other greenhouse gases to mitigate the negative consequences of climate change at the lowest probability of risk to humanity. Mitigation, although technologically feasible, has been difficult to achieve for political, economic, and social reasons that may persist well into the future. Whatever we do as a society, some adaptation will be necessary, but the degree to which it is needed depends on the amount of climate change and the degree to which future emissions of CO_2 and other greenhouse gases are reduced. Although there are ongoing efforts at climate adaptation in many communities, both humans and ecosystems face substantial challenges in adapting to the varied impacts of climate change over the coming century. For that reason, it is prudent to examine other options for limiting the risks from climate change, even as mitigation and adaptation remain the primary emphasis.

Recommendation 1: Efforts to address climate change should continue to focus most heavily on mitigating greenhouse gas emissions in combination with adapting to the impacts of climate change because these approaches do not present poorly defined and poorly quantified risks and are at a greater state of technological readiness.

ALBEDO MODIFICATION PRESENTS POORLY UNDERSTOOD RISKS

Proposed albedo modification approaches introduce environmental, ethical, social, political, economic, and legal risks associated with intended and unintended consequences that could differ in various parts of the world. Some of the risks from albedo modification can be anticipated. Observed side effects from volcanic eruptions include stratospheric ozone loss, changes to precipitation (both amounts and patterns), and likely increased growth rates of forests caused by an increase in diffuse solar radiation. Because volcanic eruptions are brief events, they are not perfect analogues for the full effects of sustained albedo modification deployment. Models also indicate that there would be consequences of concern (e.g., some ozone depletion and a weakening of global precipitation). Albedo modification does nothing to reduce the buildup of atmospheric CO_2, which is already changing the makeup of terrestrial ecosystems and causing ocean acidification and associated impacts on oceanic ecosystems.

Another risk is that the success of albedo modification could reduce the incentive to curb anthropogenic CO_2 emissions and that albedo modification would instead be deployed with ever increasing intensity. The committee considers it to be irrational and irresponsible to implement sustained albedo modification without also pursuing emissions mitigation, carbon dioxide removal, or both. Nonetheless, climate models indicate that the combination of large-scale albedo modification with large-scale CO_2 increases could lead to a climate with different characteristics than the current climate. Without reductions in CO_2 levels in the atmosphere, the amount of albedo modification required to offset the greenhouse warming would continue to escalate for millennia, generating greater risks of negative consequences if it is terminated for any reason (e.g., undesirable side effects, political unrest, and cost), because the effects of the forcing from the CO_2 concentrations present at the time of termination will be rapidly revealed.

It is not possible to quantify or even identify other environmental, social, political, legal, and economic risks at this time, given the current state of knowledge about this complex system. The uncertainties in modeling of both climate change and the consequences of albedo modification make it impossible today to provide reliable, quantitative statements about relative risks, consequences, and benefits of albedo modification to the Earth system as a whole, let alone benefits and risks to specific regions of the planet. To provide such statements, scientists would need to understand the influence of various possible activities on both clouds and aerosols, which are among the most difficult components of the climate system to model and monitor. Introducing albedo modification at scales capable of substantial reductions in climate impacts of future higher CO_2 concentrations would be introducing a novel situation into the Earth system, with consequences that are poorly constrained at present.

Gaps in our observational system also present a critical barrier to responsible deployment of albedo modification strategies. Currently, observational capabilities lack the capacity to monitor the evolution of an albedo modification deployment (e.g., the fate of the aerosols and secondary chemical reactions), its effect on albedo, or its environmental effects on climate or other important Earth systems. An international forum for cooperation and coordination on any sort of climate intervention discussion and planning is lacking.

Given the enormous uncertainties outlined in the previous chapters, what is known today about the climate system, and the alternatives available to humankind to slow or reverse the buildup of greenhouse gases, this committee does not believe that there is sufficient knowledge of the proposed albedo modification techniques to advocate the deployment of albedo modification at this time.

Recommendation 3: Albedo modification at scales sufficient to alter climate should not be deployed at this time. [1]

- Albedo modification strategies for offsetting climate impacts of high CO_2 concentrations carry risks that are poorly identified in their nature and unquantified.
- Deployment at climate-altering amplitudes should only be contemplated armed with a quantitative and accurate understanding of the processes that participate in albedo modification. This understanding should be demonstrated at smaller scales after intended and unintended impacts to the Earth system have been explicitly documented, both of which are lacking.
- There is significant potential for unanticipated, unmanageable, and regrettable consequences in multiple human dimensions from albedo modification at

---

[1] Note that Recommendation 2 involves CDR only. It is found in the Summary of this report and is discussed in more detail in Chapter 5 of the companion report, *Climate Intervention: Carbon Dioxide Removal and Reliable Sequestration.*

climate-altering scales, including political, social, legal, economic, and ethical dimensions.

- Current observing systems are insufficient to quantify the effects of any intervention at present. If albedo modification at climate-altering scales were ever to occur, it should be accompanied by an observing system that is appropriate for assessing the impacts of the deployment and informing subsequent actions.
- If research and development on albedo modification were to be done at climate-altering scales, it should be carried out only as part of coordinated national or international planning, proceeding from smaller, less risky to larger, more risky projects; more risky projects should be undertaken only as information is collected to quantify the risks at each stage.

THE NEED FOR MORE RESEARCH ON ALBEDO MODIFICATION

As described in Chapter 4, the issue of "moral hazard" is a potentially serious risk associated with any decision to pursue research on albedo modification. Several authors have examined this issue, but overall, the scholarship on this topic is relatively limited. The early results have been mixed thus far on the severity of these risks, including studies that argue there is a low risk (Kahan et al., 2014; Reynolds, 2014) and those that argue it is quite high (Lin, 2013b). Early empirical evidence shows that geoengineering is likely to pose a moral hazard for some people much more than others (Corner and Pidgeon, 2014). The moral hazard risk has potentially kept more albedo modification research from being done up to now, as described by Morgan et al. (2013):

> The climate science community has been aware of the possibility of performing SRM for decades. However, most researchers have shied away from working in this area, in part because of a concern that the more that is known, the greater the chance that someone will try to do it.

With an appreciation of the severity of these potential risks, the committee argues that, as a society, we have reached a point where the severity of the potential risks from climate change appears to outweigh the potential risks from the moral hazard associated with a suitably designed and governed research program. Overall, it is important to understand whether and to what extent albedo modification techniques are viable (Keith et al., 2010; Morgan et al., 2013). Furthermore, there is the possibility that some actor (person, organization, country) may unilaterally decide to apply one of these techniques without sufficient knowledge about its potential unintended consequences, thus putting the world at risk (Morgan et al., 2013).

Research on albedo modification techniques would allow the scientific community to learn more about the risks and benefits of these proposed approaches, which could better inform societal decisions without the scale of risks associated with deployment. One of the foremost goals of research on albedo modification should be to understand how viable these techniques are, including a better understanding of the feasibility, verifiability, consequences (intended and unintended), and efficacy of the various proposed albedo modification strategies. Indeed, current implementation options are clearly crude and method development would provide less risky options for society and state actors.

To date, very limited research has been undertaken to gain insight about whether, and how well, strategies for albedo modification might work and the intended and unintended consequences of such strategies. For example, federal investments specifically addressing albedo modification or carbon dioxide removal have been "modest" (Bracmort and Lattanzio, 2013). The U.S. Global Change Research Program (USGCRP) reported that the annual U.S. budget for climate change research exceeded $4 billion for fiscal years 2009 and 2010 (USGCRP, 2010). Of that, the U.S. Government and Accountability Office (GAO) reported about $100 million was spent during the same period on research activities "relevant to geoengineering" (GAO, 2010) and indicated that the majority of that budget focused on either mitigation strategies (e.g., carbon capture and sequestration) or basic science, and estimated that about $2 million were directed to "albedo modification and less conventional CDR approaches," so less than 0.1% of the U.S. climate change budget focused on the strategies discussed in our report.

Much of the required research on albedo modification overlaps considerably with basic scientific research that is needed to improve understanding of the climate system. Most notably, research on clouds and aerosols has the potential to advance climate research while also contributing to understanding of the effects and unintended impacts of albedo modification approaches. A number of actions can promote such "multiple-benefit research"—research that can contribute to a better understanding of the viability of albedo modification techniques and a better understanding of basic climate science—such as maintaining continuous measurements of the top-of-atmosphere radiation budget, developing improved space-borne instruments to discriminate the processes leading to changes in Earth's radiation budget, monitoring ocean-atmosphere energy exchange through programs such as the Argo float system, and improving methods of data assimilation and data analysis to make optimal use of observations in detecting and attributing albedo and climate responses.

Of necessity, much of this multiple-benefit research would be part of a comprehensive climate research portfolio or research program aimed at other purposes (e.g., effect of volcanic eruptions on aerosols). Such research projects and data sets should be identified for their multiple benefits and prioritized to aid in understanding effectiveness and consequences of albedo modification. In addition, there is research that is specific to learning about albedo modification techniques (e.g., mechanisms for delivering sulfate aerosol precursors to the stratosphere) that would not fit under this description of multiple benefit and is therefore unlikely to be supported without a research program focused on climate intervention. The committee argues that these research topics specific to albedo modification should also be identified and prioritized as part of a larger research effort on albedo modification, and they should be tasked to the relevant federal agencies for possible support within existing or expanded programs. Focusing on basic science related to albedo modification will hopefully minimize fears that resources are being used to support a potential near-term albedo modification deployment plan. Box 5.1 lists a number of important research areas.

The development of a research program on albedo modification may involve modeling, field research, satellite measurements, and laboratory studies. As such, this research will likely involve the efforts of multiple agencies, laboratories, and universities. It would be useful to have some coordination among the research efforts of these multiple organizations to avoid duplication and ensure that the most important questions are addressed. Although other organizations could perhaps fill this coordinating role, the USGCRP is the most obvious possibility and is a logical choice given the overlap of many research topics with the climate change research agenda. USGCRP coordinates and integrates federal research on changes in the global environment and their implications for society.[2] Thirteen federal departments and agencies participate in the USGCRP and also interact with a wide variety of related groups, including international organizations; national, state, tribal, and local governments; businesses; professional and other nonprofit organizations; the scientific community; and the public.

Any future decisions surrounding the use of albedo modification will need to be based on more than just scientific theories. Research results on efficacy, environmental impacts, and unintended consequences will need to be integrated with social, ethical, political, and legal discussions. A governance structure for albedo modification research will be needed within the United States and likely coordinated internationally before field studies of any significant magnitude are attempted. U.S. participation in "scenario planning" can be extremely valuable for identifying gaps in planning and understanding and thus can guide future science investments. Interdisciplinary research is also needed concerning understanding issues associated with deployment of albedo modification should it ever be deemed desirable. How should leaders weigh

---

[2] See http://www.globalchange.gov/about/overview.

BOX 5.1 RECOMMENDED AREAS OF SCIENTIFIC RESEARCH

Scientists have explored only a few issues relevant to climate intervention by albedo modification to date. More knowledge about particular climate processes and better climate models are needed. Climate models—a computational tool used to synthesize knowledge of the climate system—are incomplete and approximate representations of the real world. Climate models require more development before they can be used to quantify the risks in projections of climate impacts from albedo modification. Improvement may come from climate models and through theory, field studies, detailed process modeling, and laboratory experiments. The following areas would benefit from more attention:

Clouds, aerosols, and cloud-aerosol interactions are some of the more important climate components that need attention and improvement, because these basic Earth system components are central to the albedo modification strategies that appear most promising. Viability of particular strategies cannot be assessed until there is confidence in treatment of these components in climate models; many consequences that would arise from employing a strategy cannot be quantified without an accurate characterization of these important climate features. Work in this area would also be relevant to climate and climate change problems generally.

Regular and systematic evaluation of simulated albedo modification strategies would help in characterizing model uncertainty and climate consequences and risks. Models should be compared carefully with each other with more attention to understanding the reasons for model differences when an albedo modification scenario is employed.

The impacts of albedo modification on a variety of climate features that have not yet been examined, or have only been examined superficially to date, should be studied in more detail. It would be useful to explore and characterize consequences to these features (e.g., El Niño–Southern Oscillation, ecosystems) and to have the scientific community identify other possible consequences.

It would be useful to compare climate model process representations to more detailed and accurate "process models" that are too expensive to afford for climate change calculations. It would also be useful to systematically compare both global models and expensive process models to existing field experiment data and satellite data relevant to stratospheric aerosol and marine cloud-brightening strategies.

Small field studies would be useful that explore issues that are as yet poorly understood but influence the viability of candidate albedo modification strategies. Some studies could operate using "measurements of opportunity" by making measurements downwind of volcanoes or polluters. But there are issues that can be understood more thoroughly, and more easily via field studies making controlled emissions to the atmosphere (see Chapter 3), through injections of aerosols in the lower stratosphere or below marine clouds. The committee feels strongly that large experiments with the potential to influence climate are not appropriate and would need strict governance to be considered further. Small-scale field studies designed to clarify the mechanisms important to a particular strategy may be useful, provided they fit within the context of current research structures.

the relative risks of an immediate climate crisis versus the need to maintain albedo modification over many centuries? How could society design institutions capable of maintaining such an enormous undertaking over that timescale?

Recommendation 4: The committee recommends an albedo modification research program be developed and implemented that emphasizes multiple-benefit research that also furthers basic understanding of the climate system and its human dimensions.

- If future decision makers reach a point that they are contemplating adopting albedo modification, or assessing such an adoption by others, they will need to assess a wide range of factors, both technical and social, to compare the potential benefits and risks of an albedo modification deployment. These factors would include an assessment of the expected climate with only emissions reductions and CDR (including risks from continued greenhouse gas emissions with no intervention), the expected effects from starting albedo modification, the expected effects from terminating albedo modification, ethical issues, and social responses.
- The goal of the research program should be to improve understanding of the range of climate and other environmental effects of albedo modification, as well as understanding unintended impacts.
- U.S. research on albedo modification should be supported by a number of scientific research agencies in a coordinated manner. The U.S. Global Change Research Program could provide valuable oversight and coordination to ensure that the aspects of the research that are of benefit to both basic climate science and understanding of albedo modification are taken into account.
- Small-scale field experiments with controlled emissions may for some situations with some forms of intervention be helpful in reducing model uncertainties, validating theory, and verifying model simulations in different conditions. Experiments that involve release of gases or particles into the atmosphere (or other controlled perturbations) should be well enough understood to be benign to the larger environment, should be conducted at the smallest practical scales, should be designed so as to pose no significant risk, and should be planned subject to the deliberative process outlined in Recommendation 6.

Recommendation 5: The committee recommends that the United States improve its capacity to detect and measure changes in radiative forcing and associated changes in climate.

- A new generation of short-wavelength (albedo) and long-wavelength (outgoing infrared) space-based instruments should be developed and deployed that can measure radiative forcing with an accuracy of better than 1 W/m^2, including hyperspectral instruments that could improve discrimination of the processes that cause changes in radiative forcing. Such instruments would significantly improve understanding of the effects of clouds and stratospheric aerosols on climate, improve the ability to predict the effects of albedo modification, and provide an ability to detect large-scale albedo modification by rogue actors.
- An observational capability should be developed to make better use of future major volcanic eruptions to improve understanding of the effects of stratospheric aerosols on climate. This would involve space-based sensors and rapidly deployable ground-based and airborne sensors for monitoring stratospheric aerosols.

GOVERNANCE CONSIDERATIONS

Some types of research into intentional albedo modification will likely have legal, ethical, social, political, economic, and other important ramifications. Albedo modification research must abide by existing laws, regulations, and policies that apply to research broadly and its impacts on worker safety, the environment, and human and animal welfare. However, such research is not specifically addressed by any federal laws or regulations.

Given the perceived and real risks associated with some types of albedo modification research, open conversations about the governance of such research, beyond the more general research governance requirements, could encourage civil society engagement in the process of deciding the appropriateness of any research efforts undertaken.

“Governance” is not a synonym for “regulation.” Depending on the types and scale of the research undertaken, appropriate governance of albedo modification research could take a wide variety of forms, ranging from the direct application of existing scientific research norms, to the development of new norms, to mechanisms that are highly structured and extensive. The most appropriate type of governance structures for albedo modification research will potentially depend on the nature and scale of that research. It is not the purview of the committee to make an assessment or recommendation of the appropriate structure. However, the committee does believe that governance considerations should be targeted at ensuring civil society involvement in decision making through a transparent and open process. It should focus on enabling safe and useful research on the viability and impacts of albedo modification strategies (e.g., the efforts of the Solar Radiation Management Governance Initiative[3]). Ultimately, the goal is to ensure that the benefits of the research are realized to inform civil society decision making, the associated challenges are well understood, and risks are kept small.

To date most investigations of the efficacy and likely impacts, environmental and otherwise, of albedo modification have been confined to computer simulations and observations of volcano, ship track, and other analogues. Such work will and should continue and it can provide additional understanding that can inform future decisions on whether albedo modification can safely address some of the worst impacts of climate change without other impacts that are unacceptable. However, in addition to these approaches, some controlled emissions experiments on smaller scales (e.g., estimated forcing well below natural variability) in the environment may be proposed to understand fundamental processes that may be complex and poorly characterized at present.

Examples of experiments that have been proposed are found in Table 4.1, along with the advances in scientific understanding related to the albedo modification and climate science generally that are anticipated from these experiments. The committee recommends that the serious deliberative process related to the larger governance discussion include discussions of if and how the different scales of this type of research should be pursued and governed. Subsequent to a deliberative process, judging the merits of individual proposals for these types of experiments is best done through the existing mechanisms of peer review.

If there were to be considerations of implementation, scaling up to the larger-scale experiments would best be done in the context of a goal-driven engineering development plan. Such a plan would prioritize investments in key "show-stopper" questions while minimizing cost and risk, rather than being driven by individual investigators.

Recommendation 6: The committee recommends the initiation of a serious deliberative process to examine (a) what types of research governance, beyond those that already exist, may be needed for albedo modification research and (b) the types of research that would require such governance, potentially based on the magnitude of their expected impact on radiative forcing, their potential for detrimental direct and indirect effects, and other considerations.

---

[3] See http://www.srmgi.org/.

- If a new governance structure is determined to be needed based on deliberations among governance experts and civil society representatives, the development of the governance structure should consider the importance of being transparent and having input from a broad set of stakeholders to ensure trust among the stakeholders and appropriate consideration of all dimensions.
- Such a governance structure should consider setting clear and quantitative guidelines for experimentation and be responsive to domestic and international laws and treaties.
- The deliberative process should consider focusing on research activities that involve injecting material into the atmosphere, for example aerosol-producing substances injected into the upper atmosphere or cloud-brightening substances injected near the surface.
- If a program of research in albedo modification includes controlled-emission experiments, it should provide for a sufficiently specific governance regime to at least define the scale of experiments at which oversight begins.
- The approach to governance should consider the need for increasing supervision as the scope and scale of the research and its potential implications increase, including the amount of material emitted, the area affected, and the length of time over which emission continues.
- The goal of the governance should be to maximize the benefits of research while minimizing risks.
- The United States should help lead the development of best practices or specific norms that could serve as a model for researchers and funding agencies in other countries and could lower the risks associated with albedo modification research.

CONCLUDING THOUGHTS

Addressing the challenges of climate change requires a portfolio of actions that carry varying degrees of risk and efficacy. CDR strategies and other technologies and approaches that reduce net emissions (e.g., carbon capture and sequestration, non-carbon-based energy, and energy efficiency improvements) offer the potential to slow the growth and reverse the increase of CO_2 concentrations in the atmosphere. The lowest-risk CDR strategies are currently limited by cost and at present cannot achieve the desired result of removing climatically important amounts of CO_2 beyond the significant removal already performed by natural processes. However, with declining costs and stronger regulatory commitment, atmospheric CO_2 removal could become a valuable component of the portfolio of long-term approaches to reducing CO_2 concentrations in the atmosphere and associated impacts. Overall, there is much to be gained and very low risk in pursuing multiple parts of a portfolio of CDR strategies that demonstrate practical solutions over the short term and develop more cost-effective, regional-scale, and larger solutions for the long term.

In contrast, even the best albedo modification strategies are currently limited by unfamiliar and unquantifiable risks and governance issues rather than direct costs. The committee reiterates that it is opposed to large-scale deployment of albedo modification techniques, but it does recommend further research, particularly multiple-benefit research that furthers the basic understanding of the climate system and seeks to quantify the potential costs, consequences (intended and unintended), and risks from these proposed albedo modification techniques.

Climate change is a global challenge that will require complex and comprehensive solutions, which in turn will require that people of many nations work together toward common objectives. For the outcome to be as successful as possible, any climate intervention research should be robust and likely to yield valuable scientific information, international in nature, and open. The impacts of any potential future climate interventions should be honestly acknowledged and fairly considered. The committee firmly believes that there is no substitute for dramatic reductions in CO_2 emissions to mitigate the negative consequences of climate change at the lowest probability of risk to humanity. However, if society ultimately decides to intervene in Earth's climate, the committee most strongly recommends any such actions be informed by a far more substantive body of scientific research—encompassing climate science and economic, political, ethical, and other dimensions—than is available at present.

References

ACIA (Arctic Climate Impact Assessment). 2004. Fairbanks, AK: Arctic Climate Impact Assessment Secretariat.

Ackerman, A. S., O. B. Toon, and P. V. Hobbs. 1993. Dissipation of marine stratiform clouds and collapse of the marine boundary-layer due to the depletion of cloud condensation nuclei by clouds. Science 262(5131):226-229. DOI: 10.1126/science.262.5131.226.

Ackerman, S. A., and K. I. Strabala. 1994. Satellite remote sensing of H_2SO_4 aerosol using the 8- to 12-μm window region: Application to Mount Pinatubo. Journal of Geophysical Research: Atmospheres 99(D9):18639-18649. DOI: 10.1029/94jd01331.

Akbari, H., H. Damon Matthews, and D. Seto. 2012. The long-term effect of increasing the albedo of urban areas. Environmental Research Letters 7(2). DOI: 10.1088/1748-9326/7/2/024004.

Albrecht, B. A. 1989. Aerosols, cloud microphysics, and fractional cloudiness. Science 245(4923):1227-1230. DOI: 10.1126/science.245.4923.1227.

Alterskjær, K., and J. E. Kristjánsson. 2013. The sign of the radiative forcing from marine cloud brightening depends on both particle size and injection amount. Geophysical Research Letters 40(1):210-215. DOI: 10.1029/2012GL054286.

Alterskjær, K., J. E. Kristjánsson, and O. Seland. 2012. Sensitivity to deliberate sea salt seeding of marine clouds—observations and model simulations. Atmospheric Chemistry and Physics 12(5):2795-2807. DOI: 10.5194/acp-12-2795-2012.

Alterskjær, K., J. E. Kristjánsson, O. Boucher, H. Muri, U. Niemeier, H. Schmidt, M. Schulz, and C. Timmreck. 2013. Sea-salt injections into the low-latitude marine boundary layer: The transient response in three Earth system models. Journal of Geophysical Research: Atmospheres 118(21):12195-12206. DOI: 10.1002/2013jd020432.

Ammann, C. M., and P. Naveau. 2003. Statistical analysis of tropical explosive volcanism occurrences over the last 6 centuries. Geophysical Research Letters 30(5). DOI: 10.1029/2002gl016388.

Anderson, A., and T. Ault. 2014. Temperature and precipitation responses to a stratospheric aerosol geoengineering experiment using the Community Climate System Model 4. Journal of Emerging Investigators 2014(August).

Anderson, J. G., D. M. Wilmouth, J. B. Smith, and D. S. Sayres. 2012. UV dosage levels in summer: Increased risk of ozone loss from convectively injected water vapor. Science 337(6096):835-839. DOI: 10.1126/science.1222978.

Angel, R. 2006. Feasibility of cooling the Earth with a cloud of small spacecraft near the inner Lagrange point (L1). Proceedings of the National Academy of Sciences of the United States of America 103(46):17184-17189. DOI: 10.1073/pnas.0608163103.

Archer, D., M. Eby, V. Brovkin, A. Ridgwell, L. Cao, U. Mikolajewicz, K. Caldeira, K. Matsumoto, G. Munhoven, A. Montenegro, and K. Tokos. 2009. Atmospheric lifetime of fossil fuel carbon dioxide. Annual Review of Earth and Planetary Sciences 37:117-134.

Arfeuille, F., B. P. Luo, P. Heckendorn, D. Weisenstein, J. X. Sheng, E. Rozanov, M. Schraner, S. Bronnimann, L. W. Thomason, and T. Peter. 2013. Modeling the stratospheric warming following the Mt. Pinatubo eruption: Uncertainties in aerosol extinctions. Atmospheric Chemistry and Physics 13(22):11221-11234. DOI: 10.5194/acp-13-11221-2013.

Arnold, F., A. A. Viggiano, and H. Schlager. 1982. Implications for trace gases and aerosols of large negative-ion clusters in the stratosphere. Nature 297(5865):371-376. DOI: 10.1038/297371a0.

ASOC (Ailomar Scientific Organizing Committee). 2010. The Asilomar Conference Recommendations on Principles for Research into Climate Engineering Techniques. Presented at the Asilomar International Conference on Climate Intervention Technologies, Washington, DC.

Auchmann, R., F. Arfeuille, M. Wegmann, J. Franke, M. Barriendos, M. Prohom, A. Sanchez-Lorenzo, J. Bhend, M. Wild, D. Folini, P. Štěpánek, and S. Brönnimann. 2013. Impact of volcanic stratospheric aerosols on diurnal temperature range in Europe over the past 200 years: Observations versus model simulations. Journal of Geophysical Research: Atmospheres 118(16):9064-9067. DOI: 10.1002/jgrd.50759.

Bala, G. 2009. Problems with geoengineering schemes to combat climate change. Current Science (00113891) 96(1):41-48.

Bala, G., S. Thompson, P. B. Duffy, K. Caldeira, and C. Delire. 2002. Impact of geoengineering schemes on the terrestrial biosphere. Geophysical Research Letters 29(22). DOI: 10.1029/2002gl015911.

Bala, G., K. Caldeira, and P. B. Duffy. 2003. Geoengineering Earth's radiation balance to mitigate climate change from a quadrupling of CO_2. Global and Planetary Change 37:157-168.

Bala, G., K. Caldeira, M. Wickett, T. J. Phillips, D. B. Lobell, C. Delire, and A. Mirin. 2007. Combined climate and carbon-cycle effects of large-scale deforestation. Proceedings of the National Academy of Sciences 104(16):6550-6555. DOI: 10.1073/pnas.0608998104.

Bala, G., P. B. Duffy, and K. E. Taylor. 2008. Impact of geoengineering schemes on the global hydrological cycle. Proceedings of the National Academy of Sciences of the United States of America 105(22):7664-7669. DOI: 10.1073/pnas.0711648105.

Bala, G., K. Caldeira, R. Nemani, L. Cao, G. Ban-Weiss, and H. J. Shin. 2011. Albedo enhancement of marine clouds to counteract global warming: Impacts on the hydrological cycle. Climate Dynamics 37(5):915-931. DOI: 10.1007/s00382-010-0868-1.

Ban-Weiss, G. A., and K. Caldeira. 2010. Geoengineering as an optimization problem. Environmental Research Letters 5(3). DOI:10.1088/1748-9326/5/3/034009.

Barrett, S., T. M. Lenton, A. Millner, A. Tavoni, S. Carpenter, J. M. Anderies, F. S. Chapin, A. S. Crepin, G. Daily, P. Ehrlich, C. Folke, V. Galaz, T. Hughes, N. Kautsky, E. F. Lambin, R. Naylor, K. Nyborg, S. Polasky, M. Scheffer, J. Wilen, A. Xepapadeas and A. de Zeeuw. 2014. Commentary: Climate engineering reconsidered. Nature Climate Change 4(7):527-529.

Battisti, D. S., and R. L. Naylor. 2009. Historical warnings of future food insecurity with unprecedented seasonal heat. Science 323(5911):240-244. DOI: 10.1126/science.1164363.

Baughman, E., A. Gnanadesikan, A. Degaetano, and A. Adcroft. 2012. Investigation of the surface and circulation impacts of cloud-brightening geoengineering. Journal of Climate 25(21):7527-7543. DOI: 10.1175/JCLI-D-11-00282.1.

Bekki, S., J. A. Pyle, W. Zhong, R. Toumi, J. D. Haigh, and D. M. Pyle. 1996. The role of microphysical and chemical processes in prolonging the climate forcing of the Toba eruption. Geophysical Research Letters 23(19):2669-2672. DOI: 10.1029/96gl02088.

Bender, F. A. M., H. Rodhe, R. J. Charlson, A. M. L. Ekman, and N. Loeb. 2006. 22 views of the global albedo—comparison between 20 GCMs and two satellites. Tellus, Series A: Dynamic Meteorology and Oceanography 58(3):320-330. DOI: 10.1111/j.1600-0870.2006.00181.x.

Berdahl, M., A. Robock, D. Y. Ji, J. C. Moore, A. Jones, B. Kravitz, and S. Watanabe. 2014. Arctic cryosphere response in the Geoengineering Model Intercomparison Project G3 and G4 scenarios. Journal of Geophysical Research: Atmospheres 119(3):1308-1321. DOI: 10.1002/2013jd020627.

Bernard, A., and W. I. Rose. 1990. The injection of sulfuric acid aerosols in the stratosphere by the El Chichón volcano and its related hazards to the international air traffic. Natural Hazards 3(1):59-67.

Berner, R. A., A. C. Lasaga, and R. M. Garrels. 1983. The Carbonate-Silicate Geochemical Cycle and Its Effect on Atmospheric Carbon-Dioxide over the Past 100 Million Years. American Journal of Science 283(7):641-683.

Betz, G. 2012. The case for climate engineering research: An analysis of the "arm the future" argument. Climatic Change 111(2):473-485. DOI: 10.1007/s10584-011-0207-5.

Bodansky, D. 2011. Governing Climate Engineering: Scenarios for Analysis. Discussion Paper 2011-47. Harvard Project on Climate Agreements, Cambridge, MA.

Bony, S., and J. L. Dufresne. 2005. Marine boundary layer clouds at the heart of tropical cloud feedback uncertainties in climate models. Geophysical Research Letters 32(20). DOI: 10.1029/2005gl023851.

Boston Climate Preparedness Task Force. 2013. Climate Ready Boston: Municipal Vulnerability to Climate Change. Boston: Environment and Energy Services.

Boucher, O., D. Randall, P. Artaxo, C. Bretherton, G. Feingold, P. Forster, V.-M. Kerminen, Y. Kondo, H. Liao, U. Lohmann, P. Rasch, S. K. Satheesh, S. Sherwood, B. Stevens, and X. Y. Zhang. 2013. Clouds and aerosols. In Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. T. F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P. M. Midgley, eds. Cambridge, UK: Cambridge University Press.

Bower, K., T. Choularton, J. Latham, J. Sahraei, and S. Salter. 2006. Computational assessment of a proposed technique for global warming mitigation via albedo-enhancement of marine stratocumulus clouds. Atmospheric Research 82(1-2):328-336. DOI: 10.1016/j.atmosres.2005.11.013.

BPC (Bipartisan Policy Center). 2011. Geoengineering: A National Strategic Plan for Research on the Potential Effectiveness, Feasibility, and Consequences of Climate Remediation Technologies. Bipartisan Policy Center Task Force on Climate Remediation Research, Washington, DC.

Bracmort, K., and R. K. Lattanzio. 2013. Geoengineering: Governance and Technology Policy. Washington, DC: Congressional Research Service.

Breed, D., R. Rasmussen, C. Weeks, B. Boe, and T. Deshler. 2014. Evaluating winter orographic cloud seeding: Design of the Wyoming Weather Modification Pilot Project (WWMPP). Journal of Applied Meteorology and Climatology 53(2):282-299. DOI: 10.1175/Jamc-D-13-0128.1.

Bretherton, C. S., R. Wood, R. C. George, D. Leon, G. Allen, and X. Zheng. 2010. Southeast Pacific stratocumulus clouds, precipitation and boundary layer structure sampled along 20° S during VOCALS-REx. Atmospheric Chemistry and Physics 10(21):10639-10654. DOI: 10.5194/acp-10-10639-2010.

Broecker, W. S., and R. Kunzig. 2008. Fixing Climate: What Past Climate Changes Reveal about the Current Threat—and How to Counter It. New York: Hill and Wang.

Brovkin, V., V. Petoukhov, M. Claussen, E. Bauer, D. Archer, and C. Jaeger. 2009. Geoengineering climate by stratospheric sulfur injections: Earth system vulnerability to technological failure. Climatic Change 92(3/4):243-259. DOI: 10.1007/s10584-008-9490-1.

Budyko, M. I. 1974. Climate and Life. New York: Academic Press.

Budyko, M. I. 1977. Climatic Change. Washington, DC: American Geophysical Union.

Bunzl, M. 2009. Researching geoengineering: Should not or could not? Environmental Research Letters 4(4). DOI: 10.1088/1748-9326/4/4/045104.

Burns, W. C. G. 2011. Climate geoengineering: Solar radiation management and its implications for intergenerational equity. Stanford Journal of Law, Science & Policy 4(39-55).

Burns, W. C. G., and A. L. Strauss. 2013. Climate Change Geoengineering: Philosophical Perspectives, Legal Issues, and Governance Frameworks. Cambridge, UK: Cambridge University Press.

Bushell, A. C., and G. M. Martin. 1999. The impact of vertical resolution upon GCM simulations of marine stratocumulus. Climate Dynamics 15(4):293-318. DOI: 10.1007/s003820050283.

Byers, H. R. 1974. History of weather modification. In Weather and Climate Modification. W. N. Hess, ed. New York: Wiley-Interscience.

Caldeira, K., G. Bala, and L. Cao. 2013. The science of geoengineering. Annual Review of Earth and Planetary Sciences 41(1):231-256. DOI: 10.1146/annurev-earth-042711-105548.

California Department of Water Resources. 2005. Final California Water Plan Update 2005: A Framework for Action. Bulletin 160-05. State of California, Resources Agency, Department of Water Resources, Sacramento, CA.

Campbell, P., M. Mills, and T. Deshler. 2014. The global extent of the mid stratospheric CN layer: A three-dimensional modeling study. Journal of Geophysical Research: Atmospheres 119(2):1015-1030. DOI: 10.1002/2013jd020503.

Canty, T., N. R. Mascioli, M. D. Smarte, and R. J. Salawitch. 2013. An empirical model of global climate—Part 1: A critical evaluation of volcanic cooling. Atmospheric Chemistry and Physics 13(8):3997-4031. DOI: 10.5194/acp-13-3997-2013.

Cao, L., G. Bala, and K. Caldeira. 2011. Why is there a short-term increase in global precipitation in response to diminished CO_2 forcing? Geophysical Research Letters 38. DOI: 10.1029/2011gl046713.

Cao, L., G. Bala, and K. Caldeira. 2012. Climate response to changes in atmospheric carbon dioxide and solar irradiance on the time scale of days to weeks. Environmental Research Letters 7(3). DOI: 10.1088/1748-9326/7/3/034015.

Carn, S. A., A. J. Krueger, N. A. Krotkov, K. Yang, and K. Evans. 2009. Tracking volcanic sulfur dioxide clouds for aviation hazard mitigation. Natural Hazards 51(2):325-343. DOI: 10.1007/s11069-008-9228-4.

Casadevall, T. J., P. J. Delos Reyes, and D. J. Schneider. 1996. The 1991 Pinatubo eruptions and their effects on aircraft operations. In Fire and Mud: Eruptions and Lahars of Mount Pinatubo, Philippines. C. G. Newhall and R. S. Punongbayan, eds. Seattle, WA: University of Washington Press.

Chen, I. C., J. K. Hill, R. Ohlemuller, D. B. Roy, and C. D. Thomas. 2011. Rapid range shifts of species associated with high levels of climate warming. Science 333(6045):1024-1026. DOI: 10.1126/science.1206432.

Chen, T., W. B. Rossow, and Y. C. Zhang. 2000. Radiative effects of cloud-type variations. Journal of Climate 13(1):264-286. DOI: 10.1175/1520-0442(2000)013<0264:Reoctv>2.0.Co;2.

Chen, Y. C., M. W. Christensen, L. Xue, A. Sorooshian, G. L. Stephens, R. M. Rasmussen, and J. H. Seinfeld. 2012. Occurrence of lower cloud albedo in ship tracks. Atmospheric Chemistry and Physics 12(17):8223-8235. DOI: 10.5194/acp-12-8223-2012.

Chipperfield, M. P. 1999. Multiannual simulations with a three-dimensional chemical transport model. Journal of Geophysical Research: Atmospheres 104(D1):1781-1805. DOI: 10.1029/98jd02597.

Chipperfield, M. P. 2003. A three-dimensional model study of long-term mid-high latitude lower stratosphere ozone changes. Atmospheric Chemistry and Physics 3:1253-1265.

Chipperfield, M. P., V. Fioletov, B. Bregman, J. Burrows, B. J. Connor, J. D. Haigh, N. R. P. Harris, A. Hauchecorne, L. L. Hood, S. R. Kawa, J. W. Krzyscin, J. A. Logan, N. J. Muthama, L. Polvani, W. J. Randel, T. S. J. Stahelin, R. S. Stolarski, L. W. Thomason, and J. M. Zawodny. 2007. Global ozone: Past and present. In Scientific Assessment of Ozone Depletion: 2006. World Meteorological Organization, ed. Geneva: World Meteorological Organization.

Cicerone, R. J. 2006. Geoengineering: Encouraging research and overseeing implementation. Climatic Change 77(3-4):221-226. DOI: 10.1007/s10584-006-9102-x.

Cirisan, A., P. Spichtinger, B. P. Luo, D. K. Weisenstein, H. Wernli, U. Lohmann, and T. Peter. 2013. Microphysical and radiative changes in cirrus clouds by geoengineering the stratosphere. Journal of Geophysical Research: Atmospheres 118(10):4533-4548. DOI: 10.1002/Jgrd.50388.

Coakley, J. A., R. L. Bernstein, and P. A. Durkee. 1987. Effect of ship-stack effluents on cloud reflectivity. Science 237(4818):1020-1022. DOI: 10.1126/science.237.4818.1020.

Coakley, J. A., P. A. Durkee, K. Nielsen, J. P. Taylor, S. Platnick, B. A. Albrecht, D. Babb, F. L. Chang, W. R. Tahnk, C. S. Bretherton, and P. V. Hobbs. 2000. The appearance and disappearance of ship tracks on large spatial scales. Journal of the Atmospheric Sciences 57(16):2765-2778. DOI: 10.1175/1520-0469(2000)057<2765:Taados>2.0.Co;2.

Coggon, M. M., A. Sorooshian, Z. Wang, A. R. Metcalf, A. A. Frossard, J. J. Lin, J. S. Craven, A. Nenes, H. H. Jonsson, L. M. Russell, R. C. Flagan, and J. H. Seinfeld. 2012. Ship impacts on the marine atmosphere: Insights into the contribution of shipping emissions to the properties of marine aerosol and clouds. Atmospheric Chemistry and Physics 12(18):8439-8458. DOI: 10.5194/acp-12-8439-2012.

Conover, J. H. 1966. Anomalous cloud lines. Journal of the Atmospheric Sciences 23(6):778-785. DOI: 10.1175/1520-0469(1966)023<0778:Acl>2.0.Co;2.

Cooper, G., J. Foster, L. Galbraith, S. Jain, A. Neukermans, and B. Ormond. 2014. Preliminary results for salt aerosol production intended for marine cloud brightening, using effervescent spray atomization. Philosophical Transactions of the Royal Society, A: Mathematical, Physical & Engineering Sciences 372:20140055. DOI: 10.1098/rsta.2014.0055.

Corner, A., and N. Pidgeon. 2010. Geoengineering the climate: The social and ethical implications. Environment 52(1):24-37. DOI: 10.1080/00139150903479563.

Cotton, W. R. 2008. Weather and Climate Engineering. Presented at the 17th Planned and Inadvertent Weather Modification Conference, Boulder, CO.

Cotton, W. R., W. L. Woodley, I. Ginis, J. H. Golden, A. Khain, and D. Rosenfeld. 2011. The rise and fall of HAMP. Journal of Weather Modification 43(1):88-95.

Crutzen, P. J. 2006. Albedo enhancement by stratospheric sulfur injections: A contribution to resolve a policy dilemma? Climatic Change 77(3-4):211-219. DOI: 10.1007/s10584-006-9101-y.

Cziczo, D. J., K. D. Froyd, C. Hoose, E. J. Jensen, M. H. Diao, M. A. Zondlo, J. B. Smith, C. H. Twohy, and D. M. Murphy. 2013. Clarifying the dominant sources and mechanisms of cirrus cloud formation. Science 340(6138):1320-1324. DOI: 10.1126/science.1234145.

Davis, S. J., and R. H. Socolow. 2014. Commitment accounting of CO_2 emissions. Environmental Research Letters 9(8). DOI: 10.1088/1748-9326/9/8/084018.

DeFelice, T. P., J. Golden, D. Griffith, W. Woodley, D. Rosenfeld, D. Breed, M. Solak, and B. Boe. 2014. Extra area effects of cloud seeding: An updated assessment. Atmospheric Research 135:193-203. DOI: 10.1016/j.atmosres.2013.08.014.

Deligne, N. I., S. G. Coles, and R. S. J. Sparks. 2010. Recurrence rates of large explosive volcanic eruptions. Journal of Geophysical Research: Solid Earth 115(B6). DOI: 10.1029/2009jb006554.

Diamond, J. M. 2011. Collapse: How Societies Choose to Fail or Succeed. New York: Penguin Books.

Doney, S. C. 2013. Statement to the U.S. Senate, Committee on Environment and Public Works. Climate Change: It's Happening Now. Hearing, July 18, 2013. Available at http://www.epw.senate.gov/public/index.cfm?FuseAction=Files.View&FileStore_id=afb04836-4f2f-4715-9ffc-f89765126ca1, accessed September 24, 2014.

Doney, S. C., V. J. Fabry, R. A. Feely, and J. A. Kleypas. 2009. Ocean acidification: The other CO_2 problem. Annual Review of Marine Science 1:169-192. DOI: 10.1146/annurev.marine.010908.163834.

Doney, S. C., M. Ruckelshaus, J. E. Duffy, J. P. Barry, F. Chan, C. A. English, H. M. Galindo, J. M. Grebmeier, A. B. Hollowed, N. Knowlton, J. Polovina, N. N. Rabalais, W. J. Sydeman, and L. D. Talley. 2012. Climate change impacts on marine ecosystems. Annual Review of Marine Science 4:11-37. DOI: 10.1146/annurev-marine-041911-111611.

Doney, S. C., L. Bopp, and M. C. Long. 2014. Historical and future trends in ocean climate and biogeochemistry. Oceanography 27(1):108-119.

Donner, L. J., B. L. Wyman, R. S. Hemler, L. W. Horowitz, Y. Ming, M. Zhao, J. C. Golaz, P. Ginoux, S. J. Lin, M. D. Schwarzkopf, J. Austin, G. Alaka, W. F. Cooke, T. L. Delworth, S. M. Freidenreich, C. T. Gordon, S. M. Griffies, I. M. Held, W. J. Hurlin, S. A. Klein, T. R. Knutson, A. R. Langenhorst, H. C. Lee, Y. L. Lin, B. I. Magi, S. L. Malyshev, P. C. D. Milly, V. Naik, M. J. Nath, R. Pincus, J. J. Ploshay, V. Ramaswamy, C. J. Seman, E. Shevliakova, J. J. Sirutis, W. F. Stern, R. J. Stouffer, R. J. Wilson, M. Winton, A. T. Wittenberg, and F. R. Zeng. 2011. The dynamical core, physical parameterizations, and basic simulation characteristics of the atmospheric component AM3 of the GFDL global coupled model CM3. Journal of Climate 24(13):3484-3519. DOI: 10.1175/2011jcli3955.1.

Dore, J. E., R. Lukas, D. W. Sadler, M. J. Church, and D. M. Karl. 2009. Physical and biogeochemical modulation of ocean acidification in the central North Pacific. Proceedings of the National Academy of Sciences of the United States of America 106(30):12235-12240. DOI: 10.1073/pnas.0906044106.

Drdla, K. 2005. Temperature thresholds for polar stratospheric ozone. Abstract A31D-03. EOS, Transactions American Geophysical Union 86(Fall Meeting Suppl.).

Drdla, K., and R. Müller. 2010. Temperature thresholds for polar stratospheric ozone loss. Atmosperic Chemistry and Physic Discussions 10:28687-28720. DOI: 10.5194/acpd-10-28687-2010.

Driscoll, S., A. Bozzo, L. J. Gray, A. Robock, and G. Stenchikov. 2012. Coupled Model Intercomparison Project 5 (CMIP5) simulations of climate following volcanic eruptions. Journal of Geophysical Research D: Atmospheres 117(17). DOI: 10.1029/2012JD017607.

Durkee, P. A., K. J. Noone, and R. T. Bluth. 2000. The Monterey Area Ship Track experiment. Journal of the Atmospheric Sciences 57(16):2523-2541. DOI: 10.1175/1520-0469(2000)057<2523:Tmaste>2.0.Co;2.

Early, J. T. 1989. The space based solar shield to offset greenhouse effect. Journal of the British Interplanetary Society 42:567-569.

EIA (Energy Information Administration). 2013a. How old are U.S. power plants? Available at http://www.eia.gov/energy_in_brief/article/age_of_elec_gen.cfm, accessed June 13, 2014.

EIA. 2013b. Electric Power Annual 2012. Washington, DC: EIA, U.S. Department of Energy.

English, J. M., O. B. Toon, and M. J. Mills. 2012. Microphysical simulations of sulfur burdens from stratospheric sulfur geoengineering. Atmospheric Chemistry and Physics 12(10):4775-4793. DOI: 10.5194/acp-12-4775-2012.

English, J. M., O. B. Toon, and M. J. Mills. 2013. Microphysical simulations of large volcanic eruptions: Pinatubo and Toba. Journal of Geophysical Research: Atmospheres 118(4):1880-1895. DOI: 10.1002/Jgrd.50196.

Espy, J. P. 1841. The Philosophy of Storms. Boston: Charles C. Little and James Brown.

Faloona, I., D. H. Lenschow, T. Campos, B. Stevens, M. van Zanten, B. Blomquist, D. Thornton, A. Bandy, and H. Gerber. 2005. Observations of entrainment in eastern Pacific marine stratocumulus using three conserved scalars. Journal of the Atmospheric Sciences 62(9):3268-3285. DOI: 10.1175/Jas3541.1.

Feingold, G., S. M. Kreidenweis, and Y. P. Zhang. 1998. Stratocumulus processing of gases and cloud condensation nuclei: 1. Trajectory ensemble model. Journal of Geophysical Research: Atmospheres 103(D16):19527-19542. DOI: 10.1029/98jd01750.

Feingold, G., I. Koren, H. L. Wang, H. W. Xue, and W. A. Brewer. 2010. Precipitation-generated oscillations in open cellular cloud fields. Nature 466(7308):849-852. DOI: 10.1038/Nature09314.

Ferek, R. J., T. Garrett, P. V. Hobbs, S. Strader, D. Johnson, J. P. Taylor, K. Nielsen, A. S. Ackerman, Y. Kogan, Q. F. Liu, B. A. Albrecht, and D. Babb. 2000. Drizzle suppression in ship tracks. Journal of the Atmospheric Sciences 57(16):2707-2728. DOI: 10.1175/1520-0469(2000)057<2707:Dsist>2.0.Co;2.

Fetterer, F., K. Knowles, W. Meier, and M. Savoie. 2012. Sea ice index. Available at http://nsidc.org/data/seaice_index/, accessed March 16, 2015.

Fleming, J. R. 2010a. Can geoengineering be green? Issues in Science and Technology 27(1):14-14.

Fleming, J. R. 2010b. Fixing the Sky: The Checkered History of Weather and Climate Control. New York: Columbia University Press.

Fleming, J. R. 2012. Will geo-engineering bring security and peace? What does history tell us? Sicherheit und Frieden 2012(4).

Foley, A. M., M. Willeit, V. Brovkin, G. Feulner, and A. D. Friend. 2014. Quantifying the global carbon cycle response to volcanic stratospheric aerosol radiative forcing using Earth system models. Journal of Geophysical Research: Atmospheres 119(1):101-111. DOI: 10.1002/2013jd019724.

Franklin, B. 1789. Meteorological Imaginations and Conjectures (Paper Read 1784) . Memoirs of the Literary and Philosophical Society of Manchester, 2nd ed. 1789: 373-377. Reprinted 1982, Weatherwise 35(262).

Frick, G. M., and W. A. Hoppel. 2000. Airship measurements of ship's exhaust plumes and their effect on marine boundary layer clouds. Journal of the Atmospheric Sciences 57(16):2625-2648. DOI: 10.1175/1520-0469(2000)057<2625:Amosse>2.0.Co;2.

Frömming, C., M. Ponater, U. Burkhardt, A. Stenke, S. Pechtl, and R. Sausen. 2011. Sensitivity of contrail coverage and contrail radiative forcing to selected key parameters. Atmospheric Environment 45(7):1483-1490. DOI: 10.1016/j.atmosenv.2010.11.033.

Froyd, K. D., S. M. Murphy, D. M. Murphy, J. A. de Gouw, N. C. Eddingsaas, and P. O. Wennberg. 2010. Contribution of isoprene-derived organosulfates to free tropospheric aerosol mass. Proceedings of the National Academy of Sciences of the United States of America 107(50):21360-21365. DOI: 10.1073/pnas.1012561107.

GAO (U.S. Government Accountability Office). 2010. Climate Change: A Coordinated Strategy Could Focus Federal Geoengineering Research and Inform Governance Efforts. GAO-10-903. U.S. Government Accountability Office, Washington, DC.

GAO. 2011. Climate engineering: Technical status, future directions, and potential responses. GAO-11-71. U.S. Government Accountability Office, Washington, DC. Available at http://www.gao.gov/new.items/d1171.pdf, accessed March 16, 2015.

Gardiner, S. 2010. Is "arming the future" with geoengineering really the lesser evil? In Climate Ethics. C. Gardiner et al., eds. Oxford, UK: Oxford University Press.

Gaskill, A. 2004. DOE Meeting Summary: Summary of Meeting with U.S. DOE to Discuss Geoengineering Options to Prevent Long-Term Abrupt Climate Change. Held at the U. S. Department of Energy, Washington, DC, June 16, 2004.

Gattuso, J.-P., and L. Hansson. 2011. Ocean Acidification. Oxford, UK: Oxford University Press.

Gill, J. A., J. A. Alves, W. J. Sutherland, G. F. Appleton, P. M. Potts, and T. G. Gunnarsson. 2013. Why is timing of bird migration advancing when individuals are not? Proceedings of the Royal Society B: Biological Sciences 281(1774). DOI: 10.1098/rspb.2013.2161.

Goodman, J., K. G. Snetsinger, R. F. Pueschel, G. V. Ferry, and S. Verma. 1994. Evolution of Pinatubo aerosol near 19 km altitude over western North America. Geophysical Research Letters 21(12):1129-1132. DOI: 10.1029/94gl00696.

Govindasamy, B., and K. Caldeira. 2000. Geoengineering Earth's radiation balance to mitigate CO_2-induced climate change. Geophysical Research Letters 27(14):2141-2144. DOI: 10.1029/1999GL006086.

Govindasamy, B., S. Thompson, P. B. Duffy, K. Caldeira, and C. Delire. 2002. Impact of geoengineering schemes on the terrestrial biosphere. Geophysical Research Letters 29(22). DOI: 10.1029/2002gl015911.

Graf, H. F., I. Kirchner, A. Robock, and I. Schult. 1993. Pinatubo eruption winter climate effects: Model versus observations. Climate Dynamics 9(2):81-93.

Gregory, J. M., W. J. Ingram, M. A. Palmer, G. S. Jones, P. A. Stott, R. B. Thorpe, J. A. Lowe, T. C. Johns, and K. D. Williams. 2004. A new method for diagnosing radiative forcing and climate sensitivity. Geophysical Research Letters 31(3). DOI: 10.1029/2003gl018747.

Gu, L. H., D. D. Baldocchi, S. C. Wofsy, J. W. Munger, J. J. Michalsky, S. P. Urbanski, and T. A. Boden. 2003. Response of a deciduous forest to the Mount Pinatubo eruption: Enhanced photosynthesis. Science 299(5615):2035-2038. DOI: 10.1126/science.1078366.

Hadjinicolaou, P., J. A. Pyle, and N. R. P. Harris. 2005. The recent turnaround in stratospheric ozone over northern middle latitudes: A dynamical modeling perspective. Geophysical Research Letters 32(12). DOI: 10.1029/2005gl022476.

Hale, B. 2012. The world that would have been: Moral hazard arguments against geoengineering. In Engineering the Climate: The Ethics of Solar Radiation Management. C. J. Preston, ed. Lanham, MD: Lexington Books.

Hamill, P., E. J. Jensen, P. B. Russell, and J. J. Bauman. 1997. The life cycle of stratospheric aerosol particles. Bulletin of the American Meteorological Society 78(7):1395-1410. DOI: 10.1175/1520-0477(1997)078<1395:Tlcosa>2.0.Co;2.

Hamilton, C. 2013. Moral Haze Clouds Geoengineering. EuTRACE Journal (Essay No. 1).

Hamwey, R. M. 2007. Active amplification of the terrestrial albedo to mitigate climate change: An exploratory study. Mitigation and Adaptation Strategies for Global Change 12(4):419-439. DOI: 10.1007/s11027-005-9024-3.

Hanisco, T. F., E. J. Moyer, E. M. Weinstock, J. M. St Clair, D. S. Sayres, J. B. Smith, R. Lockwood, J. G. Anderson, A. E. Dessler, F. N. Keutsch, J. R. Spackman, W. G. Read, and T. P. Bui. 2007. Observations of deep convective influence on stratospheric water vapor and its isotopic composition. Geophysical Research Letters 34(4). DOI: 10.1029/2006gl027899.

Hansen, J., L. Nazarenko, R. Ruedy, M. Sato, J. Willis, A. D. Genio, D. Koch, A. Lacis, K. Lo, S. Menon, T. Novakov, J. Perlwitz, G. Russell, G. A. Schmidt, and N. Tausnev. 2005. Earth's energy imbalance: Confirmation and implications. Science 308(5727):1431-1435. DOI: 10.1126/science.1110252.

Hartmann, D. L., M. E. Ockert-Bell, and M. L. Michelsen. 1992. The effect of cloud type on Earth's energy balance: Global analysis. Journal of Climate 5:1281-1304.

Hawkins, L. N., L. M. Russell, C. H. Twohy, and J. R. Anderson. 2008. Uniform particle-droplet partitioning of 18 organic and elemental components measured in and below DYCOMS-II stratocumulus clouds. Journal of Geophysical Research: Atmospheres 113(D14). DOI: 10.1029/2007jd009150.

Haywood, J. M., A. Jones, N. Bellouin, and D. Stephenson. 2013. Asymmetric forcing from stratospheric aerosols impacts Sahelian rainfall. Nature Climate Change 3(7):660-665.

Heckendorn, P., D. Weisenstein, S. Fueglistaler, B. P. Luo, E. Rozanov, M. Schraner, L. W. Thomason, and T. Peter. 2009. The impact of geoengineering aerosols on stratospheric temperature and ozone. Environmental Research Letters 4(4). DOI: 10.1088/1748-9326/4/4/045108.

Hegg, D. A., D. S. Covert, H. H. Jonsson, and R. Woods. 2009. Differentiating natural and anthropogenic cloud condensation nuclei in the California coastal zone. Tellus, Series B: Chemical and Physical Meteorology 61(4):669-676. DOI: 10.1111/j.1600-0889.2009.00435.x.

Hersey, S. P., A. Sorooshian, S. M. Murphy, R. C. Flagan, and J. H. Seinfeld. 2009. Aerosol hygroscopicity in the marine atmosphere: A closure study using high-time-resolution, multiple-RH DASH-SP and size-resolved C-ToF-AMS data. Atmospheric Chemistry and Physics 9(7):2543-2554.

Hester, T. 2013. Remaking the world to save it: Applying US environmental laws to climate engineering projects. In Climate Change Geoengineering: Philosophical Perspectives, Legal Issues, and Governance Frameworks. W. C. G. Burns and A. L. Strauss, eds. Cambridge, UK: Cambridge University Press.

Hill, S., and Y. Ming. 2012. Nonlinear climate response to regional brightening of tropical marine stratocumulus. Geophysical Research Letters 39(15). DOI: 10.1029/2012GL052064.

Hobbs, P. V., T. J. Garrett, R. J. Ferek, S. R. Strader, D. A. Hegg, G. M. Frick, W. A. Hoppel, R. F. Gasparovic, L. M. Russell, D. W. Johnson, C. O'Dowd, P. A. Durkee, K. E. Nielsen, and G. Innis. 2000. Emissions from ships with respect to their effects on clouds. Journal of the Atmospheric Sciences 57(16):2570-2590. DOI: 10.1175/1520-0469(2000)057<2570:Efswrt>2.0.Co;2.

Hoffert, M. I., K. Caldeira, A. K. Jain, E. F. Haites, L. D. D. Harvey, S. D. Potter, M. E. Schlesinger, S. H. Schneider, R. G. Watts, T. M. L. Wigley, and D. J. Wuebbles. 1998. Energy implications of future stabilization of atmospheric CO_2 content. Nature 395(6705):881-884. DOI: 10.1038/27638.

Hoffman, R. N. 2002. Controlling the global weather. Bulletin of the American Meteorological Society 83(2):241-248. DOI: 10.1175/1520-0477(2002)083<0241:Ctgw>2.3.Co;2.

Hoffman, R. N. 2004. Controlling hurricanes. Scientific American 291(4):68-75.

Homeyer, C. R., L. L. Pan, S. W. Dorsi, L. M. Avallone, A. J. Weinheimer, A. S. O'Brien, J. P. DiGangi, M. A. Zondlo, T. B. Ryerson, G. S. Diskin, and T. L. Campos. 2014. Convective transport of water vapor into the lower stratosphere observed during double-tropopause events. Journal of Geophysical Research: Atmospheres 119(18):10941-10958. DOI: 10.1002/2014jd021485.

House of Commons Science and Technology Committee. 2010. The Regulation of Geoengineering: Fifth Report of Session 2009–10. Report, together with formal minutes, oral and written evidence. London: The Stationery Office Limited.

Huggins, A. 2006. Summary of Studies that Document the Effectiveness of Cloud Seeding for Snowfall Augmentation. Austin, TX: North American Weather Modification Council.

Hulme, M. 2014. Can Science Fix Climate: A Case Against Climate Engineering. Cambridge, UK: Polity Press.

Huschke, R. E. 1963. A brief history of weather modification Since 1946. Bulletin of the American Meteorological Society 44:425-429.

IASS (Institute for Advanced Sustainability Studies). 2014. Workshop: Understanding Process Mechanisms for the Governance of SRM Field Experiments. Brief Summary. Institute for Advanced Sustainability Studies, Potsdam, Germany.

IEA (International Energy Agency). 2013. Key World Energy Statistics. Paris: IEA.

IPCC (Intergovernmental Panel on Climate Change). 1991. The First Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, UK: Cambridge University Press.

IPCC. 1997. The Regional Impacts of Climate Change: An Assessment of Vulnerability. Summary for Policymakers. A Special Report of IPCC Working Group II. R. T. Watson, M. C. Zinyowera, R. H. Moss, and D. J. Dokken, eds. Geneva: IPCC.

IPCC. 2003. Good Practice Guidance for Land Use, Land-Use Change and Forestry. Hayama, Kanagawa, Japan: Institute for Global Environmental Strategies (IGES).

IPCC. 2007a. Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II, and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. R. K. Pachauri and A. Reisinger, eds. Geneva: IPCC.

IPCC. 2007b. Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor, and H. L. Miller, eds. Cambridge, UK: Cambridge University Press.

IPCC. 2011. Summary for Policymakers. In IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation. O. Edenhofer, R. Pichs-Madruga, Y. Sokona, K. Seyboth, P. Matschoss, S. Kadner, T. Zwickel, P. Eickemeier, G. Hansen, S. Schlömer, and C. von Stechow, eds. Cambridge, UK: Cambridge University Press.

IPCC. 2013a. Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, UK: Cambridge University Press.

IPCC. 2013b. Summary for Policymakers. In Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. T. F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P. M. Midgley, eds. Cambridge, UK: Cambridge University Press.

IPCC. 2014a. Climate Change 2014: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, UK: Cambridge University Press.

IPCC. 2014b. Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, UK: Cambridge University Press.

Irvine, P. J., A. Ridgwell, and D. J. Lunt. 2011. Climatic effects of surface albedo geoengineering. Journal of Geophysical Research D: Atmospheres 116(24). DOI: 10.1029/2011JD016281.

Jamieson, D. 1996. Ethics and intentional climate change. Climatic Change 33(3):323-336. DOI: 10.1007/BF00142580.

Jenkins, A. K. L., and P. M. Forster. 2013. The inclusion of water with the injected aerosol reduces the simulated effectiveness of marine cloud brightening. Atmospheric Science Letters 14(3):164-169. DOI: 10.1002/Asl2.434.

Jones, A., and J. M. Haywood. 2012. Sea-spray geoengineering in the HadGEM2-ES Earth-system model: Radiative impact and climate response. Atmospheric Chemistry and Physics 12(22):10887-10898. DOI: 10.5194/acp-12-10887-2012.

Jones, A., J. Haywood, and O. Boucher. 2009. Climate impacts of geoengineering marine stratocumulus clouds. Journal of Geophysical Research D: Atmospheres 114(10). DOI: 10.1029/2008JD011450.

Jones, A., J. Haywood, O. Boucher, B. Kravitz, and A. Robock. 2010. Geoengineering by stratospheric SO_2 injection: Results from the Met Office HadGEM2 climate model and comparison with the Goddard Institute for Space Studies ModelE. Atmospheric Chemistry and Physics 10(13):5999-6006. DOI: 10.5194/acp-10-5999-2010.

Jones, A., J. Haywood, and O. Boucher. 2011. A comparison of the climate impacts of geoengineering by stratospheric SO_2 injection and by brightening of marine stratocumulus cloud. Atmospheric Science Letters 12(2):176-183. DOI: 10.1002/asl.291.

Jones, A., J. M. Haywood, K. Alterskjær, O. Boucher, J. N. S. Cole, C. L. Curry, P. J. Irvine, D. Ji, B. Kravitz, J. Egill Kristjánsson, J. C. Moore, U. Niemeier, A. Robock, H. Schmidt, B. Singh, S. Tilmes, S. Watanabe, and J.-H. Yoon. 2013. The impact of abrupt suspension of solar radiation management (termination effect) in experiment G2 of the Geoengineering Model Intercomparison Project (GeoMIP). Journal of Geophysical Research: Atmospheres 118(17):9743-9752. DOI: 10.1002/jgrd.50762.

Joshi, M. M., F. H. Lambert, and M. J. Webb. 2013. An explanation for the difference between twentieth and twenty-first century land-sea warming ratio in climate models. Climate Dynamics 41(7-8):1853-1869. DOI: 10.1007/s00382-013-1664-5.

Kacenelenbogen, M., M. A. Vaughan, J. Redemann, R. M. Hoff, R. R. Rogers, R. A. Ferrare, P. B. Russell, C. A. Hostetler, J. W. Hair, and B. N. Holben. 2011. An accuracy assessment of the CALIOP/CALIPSO version 2/version 3 daytime aerosol extinction product based on a detailed multi-sensor, multi-platform case study. Atmospheric Chemistry and Physics 11(8):3981-4000. DOI: 10.5194/acp-11-3981-2011.

Kahan, D. M., H. C. Jenkins-Smith, T. Tarantola, C. L. Silva, and D. Braman. 2014. Geoengineering and climate change polarization: Testing a two-channel model of science communication. Annals of the American Academy of Political & Social Science 658:193-222. DOI: 10.2139/ssrn.1981907.

Kalidindi, S., G. Bala, A. Modak, and K. Caldeira. 2014. Modeling of solar radiation management: A comparison of simulations using reduced solar constant and stratospheric sulphate aerosols. Climate Dynamics DOI: 10.1007/s00382-014-2240-3.

Kay, J. E., B. R. Hillman, S. A. Klein, Y. Zhang, B. Medeiros, R. Pincus, A. Gettelman, B. Eaton, J. Boyle, R. Marchand, and T. P. Ackerman. 2012. Exposing global cloud biases in the Community Atmosphere Model (CAM) using satellite observations and their corresponding instrument simulators. Journal of Climate 25(15):5190-5207. DOI: 10.1175/Jcli-D-11-00469.1.

Keith, D. W. 2010. Photophoretic levitation of engineered aerosols for geoengineering. Proceedings of the National Academy of Sciences of the United States of America 107(38):16428-16431. DOI: 10.1073/pnas.1009519107.

Keith, D. W. 2013. A Case for Climate Engineering. Cambridge, MA: MIT Press.

Keith, D. W., and H. Dowlatabadi. 1992. A serious look at geoengineering. EOS, Transactions of the American Geophysical Union 73(27):289-293. DOI: 10.1029/91EO00231.

Keith, D. W., E. Parson, and M. G. Morgan. 2010. Research on global sun block needed now. Nature 463(7280):426-427. DOI: 10.1038/463426a.

Keith, D. W., R. Duren, and D. G. MacMartin. 2014. Field experiments on solar geoengineering: An exploration of a representative research portfolio. Philosophical Transctions of the Royal Society A 372(2031). DOI: 10.1098/rsta.2014.0175.

Kirchner, I., G. L. Stenchikov, H. F. Graf, A. Robock, and J. C. Antuna. 1999. Climate model simulation of winter warming and summer cooling following the 1991 Mount Pinatubo volcanic eruption. Journal of Geophysical Research: Atmospheres 104(D16):19039-19055. DOI: 10.1029/1999jd900213.

Köhler, H. 1921. Zur condensation des wasserdampfe in der atmosphere. Geofysiske Publikasjoner 2:3-15.

Korhonen, H., K. S. Carslaw, and S. Romakkaniemi. 2010. Enhancement of marine cloud albedo via controlled sea spray injections: A global model study of the influence of emission rates, microphysics and transport. Atmospheric Chemistry and Physics 10(9):4133-4143. DOI: 10.5194/acp-10-4133-2010.

Kravitz, B., and A. Robock. 2011. Climate effects of high-latitude volcanic eruptions: Role of the time of year. Journal of Geophysical Research: Atmospheres 116(D1). DOI: 10.1029/2010jd014448.

Kravitz, B., A. Robock, L. Oman, G. Stenchikov, and A. B. Marquardt. 2009. Sulfuric acid deposition from stratospheric geoengineering with sulfate aerosols. Journal of Geophysical Research: Atmospheres 114(14). DOI: 10.1029/2009JD011918.

Kravitz, B., A. Robock, and A. Bourassa. 2010. Negligible climatic effects from the 2008 Okmok and Kasatochi volcanic eruptions. Journal of Geophysical Research: Atmospheres 115(D2). DOI: 10.1029/2009jd013525.

Kravitz, B., A. Robock, O. Boucher, H. Schmidt, K. E. Taylor, G. Stenchikov, and M. Schulz. 2011a. The Geoengineering Model Intercomparison Project (GeoMIP). Atmospheric Science Letters 12(2):162-167. DOI: 10.1002/Asl.316.

Kravitz, B., A. Robock, A. Bourassa, T. Deshler, D. C. Wu, I. Mattis, F. Finger, A. Hoffmann, C. Ritter, L. Bitar, T. J. Duck, and J. E. Barnes. 2011b. Simulation and observations of stratospheric aerosols from the 2009 Sarychev volcanic eruption. Journal of Geophysical Research: Atmospheres 116(D18). DOI: 10.1029/2010jd015501.

Kravitz, B., D. G. MacMartin, and K. Caldeira. 2012a. Geoengineering: Whiter skies? Geophysical Research Letters 39(11). DOI: 10.1029/2012GL051652.

Kravitz, B., A. Robock, D. T. Shindell, and M. A. Miller. 2012b. Sensitivity of stratospheric geoengineering with black carbon to aerosol size and altitude of injection. Journal of Geophysical Research: Atmospheres 117(D9). DOI: 10.1029/2011jd017341.

Kravitz, B., K. Caldeira, O. Boucher, A. Robock, P. J. Rasch, K. Alterskjær, D. B. Karam, J. N. S. Cole, C. L. Curry, J. M. Haywood, P. J. Irvine, D. Ji, A. Jones, J. E. Kristjánsson, D. J. Lunt, J. C. Moore, U. Niemeier, H. Schmidt, M. Schulz, B. Singh, S. Tilmes, S. Watanabe, S. Yang, and J.-H. Yoon. 2013a. Climate model response from the Geoengineering Model Intercomparison Project (GeoMIP). Journal of Geophysical Research: Atmospheres 118(15):8320-8332. DOI: 10.1002/jgrd.50646.

Kravitz, B., P. J. Rasch, P. M. Forster, T. Andrews, J. N. S. Cole, P. J. Irvine, D. Ji, J. E. Kristjánsson, J. C. Moore, H. Muri, U. Niemeier, A. Robock, B. Singh, S. Tilmes, S. Watanabe, and J.-H. Yoon. 2013b. An energetic perspective on hydrological cycle changes in the Geoengineering Model Intercomparison Project. Journal of Geophysical Research: Atmospheres 118(23):13087-13102. DOI: 10.1002/2013JD020502.

Kravitz, B., D. G. MacMartin, A. Robock, P. J. Rasch, K. L. Ricke, J. N. S. Cole, C. L. Curry, P. J. Irvine, D. Ji, D. W. Keith, J. E. Kristjánsson, J. C. Moore, H. Muri, B. Singh, S. Tilmes, S. Watanabe, S. Yang, and J.-H. Yoon. 2014. A multi-model assessment of regional climate disparities caused by solar geoengineering. Environmental Research Letters 9(7).

Kubar, T. L., D. L. Hartmann, and R. Wood. 2007. Radiative and convective driving of tropical high clouds. Journal of Climate 20(22):5510-5526. DOI: 10.1175/2007jcli1628.1.

Kuebbeler, M., U. Lohmann, and J. Feichter. 2012. Effects of stratospheric sulfate aerosol geo-engineering on cirrus clouds. Geophysical Research Letters 39(23). DOI: 10.1029/2012gl053797.

Kuhn, P. M. 1970. Airborne observations of contrail effects on thermal radiation budget. Journal of the Atmospheric Sciences 27(6):937-942. DOI: 10.1175/1520-0469(1970)027<0937:Aooceo>2.0.Co;2.

Lane, D. E., R. C. Somerville, and S. F. Iacobellis. 2000. Sensitivity of cloud and radiation parametrizations to changes in vertical resolution. Journal of Climate 13:915-922.

Latham, J. 1990. Control of global warming. Nature 347(6291):339-340. DOI: 10.1038/347339b0.

Latham, J. 2002. Amelioration of global warming by controlled enhancement of the albedo and longevity of low-level maritime clouds. Atmospheric Science Letters 3(2-4):59-70. DOI: 10.1006/asle.2002.0048.

Latham, J., P. Rasch, C. C. Chen, L. Kettles, A. Gadian, A. Gettelman, H. Morrison, K. Bower, and T. Choularton. 2008. Global temperature stabilization via controlled albedo enhancement of low-level maritime clouds. Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences 366(1882):3969-3987. DOI: 10.1098/rsta.2008.0137.

Latham, J., K. Bower, T. Choularton, H. Coe, P. Connolly, G. Cooper, T. Craft, J. Foster, A. Gadian, L. Galbraith, H. Iacovides, D. Johnston, B. Launder, B. Leslie, J. Meyer, A. Neukermans, B. Ormond, B. Parkes, P. Rasch, J. Rush, S. Salter, T. Stevenson, H. Wang, Q. Wang, and R. Wood. 2012. Marine cloud brightening. Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences 370(1974):4217-4262. DOI: 10.1098/rsta.2012.0086.

Le Quéré, C., R. J. Andres, T. Boden, T. Conway, R. A. Houghton, J. I. House, G. Marland, G. P. Peters, G. R. v. d. Werf, A. Ahlström, R. M. Andrew, L. Bopp, J. G. Canadell, P. Ciais, S. C. Doney, C. Enright, P. Friedlingstein, C. Huntingford, A. K. Jain, J. Jourdain, E. Kato, R. F. Keeling, K. Klein Goldewijk, S. Levis, P. Levy, M. Lomas, B. Poulter, M. R. Raupach, J. Schwinger, S. Sitch, B. D. Stocker, N. Viovy, S. Zaehle, and N. Zeng. 2013. The global carbon budget 1959-2011. Earth System Science Data 5:165-185. DOI: 10.5194/essd-5-165-2013.

Leaitch, W. R., G. A. Isaac, J. W. Strapp, C. M. Banic, and H. A. Wiebe. 1992. The relationship between cloud droplet number concentrations and anthropogenic pollution: Observations and climatic implications. Journal of Geophysical Research: Atmospheres 97(D2):2463-2474.

Leaitch, W. R., U. Lohmann, L. M. Russell, T. Garrett, N. C. Shantz, D. Toom-Sauntry, J. W. Strapp, K. L. Hayden, J. Marshall, M. Wolde, D. R. Worsnop, and J. T. Jayne. 2010. Cloud albedo increase from carbonaceous aerosol. Atmospheric Chemistry and Physics 10(16):7669-7684. DOI: 10.5194/acp-10-7669-2010.

Lee, D. S., D. W. Fahey, P. M. Forster, P. J. Newton, R. C. N. Wit, L. L. Lim, B. Owen, and R. Sausen. 2009. Aviation and global climate change in the 21st century. Atmospheric Environment 43(22-23):3520-3537. DOI: 10.1016/j.atmosenv.2009.04.024.

Lenton, T. M., and N. E. Vaughan. 2009. The radiative forcing potential of different climate geoengineering options. Atmospheric Chemistry and Physics 9(15):5539-5561. DOI: 10.1029/2005GB002591.

Lin, A. C. 2013a. International legal regimes and principles relevant to geoengineering. In Climate Change Geoengineering: Philosophical Perspectives, Legal Issues, and Governance Frameworks. W. C. G. Burns and A. L. Strauss, eds. Cambridge, UK: Cambridge University Press.

Lin, A. C. 2013b. Does geoengineering present a moral hazard? Ecology Law Quarterly 40:673-712.

Liou, K. N. 1986. Influence of cirrus clouds on weather and climate processes: A global perspective. Monthly Weather Review 114(6):1167-1199. DOI: 10.1175/1520-0493(1986)114<1167:Ioccow>2.0.Co;2.

Liu, X., and J. E. Penner. 2002. Effect of Mount Pinatubo H_2SO_4/H_2O aerosol on ice nucleation in the upper troposphere using a global chemistry and transport model. Journal of Geophysical Research: Atmospheres 107(D12):AAC 2-1-AAC 2-18. DOI: 10.1029/2001JD000455.

Llanillo, P., P. D. Jones, and R. Von Glasow. 2010. The influence of stratospheric sulphate aerosol deployment on the surface air temperature and the risk of an abrupt global warming. Atmosphere 1(1):62-84. DOI: 10.3390/atmos1010062.

Lobell, D. B., and C. B. Field. 2007. Global scale climate: Crop yield relationships and the impacts of recent warming. Environmental Research Letters 2(1). DOI: 10.1088/1748-9326/2/1/014002.

Loeb, N. G., B. A. Wielicki, D. R. Doelling, G. L. Smith, D. F. Keyes, S. Kato, N. Manalo-Smith, and T. Wong. 2009. Toward optimal closure of the Earth's top-of-atmosphere radiation budget. Journal of Climate 22:748-766. DOI: 10.1175/2008JCLI2637.1.

Loeb, N. G., S. Kato, W. Y. Su, T. M. Wong, F. G. Rose, D. R. Doelling, J. R. Norris, and X. L. Huang. 2012. Advances in understanding top-of-atmosphere radiation variability from satellite observations. Surveys in Geophysics 33(3-4):359-385. DOI: 10.1007/s10712-012-9175-1.

Long, J. C. S., and D. Scott. 2013. Vested interests and geoengineering research. Issues in Science and Technology 29(3):45-52.

Long, J. C. S., F. Loy, and M. G. Morgan. 2015. Start research on climate engineering. Nature 518:29-31.

Lu, M. L., and J. H. Seinfeld. 2006. Effect of aerosol number concentration on cloud droplet dispersion: A large-eddy simulation study and implications for aerosol indirect forcing. Journal of Geophysical Research: Atmospheres 111(D2). DOI: 10.1029/2005jd006419.

Lu, M. L., W. C. Conant, H. H. Jonsson, V. Varutbangkul, R. C. Flagan, and J. H. Seinfeld. 2007. The Marine Stratus/Stratocumulus Experiment (MASE): Aerosol-cloud relationships in marine stratocumulus. Journal of Geophysical Research: Atmospheres 112(D10). DOI: 10.1029/2006jd007985.

Lu, M. L., A. Sorooshian, H. H. Jonsson, G. Feingold, R. C. Flagan, and J. H. Seinfeld. 2009. Marine stratocumulus aerosol-cloud relationships in the MASE-II experiment: Precipitation susceptibility in eastern Pacific marine stratocumulus. Journal of Geophysical Research: Atmospheres 114(D24). DOI: 10.1029/2009jd012774.

Luo, M., J. M. Russell, and T. Y. W. Huang. 1997. Halogen Occultation Experiment observations of the quasi-biennial oscillation and the effects of Pinatubo aerosols in the tropical stratosphere. Journal of Geophysical Research: Atmospheres 102(D15):19187-19198. DOI: 10.1029/97jd01015.

MacMartin, D. G., K. Caldeira, and D. W. Keith. 2014. Solar geoengineering to limit the rate of temperature change. Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences 372(2031).

MacMynowski, D. G., D. W. Keith, K. Caldeira, and H. J. Shin. 2011. Can we test geoengineering? Energy and Environmental Science 4(12):5044-5052. DOI: 10.1039/c1ee01256h.

Mann, M. E., J. D. Fuentes, and S. Rutherford. 2012. Underestimation of volcanic cooling in tree-ring-based reconstructions of hemispheric temperatures. Nature Geoscience 5(3):202-205. DOI: 10.1038/Ngeo1394.

Martin, G. M., D. W. Johnson, and A. Spice. 1994. The measurement and parameterization of effective radius of droplets in warm stratocumulus clouds. Journal of the Atmospheric Sciences 51(13):1823-1842. DOI: 10.1175/1520-0469(1994)051<1823:Tmapoe>2.0.Co;2.

Matthews, H. D., and K. Caldeira. 2007. Transient climate-carbon simulations of planetary geoengineering. Proceedings of the National Academy of Sciences of the United States of America 104(24):9949-9954. DOI: 10.1073/pnas.0700419104.

Matthews, H. D., L. Cao, and K. Caldeira. 2009. Sensitivity of ocean acidification to geoengineered climate stabilization. Geophysical Research Letters 36(10). DOI: 10.1029/2009GL037488.

McClellan, J., D. Keith, and J. Apt. 2012. Cost analysis of stratospheric albedo modification delivery systems. Environmental Research Letters 7(3). DOI: 10.1088/1748-9326/7/3/034019.

McCusker, K. E., K. C. Armour, C. M. Bitz, and D. S. Battisti. 2014. Rapid and extensive warming following cessation of solar radiation management. Environmental Research Letters 9(2). DOI: 10.1088/1748-9326/9/2/024005.

Mcinnes, C. R. 2002. Minimum mass solar shield for terrestrial climate control. JBIS, Journal of the British Interplanetary Society 55(9-10):307-311.

McKenzie, R. L., P. J. Aucamp, A. F. Bais, L. O. Bjorn, M. Ilyas, and S. Madronich. 2011. Ozone depletion and climate change: Impacts on UV radiation. Photochemical & Photobiological Sciences 10(2):182-198. DOI: 10.1039/C0pp90034f.

Mercado, L. M., N. Bellouin, S. Sitch, O. Boucher, C. Huntingford, M. Wild, and P. M. Cox. 2009. Impact of changes in diffuse radiation on the global land carbon sink. Nature 458(7241):1014-U1087. DOI: 10.1038/Nature07949.

Miami-Dade County. 2010. Climate Change Action Plan. Miami, FL: Miami-Dade County Board of County Commissioners.

Miller, G. H., A. Geirsdottir, Y. F. Zhong, D. J. Larsen, B. L. Otto-Bliesner, M. M. Holland, D. A. Bailey, K. A. Refsnider, S. J. Lehman, J. R. Southon, C. Anderson, H. Bjornsson, and T. Thordarson. 2012. Abrupt onset of the Little Ice Age triggered by volcanism and sustained by sea-ice/ocean feedbacks. Geophysical Research Letters 39(2). DOI: 10.1029/2011gl050168.

Miller, T. P., and T. J. Casadevall. 2000. Volcanic ash hazards to aviation. In Encyclopedia of Volcanoes. H. Sigurdsson, ed. San Diego, CA: Academic Press.

Minnis, P., E. F. Harrison, L. L. Stowe, G. G. Gibson, F. M. Denn, D. R. Doelling, and W. L. Smith. 1993. Radiative climate forcing by the Mount Pinatubo eruption. Science 259(5100):1411-1415. DOI: 10.1126/science.259.5100.1411.

Mitchell, D. L., and W. Finnegan. 2009. Modification of cirrus clouds to reduce global warming. Environmental Research Letters 4(4). DOI: 10.1088/1748-9326/4/4/045102.

Mitchell, D. L., S. Mishra, and R. P. Lawson. 2011. Cirrus clouds and climate engineering: New findings on ice nucleation and theoretical basis. In Planet Earth 2011: Global Warming Challenges and Opportunities for Policy and Practice. E. G. Caravanni, ed. Rijeka, Croatia: InTech.

Modini, R. L., A. A. Frossard, L. Ahlm, L. M. Russell, C. E. Corrigan, G. C. Roberts, L. N. Hawkins, J. C. Schroder, A. K. Bertram, R. Zhao, A. K. Y. Lee, J. P. D. Abbatt, J. Lin, A. Nenes, Z. Wang, A. Wonaschütz, A. Sorooshian, K. J. Noone, H. Jonsson, J. H. Seinfeld, D. Toom-Sauntry, A. M. Macdonald, and W. R. Leaitch. 2014. Sea-spray-aerosol-cloud interactions off the coast of California. Journal of Geophysical Research (submitted).

Moreno-Cruz, J. B., K. L. Ricke, and D. W. Keith. 2012. A simple model to account for regional inequalities in the effectiveness of solar radiation management. Climatic Change 110(3-4):649-668. DOI: 10.1007/s10584-011-0103-z.

Morgan, M. G., and K. Ricke. 2010. Cooling the Earth Through Solar Radiation Management: Need for Research and an Approach to Its Governance. Opinion piece for the International Risk Governance Council (IRGC). Carnegie Mellon University, Pittsburgh, PA.

Morgan, M. G., R. R. Nordhaus, and P. Gottlieb. 2013. Needed: Research guidelines for solar radiation management. Issues in Science and Technology 29(3):37-44.

Morrison, A. E., S. T. Siems, M. J. Manton, and A. Nazarov. 2009. On the analysis of a cloud seeding dataset over Tasmania. Journal of Applied Meteorology and Climatology 48(6):1267-1280. DOI: 10.1175/2008jamc2068.1.

Muthers, S., J. G. Anet, C. C. Raible, S. Bronnimann, E. Rozanov, F. Arfeuille, T. Peter, A. I. Shapiro, J. Beer, F. Steinhilber, Y. Brugnara, and W. Schmutz. 2014. Northern hemispheric winter warming pattern after tropical volcanic eruptions: Sensitivity to the ozone climatology. Journal of Geophysical Research: Atmospheres 119(3):1340-1355. DOI: 10.1002/2013jd020138.

Naik, V., D. J. Wuebbles, E. H. Delucia, and J. A. Foley. 2003. Influence of geoengineered climate on the terrestrial biosphere. Environmental Management 32(3):373-381. DOI: 10.1007/s00267-003-2993-7.

NCA (National Climate Assessment). 2014. National Climate Assessment. Washington, DC: U.S. Global Change Research Program.

Neukermans, A., G. Cooper, J. Foster, A. Gadian, L. Galbraith, S. Jain, J. Latham, and B. Ormond. 2014. Sub-micrometer salt aerosol production intended for marine cloud brightening. Atmospheric Research 142:158-170. DOI: 10.1016/j.atmosres.2013.10.025.

Niemeier, U., H. Schmidt, and C. Timmreck. 2011. The dependency of geoengineered sulfate aerosol on the emission strategy. Atmospheric Science Letters 12(2):189-194. DOI: 10.1002/asl.304.

Noone, K. J., D. W. Johnson, J. P. Taylor, R. J. Ferek, T. Garrett, P. V. Hobbs, P. A. Durkee, K. Nielsen, E. Ostrom, C. O'Dowd, M. H. Smith, L. M. Russell, R. C. Flagan, J. H. Seinfeld, L. De Bock, R. E. Van Grieken, J. G. Hudson, I. Brooks, R. F. Gasparovic, and R. A. Pockalny. 2000a. A case study of ship track formation in a polluted marine boundary layer. Journal of the Atmospheric Sciences 57(16):2748-2764. DOI: 10.1175/1520-0469(2000)057<2748:Acsost>2.0.Co;2.

Noone, K. J., E. Ostrom, R. J. Ferek, T. Garrett, P. V. Hobbs, D. W. Johnson, J. P. Taylor, L. M. Russell, R. C. Flagan, J. H. Seinfeld, C. D. O'Dowd, M. H. Smith, P. A. Durkee, K. Nielsen, J. G. Hudson, R. A. Pockalny, L. De Bock, R. E. Van Grieken, R. F. Gasparovic, and I. Brooks. 2000b. A case study of ships forming and not forming tracks in moderately polluted clouds. Journal of the Atmospheric Sciences 57(16):2729-2747. DOI: 10.1175/1520-0469(2000)057<2729:Acsosf>2.0.Co;2.

NRC (National Research Council). 1973. Weather and Climate Modification: Problems and Progress. Washington, DC: National Academy Press.

NRC. 1985. The Effects on the Atmosphere of a Major Nuclear Exchange. Washington, DC: National Academy Press.

NRC. 1992. Policy Implications of Greenhouse Warming: Mitigation, Adaptation, and the Science Base. Washington, DC: National Academy Press.

NRC. 2003. Critical Issues in Weather Modification Research. Washington, DC: The National Academies Press.

NRC. 2010a. Adapting to the Impacts of Climate Change. Washington, DC: The National Academies Press.

NRC. 2010b. Limiting the Magnitude of Future Climate Change. Washington, DC: The National Academies Press.

NRC. 2010c. Advancing the Science of Climate Change. Washington, DC: The National Academies Press.

NRC. 2011a. Climate Stabilization Targets: Emissions, Concentrations, and Impacts over Decades to Millennia. Washington, DC: The National Academies Press.

NRC. 2011b. America's Climate Choices. Washington, DC: The National Academies Press.

NRC. 2012a. Disaster Resilience: A National Imperative. Washington, DC: The National Academies Press.

NRC. 2012b. Sea-Level Rise for the Coasts of California, Oregon, and Washington: Past, Present, and Future. Washington, DC: The National Academies Press.

NRC. 2013a. Abrupt Impacts of Climate Change: Anticipating Surprises. Washington, DC: The National Academies Press.

NRC. 2013b. Review of the Federal Ocean Acidification Research and Monitoring Plan. Washington, DC: The National Academies Press.

NSF (National Science Foundation). 1966. Weather and Climate Modification. Report of the Special Commission on Weather Modification. NSF 66-3. NSF, Washington, DC.

Olson, R. L. 2012. Soft geoengineering: A gentler approach to addressing climate change. Environment 54(5):29-39. DOI: 10.1080/00139157.2012.711672.

Oppenheimer, C. 2003. Climatic, environmental and human consequences of the largest known historic eruption: Tambora volcano (Indonesia) 1815. Progress in Physical Geography 27(2):230-259. DOI: 10.1191/0309133303pp379ra.

Oreopoulos, L., and S. Platnick. 2008. Radiative susceptibility of cloudy atmospheres to droplet number perturbations: 2. Global analysis from MODIS. Journal of Geophysical Research: Atmospheres 113(D14). DOI: 10.1029/2007jd009655.

Parker, G. 2013. Global Crisis: War, Climate Change and Catastrophe in the Seventeenth Century. New Haven, CT: Yale University Press.

Parmesan, C. 2006. Ecological and evolutionary responses to recent climate change. Annual Review of Ecology, Evolution and Systematics 37:637-639.

Parmesan, C., and G. Yohe. 2003. A globally coherent fingerprint of climate change across natural systems. Nature 421:37-42.

Parson, E. A., and L. N. Ernst. 2013. International Governance of Climate Engineering. Public Law and Legal Research Paper Series Paper 12-23. UCLA School of Law, Los Angeles, CA.

Parson, E. A., and D. W. Keith. 2013. End the deadlock on governance of geoengineering research. Science 339(6125):1278-1279. DOI: 10.1126/science.1232527.

Partanen, A. I., H. Kokkola, S. Romakkaniemi, V. M. Kerminen, K. E. J. Lehtinen, T. Bergman, A. Arola, and H. Korhonen. 2012. Direct and indirect effects of sea spray geoengineering and the role of injected particle size. Journal of Geophysical Research: Atmospheres 117(D2). DOI: 10.1029/2011JD016428.

Pearson, J., J. Oldson, and E. Levin. 2006. Earth rings for planetary environment control. Acta Astronautica 58(1):44-57. DOI: 10.1016/j.actaastro.2005.03.071.

Penner, J. E., M. Andreae, H. Annegarn, L. Barrie, J. Feichter, D. Hegg, A. Jayaraman, R. Leaitch, D. Murphy, J. Nganga, and G. Pitari. 2001. Aerosols, their direct and indirect effects. In Climate Change 2001: The Scientific Basis. Report of Working Group I to the Intergovernmental Panel on Climate Change. J. T. Houghton, Y. Ding, D. J. Griggs, M. Noguer, P.J. van der Linden, X. Dai, K. Maskell, and C. A. Johnson, eds. Cambridge, UK: Cambridge University Press.

Peter, T., and J.-U. Grooß. 2012. Polar Stratospheric Clouds and Sulfate Aerosol Particles: Microphysics, Denitrification and Heterogeneous Chemistry in Stratospheric Ozone Depletion and Climate Change. R. Muller, ed. London: Royal Society of Chemistry.

Peters, K., J. Quaas, and H. Grassl. 2011. A search for large-scale effects of ship emissions on clouds and radiation in satellite data. Journal of Geophysical Research: Atmospheres 116(D24). DOI: 10.1029/2011jd016531.

Peters, K., J. Quaas, P. Stier, and H. Graßl. 2014. Processes limiting the emergence of detectable aerosol indirect effects on tropical warm clouds in global aerosol-climate model and satellite data. Tellus, Series B: Chemical and Physical Meteorology 33:24054.

Petters, M. D., J. R. Snider, B. Stevens, G. Vali, I. Faloona, and L. M. Russell. 2006. Accumulation mode aerosol, pockets of open cells, and particle nucleation in the remote subtropical Pacific marine boundary layer. Journal of Geophysical Research: Atmospheres 111(D2). DOI: 10.1029/2004jd005694.

Pidgeon, N., K. Parkhill, A. Corner, and N. Vaughan. 2013. Deliberating stratospheric aerosols for climate geoengineering and the SPICE project. Nature Climate Change 3(5):451-457. DOI: 10.1038/Nclimate1807.

Pierce, J. R., D. K. Weisenstein, P. Heckendorn, T. Peter, and D. W. Keith. 2010. Efficient formation of stratospheric aerosol for climate engineering by emission of condensible vapor from aircraft. Geophysical Research Letters 37(18). DOI: 10.1029/2010GL043975.

Pierrehumbert, R. T. 2002. The hydrologic cycle in deep-time climate problems. Nature 419(6903):191-198. DOI: 10.1038/Nature01088.

Pierrehumbert, R. T. 2010. Principles of planetary climate. Cambridge, UK: Cambridge University Press.

Pierrehumbert, R. T. 2014. Short-lived climate pollution. Annual Reviews of Earth and Planetary Sciences 42(341-379). DOI: 10.1146/annurev-earth-060313-054843.

Pimm, S. L. 2009. Climate disruption and biodiversity. Current Biology 19(14):R595-R601. DOI: 10.1016/j.cub.2009.05.055.

Pitari, G., V. Aquila, B. Kravitz, A. Robock, S. Watanabe, I. Cionni, N. De Luca, G. Di Genova, E. Mancini, and S. Tilmes. 2014. Stratospheric ozone response to sulfate geoengineering: Results from the Geoengineering Model Intercomparison Project (GeoMIP). Journal of Geophysical Research: Atmospheres 119(5):2629-2653. DOI: 10.1002/2013jd020566.

Pittman, J. V., E. M. Weinstock, R. J. Oglesby, D. S. Sayres, J. B. Smith, J. G. Anderson, O. R. Cooper, S. C. Wofsy, I. Xueref, C. Gerbig, B. C. Daube, E. C. Richard, B. A. Ridley, A. J. Weinheimer, M. Loewenstein, H. J. Jost, J. P. Lopez, M. J. Mahoney, T. L. Thompson, W. W. Hargrove, and F. M. Hoffman. 2007. Transport in the subtropical lowermost stratosphere during the Cirrus Regional Study of Tropical Anvils and Cirrus Layers-Florida Area Cirrus Experiment. Journal of Geophysical Research: Atmospheres 112(D8). DOI: 10.1029/2006jd007851.

PlaNYC. 2013. A Stronger, More Resilient New York. New York: Office of the Mayor.

Poloczanska, E. S., C. J. Brown, W. J. Sydeman, W. Kiessling, D. S. Schoeman, P. J. Moore, K. Brander, J. F. Bruno, L. B. Buckley, M. T. Burrows, C. M. Duarte, B. S. Halpern, J. Holding, C. V. Kappel, M. I. O'Connor, J. M. Pandolfi, C. Parmesan, F. Schwing, S. A. Thompson, and A. J. Richardson. 2013. Global imprint of climate change on marine life. Nature Climate Change 3:919-925. DOI: 10.1038/nclimate1958.

Pongratz, J., D. B. Lobell, L. Cao, and K. Caldeira. 2012. Crop yields in a geoengineered climate. Nature Climate Change 2(2):101-105. DOI: 10.1038/Nclimate1373.

Preston, C. J. 2012. Engineering the Climate: The Ethics of Solar Radiation Management. Lanham, MD: Lexington Books.

Pruppacher, H. R., and J. D. Klett. 1997. Microphysics of Clouds and Precipitation. Dordrecht, Netherlands: Kluwer Academic Publishers.

PSAC (President's Science Advisory Committee). 1965. Restoring the Quality of Our Environment. Report of the Environmental Pollution Panel, PSAC. Washington, DC: U.S. Government Printing Office.

Quinn, P. K., T. S. Bates, K. S. Schulz, D. J. Coffman, A. A. Frossard, L. M. Russell, W. C. Keene, and D. J. Kieber. 2014. Contribution of sea surface carbon pool to organic matter enrichment in sea spray aerosol. Nature Geoscience 7(3):228-232. DOI: 10.1038/Ngeo2092.

Rasch, P. J., P. J. Crutzen, and D. B. Coleman. 2008a. Exploring the geoengineering of climate using stratospheric sulfate aerosols: The role of particle size. Geophysical Research Letters 35(2). DOI: 10.1029/2007GL032179.

Rasch, P. J., S. Tilmes, R. P. Turco, A. Robock, L. Oman, C. C. Chen, G. L. Stenchikov, and R. R. Garcia. 2008b. An overview of geoengineering of climate using stratospheric sulphate aerosols. Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences 366(1882):4007-4037. DOI: 10.1098/rsta.2008.0131.

Rasch, P. J., J. Latham, and C. C. Chen. 2009. Geoengineering by cloud seeding: Influence on sea ice and climate system. Environmental Research Letters 4(4). DOI: 10.1088/1748-9326/4/4/045112.

Rayner, S., C. Heyward, T. Kruger, N. Pidgeon, C. Redgwell, and J. Savulescu. 2013. The Oxford Principles. Climatic Change 121(3):499-512. DOI: 10.1007/s10584-012-0675-2.

RCEP (Royal Commission on Environmental Pollution). 2008. Novel Materials in the Environment: The Case of Nanotechnology. Royal Commission on Environmental Pollution, London.

Read, W. G., L. Froidevaux, and J. W. Waters. 1993. Microwave limb sounder measurements of stratospheric SO_2 from the Mt. Pinatubo eruption. Geophysical Research Letters 20:1299-1302. DOI: 10.1029/93GL00831.

Reynolds, J. 2014. The international regulation of climate engineering: Lessons from nuclear power. Journal of Environmental Law 26(2):269-289. DOI: 10.1093/Jel/Equ006.

Ricke, K. L., M. G. Morgan, and M. R. Allen. 2010. Regional climate response to solar-radiation management. Nature Geoscience 3(8):537-541. DOI: 10.1038/ngeo915.

Ricke, K. L., D. J. Rowlands, W. J. Ingram, D. W. Keith, and M. Granger Morgan. 2012. Effectiveness of stratospheric solar-radiation management as a function of climate sensitivity. Nature Climate Change 2(2):92-96. DOI: 10.1038/nclimate1328.

Ricke, K. L., J. B. Moreno-Cruz, and K. Caldeira. 2013. Strategic incentives for climate geoengineering coalitions to exclude broad participation. Environmental Research Letters 8(1). DOI: 10.1088/1748-9326/8/1/014021.

Ridgwell, A., J. S. Singarayer, A. M. Hetherington, and P. J. Valdes. 2009. Tackling regional climate change by leaf albedo biogeoengineering. Current Biology 19(2):146-150. DOI: 10.1016/j.cub.2008.12.025.

Robock, A. 2008. 20 reasons why geoengineering may be a bad idea. Bulletin of the Atomic Scientists 64(2):14-18.

Robock, A. 2012. Is geoengineering research ethical? Peace and Security 4(226-229).

Robock, A. 2014. Stratospheric aerosol geoengineering. Issues in Environmental Science and Technology 38:162-185.

Robock, A., and J. P. Mao. 1992. Winter warming from large volcanic eruptions. Geophysical Research Letters 19(24):2405-2408. DOI: 10.1029/92gl02627.

Robock, A., and O. B. Toon. 2010. Local nuclear war, global suffering. Scientific American 302(1):74-81.

Robock, A., L. Oman, and G. L. Stenchikov. 2008. Regional climate responses to geoengineering with tropical and Arctic SO_2 injections. Journal of Geophysical Research: Atmospheres 113(D16). DOI: 10.1029/2008JD010050.

Robock, A., C. M. Ammann, L. Oman, D. Shindell, S. Levis, and G. Stenchikov. 2009a. Did the Toba volcanic eruption of ~74 ka BP produce widespread glaciation? Journal of Geophysical Research: Atmospheres 114(D10). DOI: 10.1029/2008jd011652.

Robock, A., A. Marquardt, B. Kravitz, and G. Stenchikov. 2009b. Benefits, risks, and costs of stratospheric geoengineering. Geophysical Research Letters 36(19). DOI: 10.1029/2009GL039209.

Robock, A., M. Bunzl, B. Kravitz, and G. L. Stenchikov. 2010. A test for geoengineering? Science 327(5965):530-531. DOI: 10.1126/science.1186237.

Robock, A., D. G. MacMartin, R. Duren, and M. W. Christensen. 2013. Studying geoengineering with natural and anthropogenic analogs. Climatic Change 121:445-458.

Roderick, M. L., G. D. Farquhar, S. L. Berry, and I. R. Noble. 2001. On the direct effect of clouds and atmospheric particles on the productivity and structure of vegetation. Oecologia 129(1):21-30. DOI: 10.1007/s004420100760.

Roeckner, E., R. Brokopf, M. Esch, M. Giorgetta, S. Hagemann, L. Kornblueh, E. Manzini, U. Schlese, and U. Schulzweida. 2006. Sensitivity of simulated climate to horizontal and vertical resolution in the ECHAM5 atmosphere model. Journal of Climate 19(16):3771-3791. DOI: 10.1175/Jcli3824.1.

Rogers, H. W., M. A. Weinstock, A. R. Harris, M. R. Hinckley, S. R. Feldman, A. B. Fleischer, and B. M. Coldiron. 2010. Incidence estimate of nonmelanoma skin cancer in the United States, 2006. Archives of Dermatology 146(3):283-287.

Root, T. L., J. T. Price, K. R. Hall, S. H. Schneider, C. Rosenzweig, and J. A. Pounds. 2003. Fingerprints of global warming on wild animals and plants. Nature 421:57-60.

Rosenfeld, D., R. Wood, L. J. Donner, and S. C. Sherwood. 2013. Aerosol cloud-mediated radiative forcing: Highly uncertain and opposite effects from shallow and deep clouds. In Climate Science for Serving Society. G. R. Asrar and J. W. Hurrell, eds. Dordrecht, Netherlands: Springer.

Rosenzweig, C., J. Elliott, D. Deryng, A. C. Ruane, C. Muller, A. Arneth, K. J. Boote, C. Folberth, M. Glotter, N. Khabarov, K. Neumann, F. Piontek, T. A. M. Pugh, E. Schmid, E. Stehfest, H. Yang, and J. W. Jones. 2014. Assessing agricultural risks of climate change in the 21st century in a global gridded crop model intercomparison. Proceedings of the National Academy of Sciences of the United States of America 111(9):3268-3273. DOI: 10.1073/pnas.1222463110.

The Royal Society. 2009. Geoengineering the Climate: Science, Governance and Uncertainty. London: The Royal Society.

Russell, L. M., J. H. Seinfeld, R. C. Flagan, R. J. Ferek, D. A. Hegg, P. V. Hobbs, W. Wobrock, A. I. Flossmann, C. D. O'Dowd, K. E. Nielsen, and P. A. Durkee. 1999. Aerosol dynamics in ship tracks. Journal of Geophysical Research: Atmospheres 104(D24):31077-31095. DOI: 10.1029/1999jd900985.

Russell, L. M., P. J. Rasch, G. M. Mace, R. B. Jackson, J. Shepherd, P. Liss, M. Leinen, D. Schimel, N. E. Vaughan, A. C. Janetos, P. W. Boyd, R. J. Norby, K. Caldeira, J. Merikanto, P. Artaxo, J. Melillo, and M. G. Morgan. 2012. Ecosystem impacts of geoengineering: A review for developing a science plan. Ambio 41(4):350-369. DOI: 10.1007/s13280-012-0258-5.

Russell, L. M., A. Sorooshian, J. H. Seinfeld, B. A. Albrecht, A. Nenes, L. Ahlm, Y.-C. Chen, M. Coggon, J. S. Craven, R. C. Flagan, A. A. Frossard, H. Jonsson, E. Jung, J. J. Lin, A. R. Metcalf, R. Modini, J. Mülmenstädt, G. C. Roberts, T. Shingler, S. Song, Z. Wang, and A. Wonaschütz. 2013. Eastern Pacific Emitted Aerosol Cloud Experiment (E-PEACE). Bulletin of the American Meterological Society 94:709-729.

Russell, P. B., J. M. Livingston, R. F. Pueschel, J. J. Bauman, J. B. Pollack, S. L. Brooks, P. Hamill, L. W. Thomason, L. L. Stowe, T. Deshler, E. G. Dutton, and R. W. Bergstrom. 1996. Global to microscale evolution of the Pinatubo volcanic aerosol derived from diverse measurements and analyses. Journal of Geophysical Research: Atmospheres 101(D13):18745-18763. DOI: 10.1029/96jd01162.

Salawitch, R. J., D. K. Weisenstein, L. J. Kovalenko, C. E. Sioris, P. O. Wennberg, K. Chance, M. K. W. Ko, and C. A. McLinden. 2005. Sensitivity of ozone to bromine in the lower stratosphere. Geophysical Research Letters 32(5). DOI: 10.1029/2004gl021504.

Salter, S., G. Sortino, and J. Latham. 2008. Sea-going hardware for the cloud albedo method of reversing global warming. Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences 366(1882):3989-4006. DOI: 10.1098/rsta.2008.0136.

Sandu, I., B. Stevens, and R. Pincus. 2010. On the transitions in marine boundary layer cloudiness. Atmospheric Chemistry and Physics 10(5):2377-2391.

Sayres, D. S., L. Pfister, T. F. Hanisco, E. J. Moyer, J. B. Smith, J. M. St Clair, A. S. O'Brien, M. F. Witinski, M. Legg, and J. G. Anderson. 2010. Influence of convection on the water isotopic composition of the tropical tropopause layer and tropical stratosphere. Journal of Geophysical Research: Atmospheres 115(D10). DOI: 10.1029/2009jd013100.

Schelling, T. C. 1996. The economic diplomacy of geoengineering. Climatic Change 33(3):303-307. DOI: 10.1007/bf00142578.

Schneider, S. H. 1996. Geoengineering: Could or should we do it? Climatic Change 33(3):291-302. DOI: 10.1007/bf00142577.

Schroder, J. C., S. J. Hanna, R. L. Modini, A. L. Corrigan, A. M. Macdonald, K. J. Noone, L. M. Russell, W. R. Leaitch, and A. K. Bertram. 2014. Size-resolved observations of refractory black carbon particles in cloud droplets at a marine boundary layer site. Atmopsheric Chemistry and Physics Discussion 14:11447-11491.

Schumann, U., and K. Graf. 2013. Aviation-induced cirrus and radiation changes at diurnal timescales. Journal of Geophysical Research: Atmospheres 118(5):2404-2421. DOI: 10.1002/Jgrd.50184.

Schwartz, M. J., W. G. Read, M. L. Santee, N. J. Livesey, L. Froidevaux, A. Lambert, and G. L. Manney. 2013. Convectively injected water vapor in the North American summer lowermost stratosphere. Geophysical Research Letters 40(10):2316-2321. DOI: 10.1002/Grl.50421.

Seidel, D. J., G. Feingold, A. R. Jacobson, and N. Loeb. 2014. Detection limits of albedo changes induced by climate engineering. Nature Climate Change 4:93-98.

Seinfeld, J. H., and S. N. Pandis. 2006. Atmospheric Chemistry and Physics: From Air Pollution to Climate Change. Hoboken, NJ: John Wiley.

Seitz, R. 2011. Bright water: Hydrosols, water conservation and climate change. Climatic Change 105(3-4):365-381. DOI: 10.1007/s10584-010-9965-8.

Sharon, T. M., B. A. Albrecht, H. H. Jonsson, P. Minnis, M. M. Khaiyer, T. M. van Reken, J. Seinfeld, and R. Flagan. 2006. Aerosol and cloud microphysical characteristics of rifts and gradients in maritime stratocumulus clouds. Journal of the Atmospheric Sciences 63(3):983-997. DOI: 10.1175/Jas3667.1.

Shepherd, J., and G. Morgan. 2011. SRMGI Background Paper: Thresholds and Categories. Working Paper of the Solar Radiation Management Governance Initiative Conference, Chicheley, UK. London: The Royal Society.

Shepherd, J., K. Caldeira, P. Cox, J. Haigh, D. Keith, B. Launder, G. Mace, G. MacKerron, J. Pyle, S. Rayner, C. Redgwell, and A. Watson. 2009. Geoengineering the Climate: Science, Governance and Uncertainty. London: The Royal Society.

Shi, Q., J. T. Jayne, C. E. Kolb, D. R. Worsnop, and P. Davidovits. 2001. Kinetic model for reaction of $ClONO_2$ with H_2O and HCl and HOCl with HCl in sulfuric acid solutions. Journal of Geophysical Research: Atmospheres 106(D20):24259-24274. DOI: 10.1029/2000jd000181.

Slingo, A. 1990. Sensitivity of the Earth's radiation budget to changes in low clouds. Nature 343:49-51.

Smil, V. 2010. Energy Transitions: History, Requirements, Prospects. Santa Barbara, CA: Praeger.

Smith, S. J., and P. J. Rasch. 2012. The long-term policy context for solar radiation management. Climatic Change 121(3):487-497. DOI: 10.1007/s10584-012-0577-3.

Soden, B. J., R. T. Wetherald, G. L. Stenchikov, and A. Robock. 2002. Global cooling after the eruption of Mount Pinatubo: A test of climate feedback by water vapor. Science 296(5568):727-730. DOI: 10.1126/science.296.5568.727.

Solomon, S. 1999. Stratospheric ozone depletion: A review of concepts and history. Reviews of Geophysics 37(3):275-316. DOI: 10.1029/1999rg900008.

Solomon, S., R. W. Portmann, R. R. Garcia, L. W. Thomason, L. R. Poole, and M. P. McCormick. 1996. The role of aerosol variations in anthropogenic ozone depletion at northern midlatitudes. Journal of Geophysical Research: Atmospheres 101(D3):6713-6727. DOI: 10.1029/95jd03353.

Solomon, S., G. K. Plattner, R. Knutti, and P. Friedlingstein. 2009. Irreversible climate change due to carbon dioxide emissions. Proceedings of the National Academy of Sciences of the United States of America 106(6):1704-1709. DOI: 10.1073/pnas.0812721106.

Sorooshian, A., M. L. Lu, F. J. Brechtel, H. Jonsson, G. Feingold, R. C. Flagan, and J. H. Seinfeld. 2007. On the source of organic acid aerosol layers above clouds. Environmental Science & Technology 41(13):4647-4654. DOI: 10.1021/Es0630442.

Sorooshian, A., G. Feingold, M. D. Lebsock, H. L. Jiang, and G. L. Stephens. 2009a. On the precipitation susceptibility of clouds to aerosol perturbations. Geophysical Research Letters 36(13). DOI: 10.1029/2009gl038993.

Sorooshian, A., L. T. Padro, A. Nenes, G. Feingold, A. McComiskey, S. P. Hersey, H. Gates, H. H. Jonsson, S. D. Miller, G. L. Stephens, R. C. Flagan, and J. H. Seinfeld. 2009b. On the link between ocean biota emissions, aerosol, and maritime clouds: Airborne, ground, and satellite measurements off the coast of California. Global Biogeochemical Cycles 23(4). DOI: 10.1029/2009gb003464.

Sorooshian, A., J. Csavina, T. Shingler, S. Dey, F. J. Brechtel, A. E. Saez, and E. A. Betterton. 2012. Hygroscopic and chemical properties of aerosols collected near a copper smelter: Implications for public and environmental health. Environmental Science & Technology 46(17):9473-9480. DOI: 10.1021/Es302275k.

SPARC (Stratospheric Processes and their Role in Climate). 2006. Assessment of Stratospheric Aerosol Properties. L. Thomason and T. Peter, eds. Zurich: World Climate Research Programme, Stratospheric Processes and their Role in Climate.

SRMGI (Solar Radiation Management Governance Initiative). 2013a. Solar Radiation Management: The Governance of Research. London: The Royal Society.

SRMGI. 2013b. Governance of Research on Solar Geoengineering: African Perspectives. Consolidated Report of three workshops in Senegal, South Africa, and Ethiopia. Nairobi: The African Academy of Sciences.

Stafford-Smith, M., and L. Russell. 2012. A resilience view on reframing geoengineering research and implementation. Carbon Management 3(1):23-25. DOI: 10.4155/cmt.11.71.

Standler, R. B. 2006. Weather modification law in the U.S.A.: Summary of court cases and principles of tort liability for cloud seeding, including both drought or flood alleedely caused by cloud seeding. Available at http://www.rbs2.com/weather.pdf, accessed March 17, 2015.

Staudinger, M. D., N. B. Grimm, A. Staudt, S. L. Carter, F. S. C. III, P. Kareiva, M. Ruckelshaus, and B. A. Stein. 2012. Impacts of Climate Change on Biodiversity, Ecosystems, and Ecosystem Services: Technical Input to the 2013 National Climate Assessment. Washington, DC: U.S. Global Change Research Program.

Stein, B. A., P. Glick, N. Edelson, and A. Staudt. 2014. Climate-Smart Conservation: Putting Adaptation Principles into Practice. Washington, DC: National Wildlife Federation.

Stenchikov, G., K. Hamilton, A. Robock, V. Ramaswamy, and M. D. Schwarzkopf. 2004. Arctic oscillation response to the 1991 Pinatubo eruption in the SKYHI general circulation model with a realistic quasi-biennial oscillation. Journal of Geophysical Research: Atmospheres 109(D3). DOI: 10.1029/2003jd003699.

Stephens, G. L. 2005. Cloud feedbacks in the climate system: A critical review. Journal of Climate 18(2):237-273. DOI: 10.1175/Jcli-3243.1.

Stephens, G. L., J. L. Li, M. Wild, C. A. Clayson, N. Loeb, S. Kato, T. L'Ecuyer, P. W. Stackhouse, M. Lebsock, and T. Andrews. 2012. An update on Earth's energy balance in light of the latest global observations. Nature Geoscience 5(10):691-696. DOI: 10.1038/Ngeo1580.

Stern, R. S. 2010. Prevalence of a history of skin cancer in 2007: Results of an incidence-based model. Archives of Dermatology 146(3):279-282. DOI: 10.1001/archdermatol.2010.4.

Stevens, B., D. H. Lenschow, G. Vali, H. Gerber, A. Bandy, B. Blomquist, J. L. Brenguier, C. S. Bretherton, F. Burnet, T. Campos, S. Chai, I. Faloona, D. Friesen, S. Haimov, K. Laursen, D. K. Lilly, S. M. Loehrer, S. P. Malinowski, B. Morley, M. D. Petters, D. C. Rogers, L. Russell, V. Savic-Jovac, J. R. Snider, D. Straub, M. J. Szumowski, H. Takagi, D. C. Thornton, M. Tschudi, C. Twohy, M. Wetzel, and M. C. van Zanten. 2003. Dynamics and chemistry of marine stratocumulus: DYCOMS-II. Bulletin of the American Meteorological Society 84(5):579-593. DOI: 10.1175/Bams-84-5-579.

Stevens, B., G. Vali, K. Comstock, R. Wood, M. C. van Zanten, P. H. Austin, C. S. Bretherton, and D. H. Lenschow. 2005. Pockets of open cells and drizzle in marine stratocumulus. Bulletin of the American Meteorological Society 86(1):51-57. DOI: 10.1175/Bams-86-1-51.

Stolarski, R. S., A. R. Douglass, S. Steenrod, and S. Pawson. 2006. Trends in stratospheric ozone: Lessons learned from a 3D chemical transport model. Journal of the Atmospheric Sciences 63(3):1028-1041. DOI: 10.1175/Jas3650.1.

Storelvmo, T., and N. Herger. 2014. Cirrus cloud susceptibility to the injection of ice nuclei in the upper troposphere. Journal of Geophysical Research: Atmospheres 119(5):2375-2389. DOI: 10.1002/2013jd020816.

Storelvmo, T., J. E. Kristjánsson, H. Muri, M. Pfeffer, D. Barahona, and A. Nenes. 2013. Cirrus cloud seeding has potential to cool climate. Geophysical Research Letters 40(1):178-182. DOI: 10.1029/2012gl054201.

Storelvmo, T., W. Boos, and N. Herger. 2014. Cirrus cloud seeding: A climate engineering mechanism with reduced side effects? Philosophical Transactions of the Royal Society of London A: Mathematical, Physical and Engineering Sciences 372(2031). DOI: 10.1098/rsta.2014.0116.

Strauss, B., C. Tebaldi, S. Kulp, S. Cutter, C. Emrich, D. Rizza, and D. Yawitz. 2013. Florida and the Surging Sea: A Vulnerability Assessment with Projections for Sea Level Rise and Coastal Flood Risk. Princeton, NJ: Climate Central.

Strauss, B. H., R. Ziemlinski, J. L. Weiss, and J. T. Overpeck. 2012. Tidally adjusted estimates of topographic vulnerability to sea level rise and flooding for the contiguous United States. Environmental Research Letters 7(1). DOI: 10.1088/1748-9326/7/1/014033.

Stroeve, J. C., V. Kattsov, A. Barrett, M. Serreze, T. Pavlova, M. Holland, and W. N. Meier. 2012a. Trends in Arctic sea ice extent from CMIP5, CMIP3 and observations. Geophysical Research Letters 39(16). DOI: 10.1029/2012gl052676.

Stroeve, J. C., M. C. Serreze, M. M. Holland, J. E. Kay, J. Malanik, and A. P. Barrett. 2012b. The Arctic's rapidly shrinking sea ice cover: a research synthesis. Climatic Change 110(3-4):1005-1027. DOI: 10.1007/s10584-011-0101-1.

Stuart, G. S., R. G. Stevens, A. I. Partanen, A. K. L. Jenkins, H. Korhonen, P. M. Forster, D. V. Spracklen, and J. R. Pierce. 2013. Reduced efficacy of marine cloud brightening geoengineering due to in-plume aerosol coagulation: Parameterization and global implications. Atmospheric Chemistry and Physics Discussion 13(7):18679-18711. DOI: 10.5194/acpd-13-18679-2013.

Super, A. B., and J. A. Heimbach. 1983. Evaluation of the Bridger Range winter cloud seeding experiment using control gauges. Journal of Climate and Applied Meteorology 22(12):1989-2011. DOI: 10.1175/1520-0450(1983)022<1989:Eotbrw>2.0.Co;2.

Tainter, J. A. 1988. The Collapse of Complex Societies. Cambridge, UK: Cambridge University Press.

Tebaldi, C., B. H. Strauss, and C. E. Zervas. 2012. Modelling sea level rise impacts on storm surges along US coasts. Environmental Research Letters 7(1). DOI: 10.1088/1748-9326/7/1/014032.

Teller, E., L. Wood, and R. Hyde. 1997. Global Warming and Ice Ages: I. Prospects for Physics-Based Modulation of Global Change. Prepared for the 22nd International Seminar on Planetary Emergencies Erice (Sicily), Italy, August 20-23, 1997. Lawrence Livermore National Laboratory, Livermore, CA.

Thomas, M. A., M. A. Giorgetta, C. Timmreck, H. F. Graf, and G. Stenchikov. 2009a. Simulation of the climate impact of Mt. Pinatubo eruption using ECHAM5-Part 2: Sensitivity to the phase of the QBO and ENSO. Atmospheric Chemistry and Physics 9(9):3001-3009.

Thomas, M. A., C. Timmreck, M. A. Giorgetta, H. F. Graf, and G. Stenchikov. 2009b. Simulation of the climate impact of Mt. Pinatubo eruption using ECHAM5-Part 1: Sensitivity to the modes of atmospheric circulation and boundary conditions. Atmospheric Chemistry and Physics 9(2):757-769.

Thomason, L. W., and T. Peter. 2006. SPARC Assessment of Stratospheric Aerosol Properties. WCRP-124, WMO/TD-No. 1295. Geneva: World Climate Research Programme.

Thompson, D. W. J., J. M. Wallace, P. D. Jones, and J. J. Kennedy. 2009. Identifying signatures of natural climate variability in time series of global-mean surface temperature: Methodology and insights. Journal of Climate 22(22):6120-6141. DOI: 10.1175/2009jcli3089.1.

Tie, X. X., and G. Brasseur. 1995. The response of stratospheric ozone to volcanic eruptions: Sensitivity to atmospheric chlorine loading. Geophysical Research Letters 22(22):3035-3038. DOI: 10.1029/95gl03057.

Tie, X. X., G. P. Brasseur, B. Briegleb, and C. Granier. 1994. Two-dimensional simulation of Pinatubo aerosol and its effect on stratospheric ozone. Journal of Geophysical Research 99(D10):20545-20562.

Tilmes, S., R. Müller, and R. Salawitch. 2008. The sensitivity of polar ozone depletion to proposed geoengineering schemes. Science 320(5880):1201-1204. DOI: 10.1126/science.1153966.

Tilmes, S., R. R. Garcia, D. E. Kinnison, A. Gettelman, and P. J. Rasch. 2009. Impact of geoengineered aerosols on the troposphere and stratosphere. Journal of Geophysical Research: Atmospheres 114(D12). DOI: 10.1029/2008JD011420.

Tilmes, S., J. Fasullo, J. F. Lamarque, D. R. Marsh, M. Mills, K. Alterskjær, H. Muri, J. E. Kristjánsson, O. Boucher, M. Schulz, J. N. S. Cole, C. L. Curry, A. Jones, J. Haywood, P. J. Irvine, D. Ji, J. C. Moore, D. B. Karam, B. Kravitz, P. J. Rasch, B. Singh, J.-H. Yoon, U. Niemeier, H. Schmidt, A. Robock, S. Yang, and S. Watanabe. 2013. The hydrological impact of geoengineering in the Geoengineering Model Intercomparison Project (GeoMIP). Journal of Geophysical Research: Atmospheres 118(19):11036-11058. DOI: 10.1002/jgrd.50868.

Tilmes, S., A. Jahn, J. E. Kay, M. Holland, and J. F. Lamarque. 2014. Can regional climate engineering save the summer Arctic sea ice? Geophysical Research Letters 41(3):880-885. DOI: 10.1002/2013gl058731.

Timmreck, C. 2012. Modeling the climatic effects of large explosive volcanic eruptions. Wiley Interdisciplinary Reviews: Climate Change 3(6):545-564. DOI: 10.1002/wcc.192.

Tompkins, A. M., and K. A. Emanuel. 2000. The vertical resolution sensitivity of simulated equilibrium temperature and water-vapour profiles. Quarterly Journal of the Royal Meteorological Society 126(565):1219-1238. DOI: 10.1256/Smsqj.56501.

Toohey, M., K. Kruger, and C. Timmreck. 2013. Volcanic sulfate deposition to Greenland and Antarctica: A modeling sensitivity study. Journal of Geophysical Research: Atmospheres 118(10):4788-4800. DOI: 10.1002/Jgrd.50428.

Trenberth, K. E., and A. Dai. 2007. Effects of Mount Pinatubo volcanic eruption on the hydrological cycle as an analog of geoengineering. Geophysical Research Letters 34(15). DOI: 10.1029/2007GL030524.

Turco, R. P., and F. Yu. 1997. Aerosol invariance in expanding coagulating plumes. Geophysical Research Letters 24(10):1223-1226. DOI: 10.1029/97GL01092.

Turco, R. P., and F. Yu. 1998. Aerosol size distribution in a coagulating plume: Analytical behavior and modeling applications. Geophysical Research Letters 25(6):927-930. DOI: 10.1029/98gl00324.

Turco, R. P., and F. Yu. 2012. Particle size distributions in an expanding plume undergoing simultaneous coagulation and condensation. Journal of Geophysical Research: Atmospheres 104(D16):19227-19241. DOI: 10.1029/1999JD900321.

Turco, R. P., O. B. Toon, T. P. Ackerman, J. B. Pollack, and C. Sagan. 1990. Climate and smoke: An appraisal of nuclear winter. Science 247(4939):166-176. DOI: 10.1126/science.11538069.

Twohy, C. H., M. D. Petters, J. R. Snider, B. Stevens, W. Tahnk, M. Wetzel, L. Russell, and F. Burnet. 2005. Evaluation of the aerosol indirect effect in marine stratocumulus clouds: Droplet number, size, liquid water path, and radiative impact. Journal of Geophysical Research: Atmospheres 110(D8). DOI: 10.1029/2004jd005116.

Twomey, S. 1974. Pollution and the planetary albedo. Atmospheric Environment 8(12):1251-1256. DOI: 10.1016/0004-6981(74)90004-3.

Twomey, S. 1977. The influence of pollution on the shortwave albedo of clouds. Journal of the Atmospheric Sciences 34(7):1149-1152.

Twomey, S., H. B. Howell, Wojciech.Ta and J. H. Conover. 1968. Comments on "anomalous cloud lines." Journal of the Atmospheric Sciences 25(2):333-334. DOI: 10.1175/1520-0469(1968)025<0333:Cocl>2.0.Co;2.

U.S. Census Bureau. 2012. Population and Housing Unit Counts. CPH-2-1, United States Summary. U.S. Government Printing Office, Washington, DC.

U.S. Congress. 2010. Hearings on Geoengineering Before the Committee on Science and Technology, U.S. House of Representatives, 111th Congress. U.S. Government Printing Office, Washington, DC.

UNFCCC (United Nations Framework Convention on Climate Change). 1992a. Article 2: Objective. UNFCCC.

UNFCCC. 1992b. Article 3: Principles. UNFCCC.

USGCRP (U.S. Global Change Research Program). 2010. Our Changing Planet: The U.S. Global Change Research Program for Fiscal Year 2010. A Report by the U.S. Global Change Research Program and the Subcommittee on Global Change Research. A Supplement to the President's Budget for Fiscal Year 2010. USGCRP, Washington, DC.

USGS (U.S. Geological Survey). 2013. Providing Science for Climate Adaptation: The National Climate Change and Wildlife Science Center and DOI Climate Science Centers. Progress Report—Summer 2013. Prepared for the Advisory Committee on Climate Change and Natural Resource Science, Washington, DC.

van Zanten, M. C., and B. Stevens. 2005. Observations of the structure of heavily precipitating marine stratocumulus. Journal of the Atmospheric Sciences 62(12):4327-4342. DOI: 10.1175/Jas3611.1.

Victor, D. G. 2008. On the regulation of geoengineering. Oxford Review of Economic Policy 24(2):322-336.

Victor, D. G., M. G. Morgan, F. Apt, J. Steinbruner, and K. Ricke. 2009. The geoengineering option: A last resort against global warming? Foreign Affairs 88(2):64-76.

Vogt, M., M. Steinke, S. Turner, A. Paulino, M. Meyerh**öfer, U. Riebesell, C. LeQuéré, and P. Liss. 2008. Dynamics of dimethyl**sulphoniopropionate and dimethylsulphide under different CO_2 concentrations during a mesocosm experiment. Biogeosciences 5(2):407-419. DOI: 10.5194/bg-5-407-2008.

Wang, H. L., and G. Feingold. 2009a. Modeling mesoscale cellular structures and drizzle in marine stratocumulus. Part II: The microphysics and dynamics of the boundary region between open and closed cells. Journal of the Atmospheric Sciences 66(11):3257-3275. DOI: 10.1175/2009jas3120.1.

Wang, H. L., and G. Feingold. 2009b. Modeling mesoscale cellular structures and drizzle in marine stratocumulus. Part I: Impact of drizzle on the formation and evolution of open cells. Journal of the Atmospheric Sciences 66(11):3237-3256. DOI: 10.1175/2009jas3022.1.

Wang, H. L., P. J. Rasch, and G. Feingold. 2011. Manipulating marine stratocumulus cloud amount and albedo: A process-modelling study of aerosol-cloud-precipitation interactions in response to injection of cloud condensation nuclei. Atmospheric Chemistry and Physics 11(9):4237-4249. DOI: 10.5194/acp-11-4237-2011.

Washington State Blue Ribbon Panel on Ocean Acidification. 2012. Ocean Acidification: From Knowledge to Action, Washington State's Strategic Response. H. Adelsman and L. Whitely Binder, eds. Publication 12-01-015. Washington Department of Ecology, Olympia, WA.

Weinstock, E. M., J. V. Pittman, D. S. Sayres, J. B. Smith, J. G. Anderson, S. C. Wofsy, I. Xueref, C. Gerbig, B. C. Daube, L. Pfister, E. C. Richard, B. A. Ridley, A. J. Weinheimer, H. J. Jost, J. P. Lopez, M. Loewenstein, and T. L. Thompson. 2007. Quantifying the impact of the North American monsoon and deep midlatitude convection on the subtropical lowermost stratosphere using in situ measurements. Journal of Geophysical Research: Atmospheres 112(D18). DOI: 10.1029/2007jd008554.

Weisenstein, D., and S. Bekki. 2006. Modeling of stratospheric aerosols. In SPARC Assessment of Stratospheric Aerosol Properties, WCRP-124, WMO/TD no. 1295. L. Thomason and T. Peter, eds. Geneva: World Climate Research Programme.

Weisenstein, D. K., J. E. Penner, M. Herzog, and X. Liu. 2007. Global 2-D intercomparison of sectional and modal aerosol modules. Atmospheric Chemistry and Physics 7(9):2339-2355.

Wigley, T. M. L. 2006. A combined mitigation/geoengineering approach to climate stabilization. Science 314(5798):452-454. DOI: 10.1126/science.1131728.

Wilcox, E. M., G. Roberts, and V. Ramanathan. 2006. Influence of aerosols on the shortwave cloud radiative forcing from North Pacific oceanic clouds: Results from the Cloud Indirect Forcing Experiment (CIFEX). Geophysical Research Letters 33(21). DOI: 10.1029/2006gl027150.

Willoughby, H. E., D. P. Jorgensen, R. A. Black, and S. L. Rosenthal. 1985. Project Stormfury: A scientific chronicle 1962-1983. Bulletin of the American Meteorological Society 66(5):505-514. DOI: 10.1175/1520-0477(1985)066<0505:Psasc>2.0.Co;2.

Wingenter, O. W., K. B. Haase, M. Zeigler, D. R. Blake, F. S. Rowland, B. C. Sive, A. Paulino, R. Thyrhaug, A. Larsen, K. G. Schulz, M. Meyerhofer, and U. Riebesell. 2007. Unexpected consequences of increasing CO_2 and ocean acidity on marine production of DMS and CH_2ClI: Potential climate impacts. Geophysical Research Letters 34(5). DOI: 10.1029/2006gl028139.

Winker, D. M., M. A. Vaughan, A. Omar, Y. X. Hu, K. A. Powell, Z. Y. Liu, W. H. Hunt, and S. A. Young. 2009. Overview of the CALIPSO mission and CALIOP data processing algorithms. Journal of Atmospheric and Oceanic Technology 26(11):2310-2323. DOI: 10.1175/2009jtecha1281.1.

WMO (World Meteorological Organization). 2003. Scientific Assessment of Ozone Depletion: 2002, Global Ozone Research and Monitoring Project. Report 47. Geneva: WMO.

WMO. 2011. Scientific Assessment of Ozone Depletion: 2010. Global Ozone Research and Monitoring Project. Report 52. Geneva: WMO.

Wonaschutz, A., M. Coggon, A. Sorooshian, R. Modini, A. A. Frossard, L. Ahlm, J. Mulmenstadt, G. C. Roberts, L. M. Russell, S. Dey, F. J. Brechtel, and J. H. Seinfeld. 2013. Hygroscopic properties of smoke-generated organic aerosol particles emitted in the marine atmosphere. Atmospheric Chemistry and Physics 13(19):9819-9835. DOI: 10.5194/acp-13-9819-2013.

Wood, G. D. A. 2014. Tambora: The Eruption that Changed the World. Princeton, NJ: Princeton University Press.

Wood, R., and T. P. Ackerman. 2013. Defining success and limits of field experiments to test geoengineering by marine cloud brightening. Climatic Change 121:459-472.

Wood, R., C. S. Bretherton, D. Leon, A. D. Clarke, P. Zuidema, G. Allen, and H. Coe. 2011. An aircraft case study of the spatial transition from closed to open mesoscale cellular convection over the Southeast Pacific. Atmospheric Chemistry and Physics 11(5):2341-2370. DOI: 10.5194/acp-11-2341-2011.

Woodhouse, M. T., G. W. Mann, K. S. Carslaw, and O. Boucher. 2008. New directions: The impact of oceanic iron fertilisation on cloud condensation nuclei. Atmospheric Environment 42(22):5728-5730. DOI: 10.1016/j.atmosenv.2008.05.005.

Wylie, D. P., W. P. Menzel, H. M. Woolf, and K. I. Strabala. 1994. Four years of global cirrus cloud statistics using HIRS. Journal of Climate 7(1972-1986).

Xia, L. L., A. Robock, J. Cole, C. L. Curry, D. Y. Ji, A. Jones, B. Kravitz, J. C. Moore, H. Muri, U. Niemeier, B. Singh, S. Tilmes, S. Watanabe, and J. H. Yoon. 2014. Solar radiation management impacts on agriculture in China: A case study in the Geoengineering Model Intercomparison Project (GeoMIP). Journal of Geophysical Research: Atmospheres 119(14):8695-8711. DOI: 10.1002/2013jd020630.

Zickfeld, K., M. Eby, A. J. Weaver, K. Alexander, E. Crespin, N. R. Edwards, A. V. Eliseev, G. Feulner, T. Fichefet, C. E. Forest, P. Friedlingstein, H. Goosse, P. B. Holden, F. Joos, M. Kawamiya, D. Kicklighter, H. Kienert, K. Matsumoto, I. I. Mokhov, E. Monier, S. M. Olsen, J. O. P. Pedersen, M. Perrette, G. Philippon-Berthier, A. Ridgwell, A. Schlosser, T. S. Von Deimling, G. Shaffer, A. Sokolov, R. Spahni, M. Steinacher, K. Tachiiri, K. S. Tokos, M. Yoshimori, N. Zeng, and F. Zhao. 2013. Long-term climate change commitment and reversibility: An EMIC intercomparison. Journal of Climate 26(16):5782-5809. DOI: 10.1175/Jcli-D-12-00584.1.

APPENDIX A

Statement of Task for the Committee

The Committee on Geoengineering Climate: Technical Evaluation and Discussion of Impacts was charged with the following task:

An ad hoc committee will conduct a technical evaluation of a limited number of proposed geoengineering techniques, including examples of both solar radiation management and carbon dioxide removal techniques, and comment generally on the potential impacts of deploying these technologies, including possible environmental, economic, and national security concerns. The study will

1. Evaluate what is currently known about the science of several (3 or 4) selected example techniques, including potential risks and consequences (both intended and unintended), such as impacts, or lack thereof, on ocean acidification;
2. Describe what is known about the viability for implementation of the proposed techniques, including technological and cost considerations;
3. Briefly explain other geoengineering technologies that have been proposed (beyond the selected examples); and
4, Identify future research needed to provide a credible scientific underpinning for future discussions.

The study will also discuss historical examples of related technologies (e.g., cloud seeding and other weather modification) for lessons that might be learned about societal reactions, examine what international agreements exist which may be relevant to the experimental testing or deployment of geoengineering technologies, and briefly explore potential societal and ethical considerations related to geoengineering. This study is intended to provide a careful, clear scientific foundation that informs ethical, legal, and political discussions surrounding geoengineering.

This study was sponsored by the U.S. intelligence community, the National Oceanic and Atmospheric Administration, the National Aeronautics and Space Administration, the Department of Energy, and the National Academies.

APPENDIX B

Committee Biographies

Dr. Marcia K. McNutt, American Association for the Advancement of Science (*Committee Chair***)** is the former Director of the U.S. Geological Survey and current Editor-in-Chief of the Science family of journals. She is a member of the National Academy of Sciences, the American Philosophical Society, and the American Academy of Arts and Sciences. She was awarded by the American Geophysical Union the Macelwane Medal in 1988 for research accomplishments by a young scientist and the Maurice Ewing Medal in 2007 for her significant contributions to deep-sea exploration. She holds honorary doctoral degrees from the University of Minnesota, Colorado College, Monmouth University, and Colorado School of Mines. Dr. McNutt received her Ph.D. in Earth Sciences from Scripps Institution of Oceanography.

Dr. Waleed Abdalati, University of Colorado, Boulder, is Director of the Cooperative Institute for Research in Environmental Sciences at the University of Colorado, a professor in the Department of Geography, and Director of the Earth Science and Observation Center. In 2011 and 2012 he was on a leave of absence from the university to serve as the Chief Scientist at the National Aeronautics and Space Administration (NASA). In this role he oversaw the full portfolio of NASA science activities and served as advisor on agency science matters to the NASA administrator and NASA leadership. His research has focused on the study of polar ice cover using satellite and airborne instruments. During his initial tenure at NASA from 1998 to 2008 he held a variety of positions in the areas of scientific research, program management, scientific management, and mission science oversight. Prior to his joining NASA, he worked as an engineer in the aerospace industry. Dr. Abdalati received a B.S. in mechanical engineering from Syracuse University in 1986, and an M.S. in aerospace Engineering and a Ph.D. in geography from the University of Colorado in 1991 and 1996, respectively.

Dr. Ken Caldeira, Carnegie Institution for Science, is a senior member of the Carnegie Institution's Department of Global Ecology staff and a professor, by courtesy, in Stanford's Environmental Earth System Sciences department. Dr. Caldeira has a wide-spectrum approach to analyzing the world's climate systems. He studies the global carbon cycle; marine biogeochemistry and chemical oceanography, including ocean acidification and the atmosphere-ocean carbon cycle; land cover and climate change; the long-term evolution of climate and geochemical cycles; and energy technology. In 2001, he was a contributing author to the Intergovernmental Panel on Cliamte Change (IPCC) Working Group I Third Assessment Report. In 2005, he was coordinating lead author for the ocean storage chapter of the IPCC Special Report on Carbon Capture and Storage. He was on the UK Royal Society ocean acidification panel in 2005 and geoengineering panel in 2009. He was a lead author of the 2007 U.S. *State of the Carbon Cycle Report*. He was a co-author of the 2010 National Academy of Sciences (NAS) *America's Climate Choices* report. In 2010, Caldeira was elected Fellow of the American Geophysical Union. Caldeira was a contributing author to the 2014 IPCC Fifth Assessment Report (IPCC AR5).

Dr. Scott Doney, Woods Hole Oceanographic Institution, is a Senior Scientist and Chair of the Department of Marine Chemistry and Geochemistry at the Woods Hole Oceanographic Institution (WHOI). He graduated with a B.A. in chemistry from the University of California, San Diego, in 1986 and a Ph.D. in chemical oceanography from the Massachusetts Institute of Technology/Woods Hole Oceanographic Institution Joint Program in Oceanography in 1991. He was a postdoctoral fellow and later a scientist at the National Center for Atmospheric Research, before returning to Woods Hole in 2002. He was awarded the James B. Macelwane Medal from the American Geophysical Union (AGU) in 2000, an Aldo Leopold Leadership Fellow in 2004, the WHOI W. Van Alan Clark Sr. Chair in 2007, and the A.G. Huntsman Award for Excellence in Marine Science in 2013. He is an AGU Fellow (2000) and an American Association for the Advancement of Science (AAAS) Fellow (2010). His science interests span oceanography, climate, and biogeochemistry. Much of his research focuses on how the global carbon cycle and ocean ecology respond to natural and human-driven climate change. A key focus is on ocean acidification due to the invasion into the ocean of carbon dioxide from fossil fuel burning. He was the inaugural chair of the U.S. Ocean Carbon and Biogeochemistry Program, past director of the WHOI Ocean and Climate Change Institute, and a convening lead author of the Oceans and Marine Resources chapter of the 2014 U.S. National Climate Assessment.

Dr. Paul G. Falkowski, Rutgers, The State University of New Jersey, is Bennett L. Smith Professor of Business and Natural Resources at Rutgers, The State University of New Jersey and Director of the Rutgers Energy Institute. His research interests include biogeochemical cycles, photosynthesis, biological oceanography, molecular biology, biochemistry and biophysics, physiological adaptation, plant physiology, evolution, mathematical modeling, and symbiosis. Dr. Falkowski is also the Lead Principal Investigator in the Environmental Biophysics and Molecular Ecology (EBME) program. That program focuses on molecular biology and biophysics to address key questions in biological oceanography and marine biology. The EBME program provides a laboratory in the Institute of Marine and Coastal Sciences at Rutgers University that addresses the application of similar techniques to primary production, nitrogen fixation, and other rate-determining processes in aquatic as well as terrestrial ecosystems.

Dr. Falkowski has received many awards; his most recent include the Board of Trustees Award for Excellence in Research, Rutgers University (2000); Vernadsky Medal, European Geosciences Union (2005); and Board of Governors Professor, Rutgers University (2005). Dr. Falkowski was elected to the NAS as a member in 2007. He has also received numerous grants, some from NASA, the National Science Foundation (NSF), the Department of Defense, the Department of Energy (DOE), and the Moore Foundation. Dr. Falkowski received his Ph.D. in biology at the University of British Columbia.

Dr. Steve Fetter, University of Maryland, is Associate Provost for Academic Affairs at the University of Maryland. He has been a professor in the Maryland School of Public Policy since 1988, serving as Dean from 2005 to 2009. In 2009-2012 he was Assistant Director At-Large in the Office of Science and Technology Policy in the White House. Dr. Fetter is a member of the Council on Foreign Relations, a Fellow of the American Physical Society (APS), and a recipient of the APS Joseph A. Burton Forum Award. He has been a member of the Director of National Intelligence's Intelligence Science Board and the Department of Energy's Nuclear Energy Advisory Committee, served as President of the Association of Professional Schools of International Affairs and Vice Chairman of the Federation of American Scientists (FAS), and received the FAS Hans Bethe Science in the Public Service award. He has been an advisor to the U.S. departments of State, Defense, and Energy, and has held visiting positions at Stanford, Harvard, and MIT. He received a Ph.D. in energy and resources from the University of California, Berkeley, and a S.B. in physics from MIT.

Dr. James R. Fleming, Colby College, is a historian of science and technology and Professor of Science, Technology and Society at Colby College. He is a fellow of the AAAS and the American Meteorological Society (AMS), series editor of *Palgrave Studies in the History of Science and Technology*, contributing author to the Intergovernmental Panel on Climate Change, and chair of the AAAS Section on Societal Impacts of Science and Engineering. Dr. Fleming earned a B.S. in astronomy from Pennsylvania State University, an M.S. in atmospheric science from Colorado State University, and an M.A. and Ph.D. in history from Princeton University. He has held a number of major fellowships and lectureships, including the Charles A. Lindbergh Chair in Aerospace History at the Smithsonian Institution, the Roger Revelle Fellowship of the AAAS, the Ritter Memorial Fellowship at the Scripps Institution of Oceanography, the H. Burr Steinbach Lectureship at the Woods Hole Oceanographic Institute, the Gordon Cain Conference Fellowship at the Chemical Heritage Foundation, a Woodrow Wilson Center policy scholarship, and a Scholar's Award from the U.S. National Science Foundation. He is currently a visiting scholar in the history department at Columbia University.

Dr. Steven P. Hamburg, Environmental Defense Fund, is Chief Scientist at Environmental Defense Fund. He is an ecosystem ecologist specializing in the impacts of disturbance on forest structure and function. He has served as an advisor to both corporations and nongovernmental organizations on ecological and climate change mitigation issues. Previously, he spent 16 years as a tenured member of the Brown University faculty and was founding Director of the Global Environment Program at the Watson Institute for International Studies. Dr. Hamburg is the Co-Chair of the Royal Society's Solar Radiation Management Governance Initiative and a member of the U.S. Department of Agriculture Advisory Committee on Research, Economics, Extension and Education. He has been the recipient of several awards, including recognition by the Intergovernmental Panel on Climate Change as contributing to its award of the 2007 Nobel Peace Prize. Dr. Hamburg earned a Ph.D. in forest ecology from Yale University.

Dr. M. Granger Morgan, Carnegie Mellon University, is Lord Chair Professor in Engineering; Professor and Department Head, Engineering and Public Policy; Professor in Electrical and Computer Engineering; and professor in The H. John Heinz III School of Public Policy and Management, Carnegie Mellon University (CMU). Dr. Morgan's research interests are focused on policy problems in which technical and scientific issues play a central role. Methodological interests include problems in the integrated analysis of large complex systems; problems in the characterization and treatment of uncertainty; problems in the improvement of regulation; and selected issues in risk analysis and risk communication. Application areas of current interest include global climate change; the future of the energy system, especially electric power; risk analysis, including risk ranking; health and environmental impacts of energy systems; security aspects of engineered civil systems; national research and development policy; radio interference on commercial airliners; issues of privacy and anonymity; and a number of general policy, management, and manpower problems involving science and technology. Most of Dr. Morgan's professional career has been spent at CMU with short stints at Brookhaven National Labs, the National Science Foundation, and the University of California, San Diego. His professional activities include a large number of publications, memberships on numerous panels, including the Electric Power Research Institute Advisory Board (which he previously chaired) and the Scientific and Technical Council of the International Risk Governance Council (which he chairs). He is past chair of the Environmental Protection Agency (EPA) Science Advisory Board. He is a member of the NAS and has served on and chaired many National Research Council (NRC) committees. He earned his Ph.D. in applied physics and information science from the University of California, San Diego.

Dr. Joyce E. Penner, University of Michigan, is the Ralph J. Cicerone Distinguished University Professor of Atmospheric Science and Associate Chair for the Atmospheric, Oceanic, and Space Sciences Department. Dr. Penner's research focuses on improving climate models through the addition of interactive chemistry and the description of aerosols and their direct and indirect effects on the radiation balance in climate models. She is interested in cloud and aerosol interactions and cloud microphysics, climate and climate change, and model development and interpretation. Dr. Penner has been a member of numerous advisory committees related to atmospheric chemistry, global change, and Earth science, including the IPCC, which was awarded the 2007 Nobel Peace Prize. She was the coordinating lead author for IPCC (2001) Chapter 5 on aerosols and report coordinator for the 1999 IPCC report: *Aviation and the Global Atmosphere*. Dr. Penner received a B.A. in applied mathematics from the University of California, Santa Barbara, and her M.S. and Ph.D. in applied mathematics from Harvard University. She is currently a member of the NRC U.S. National Committee for the International Union of Geodesy and Geophysics, as well as the Vice-Chair of the Committee on Earth Science and Applications from Space. Prior NRC service includes being a member of the Space Studies Board, the planning committee for the Workshop on Uncertainty Management in Remote Sensing of Climate Data, and the Panel on Climate Variability and Change for the 2007 decadal survey on Earth science and applications from space.

Dr. Raymond T. Pierrehumbert, University of Chicago, is the Louis Block Professor in Geophysical Sciences at the University of Chicago, having earlier served on the atmospheric science faculties of Massachusetts Institute of Technology (MIT) and Princeton. His research work has dealt with a wide range of problems in the physics of climate, including anthropogenic climate change, climate of the early Earth, climate of Mars and Titan, and most recently exoplanet climate. He was a lead author of the IPCC Third Assessment Report, and a co-author of the NRC report on abrupt climate change and of the report on climate stabilization targets. He is a Fellow of the AGU, and in recognition of his work on climate he has been named Chevalier de l'Ordre des Palmes Academiques by the Republic of France. Dr. Pierrehumbert is the author of *Principles of Planetary Climate*, a textbook on comparative planetary climate published by Cambridge University Press, and, with David Archer, co-author of *The Warming Papers* (Wiley/Blackwell). He received his Ph.D. from MIT.

Dr. Philip J. Rasch, Pacific Northwest National Laboratory, serves as the Chief Scientist for Climate Science at the Pacific Northwest National Laboratory (PNNL), a Department of Energy Office of Science research laboratory. In his advisory role, he provides leadership and direction to PNNL's Atmospheric Sciences and Global Change Division. The division conducts research on the long-term impact of human activities on climate and natural resources using a research strategy that starts with measurements and carries that information into models, with a goal of improving the nation's ability to predict climate change. Dr. Rasch provides oversight to more than 90 researchers who lead and contribute to programs within a number of government agencies and industry. These programs focus on climate, aerosol and cloud physics; global and regional scale modeling; integrated assessment of global change; and complex regional meteorology and chemistry. Dr. Rasch earned bachelor's degrees in chemistry and atmospheric science from the University of Washington and master's and Ph.D. degrees in meteorology from Florida State University.

Dr. Lynn M. Russell, Scripps Institution of Oceanography, is professor in the Climate, Ocean, and Atmosphere program at Scripps Institution of Oceanography on the faculty of the University of California, San Diego, where she has led the Climate Sciences Curricular Group since 2009. Her research is in the area of aerosol particle composition and microphysics, including the behavior of particles from both biogenic and combustion processes. Her research group pursues both modeling and measurement studies of atmospheric aerosols, using the combination of these approaches to advance our understanding of fundamental processes that affect atmospheric aerosols. She completed her undergraduate work at Stanford University, and she received her Ph.D. in chemical engineering from the California Institute of Technology for her studies of marine aerosols. Her postdoctoral work as part of the National Center for Atmospheric Research Advanced Studies Program investigated aerosol and trace gas flux and entrainment in the marine boundary layer. She served on the faculty of Princeton University in the Department of Chemical Engineering before accepting her current position at Scripps in 2003. She has been honored with young investigator awards from the Office of Naval Research, NASA, the Dreyfus Foundation, NSF, and the James S. McDonnell Foundation. In 2003 she received the Kenneth T. Whitby Award from the American Association for Aerosol Research (AAAR; 2003) for her contributions on atmospheric aerosol processes, and she was named AAAR Fellow in 2013.

Dr. John T. Snow, University of Oklahoma, is a Regents' Professor of Meteorology and Dean Emeritus of the College of Atmospheric and Geographic Sciences at the University of Oklahoma. Currently, Dr. Snow's professional interests lie in the field of "Earth system science," merging research in the Earth and life sciences to generate a comprehensive explanation for "how the world works." In recent years, Dr. Snow has been involved in a number of local and regional economic development projects and technology transfer efforts. Dr. Snow is involved with a number of professional organizations, serving as an AMS Fellow, a Royal Meteorological Society Fellow, and a member of the NSF Geosciences Advisory Committee to name a few. The AMS has honored Dr. Snow with the Charles Anderson Award for his efforts in improving education and diversity in the atmospheric sciences, and the Cleveland Abbey Award for his excellent service to both the Society and the profession. Dr. Snow earned both his B.S. and M.S. in electric engineering from the Rose-Hulman Institute of Technology, and his Ph.D. in atmospheric sciences from Purdue University in 1977.

RADM David W. Titley, USN [Ret.], Pennsylvania State University, is currently the Director of the Center for Solutions to Weather and Climate Risk at Pennsylvania State University. He is a nationally known expert in the field of climate, the Arctic, and National Security. He served as a naval officer for 32 years and rose to the rank of Rear Admiral. Dr. Titley's career included duties as Oceanographer and Navigator of the Navy and Deputy Assistant Chief of Naval Operations for Information Dominance. While serving in the Pentagon, Dr. Titley initiated and led the U.S. Navy's Task Force on Climate Change. After retiring from the Navy, Dr. Titley served as the Deputy Undersecretary of Commerce for Operations, the Chief Operating Officer position at the National Oceanic and Atmospheric Administration. Dr. Titley has spoken across the country and throughout the world on the importance of climate change as it relates to National Security. He was invited to present on behalf of the Department of Defense at both Congressional Hearings and the IPCC meetings from 2009 to 2011. He has presented a TEDx talk on climate change and speaks regularly on this topic at universities across the country. He currently serves on the Advisory Board of the Center of Climate and Security based in Washington DC. Dr. Titley holds a B.S. in meteorology from the Pennsylvania State University. From the Naval Postgraduate School, he earned an M.S. in meteorology and physical oceanography, and a Ph.D. in meteorology. He was elected a Fellow of the American Meteorological Society in 2009 and was awarded an honorary doctorate from the University of Alaska, Fairbanks.

Dr. Jennifer Wilcox, Stanford University, is an Assistant Professor of Energy Resources Engineering in the School of Earth Sciences and an affiliate faculty member in the Emmet Interdisciplinary Program for the Environment and Resources at Stanford University. Her research efforts include sorbent design and testing for carbon and trace-metal capture from fossil fuels, adsorption studies of CO_2 on coal and gas shales, and membrane design for N_2 and H_2 separations. She also heads the Clean Conversion Laboratory in the School of Earth Sciences. She received the NSF Career Award (2005) and the Army Research Office Young Investigator Award (2009). Wilcox earned a B.A. in mathematics from Wellesley College, and an M.A. in physical chemistry, and a Ph.D. in chemical engineering from the University of Arizona. She recently authored the first textbook on carbon capture.

APPENDIX C

Planned Weather Modification

PLANNED WEATHER MODIFICATION VERSUS CLIMATE INTERVENTION

Weather modification, which could also be called "weather intervention," is the intentional alteration of the composition, behavior, or dynamics of the atmosphere occurring over a specified area and time period to accomplish a particular goal (NRC, 2003). The area could be local (an airfield) or regional (a county on the Great Plains or the windward slopes of the Sierra Nevada mountains); the time period could range from a few days to a few months. The goals can be very diverse, including enhancement of water supplies, clearing of fog over an airfield, reduction in the number of lightning-initiated wildfires, or denial of use of trails or rivers (potentially as a military application). It is important to clearly distinguish such intentional, goal-oriented activities from "inadvertent weather modification"—the impacts on local or regional weather that are unintended consequences of human activities. Included in this last are urban heat islands, air pollution, and acid rain.

The most common form of weather modification is the seeding of convective or cumuliform clouds with an appropriate agent to produce or increase rainfall, reduce hail size, or suppress lightning. Wintertime stratiform clouds can also be seeded to attempt to increase snowfall and so enhance the depth of the snowpack on windward slopes of mountains. Clouds within hurricanes have been seeded on an experimental basis with the goals of diverting such storm systems away from coastal areas and/or reducing wind speeds (see Box 2.2). Various glaciogenic (for cold clouds) and hygroscopic (for warm clouds) seeding agents have been tried, including silver iodide, lead iodide, aluminum oxide, barium, soot, frozen carbon dioxide (dry ice), common salt, and water sprays. In the United States, silver iodide, which produces small particles that closely resemble ice crystals, is the commonly used agent for cold clouds.

As discussed previously in this report, climate intervention typically refers to proposed strategies and technologies for diminishing the risk and/or damages from such long-term changes in the global climate (Chapter 1). Even through some weather modification and climate intervention efforts appear similar—for example, the brightening of marine cumulus clouds (Chapter 3)—these two approaches to modify atmospheric processes target atmospheric phenomena operating on very different space and timescales and, consequently, differ significantly in strategies and technologies.[1] The goals of weather modification are to influence precipitation and/or lightning over relatively small areas for short timescales while those of climate intervention are to influence flows of radiant energy through the atmosphere that are global in extent; relevant timescales likely are centuries or even longer.

LESSONS FROM WEATHER MODIFICATION FOR CLIMATE INTERVENTION

Historical Attempts at Weather Modification

There is a long and checkered history of attempted control of weather. The first U.S. national meteorologist, James P. Espy, proposed to modify rainfall along the entire eastern seaboard by lighting gigantic fires along the Appalachian Mountains (Espy, 1841; Fleming, 2010b). The first attempt to actually modify a hurricane occurred in the late 1940s under Project Cirrus, a collaborative effort by the General Electric Company and the three military services (see Box 2.2). Although it was difficult to discern the impact of seeding on an October 1947 hurricane off the Florida-Georgia Atlantic coast, the seeded storm made an abrupt turn to the west and made landfall over the city of Savannah, Georgia. Subsequent investigations and threats of litigation were successfully defended, but further such experiments were delayed for more than a decade.

For over two decades, the federal program Project STORMFURY (1962-1983, with the last actual seeding in 1971) explored the possibility of weakening tropical cyclones by seeding the eyewall clouds (the most active region of the systems) with silver iodide (Willoughby et al., 1985). Although STORMFURY was ultimately judged a failure in terms of development of techniques for modifying hurricanes, its many observations greatly improved understanding of the functioning of these enormous storm systems and provided the basis for today's federal hurricane research program (which seeks to advance our knowledge of tropical cyclones for the purpose of improving forecasting tools and techniques). The committee has been unable to locate evidence of any federal program attempting to modify hurricanes since the shutdown of Project STORMFURY and the subsequent refocusing of most tropical cyclone research on improving forecasting.

Today, the main technologies in use are seeding from aircraft, explosive artillery shells and rockets, and ground-based burner generators. In an effort to ensure the best pos-

---

[1] According to the Intergovernmental Panel on Climate Change (IPCC) definition of geoengineering, "Geoengineering is different from weather modification and ecological engineering, but the boundary can be fuzzy" (IPCC, 2012, p. 2).

sible weather for the 2008 Summer Olympic Games, the People's Republic of China put on one of the largest public displays of weather modification technology in recent years. The Chinese government deployed 30 airplanes, 4,000 rocket launchers, and 7,000 anti-aircraft guns to launch a seeding agent into any cloud that threatened an Olympic venue.[2] During the hours preceding the opening ceremony, rockets were reportedly fired from 21 sites around Beijing to intercept a potentially disruptive rain belt before it reached the capital. Baoding City, southwest of Beijing, received about 100 mm (4 in.) of precipitation that night but in the capital the rain held off, even though August is normally Beijing's rainy season.[3]

Current activities in the United States include numerous cloud-seeding projects[4] at the state level (see Figure C.1). At present in the United States, all weather modification is carried out by private companies. The relevant trade and professional organization is the Weather Modification Association[5] (WMA); the WMA publishes *The Journal of Weather Modification*.[6] In addition, the American Meteorological Society has provided an information statement[7] on weather modification, discussing some of the uncertainties involved and the need for careful risk management.

Cloud-Seeding Activities Continue with No Robust Research Program Supporting Them

Though it is the most common form of weather modification, seeding of convective clouds to produce or enhance rainfall appears to have little if any effect (NRC, 2003). Any project to properly measure the effects of cloud seeding is likely to be expensive because discerning the effects of cloud seeding from natural variability is difficult. However, seeding of convective clouds has been shown to reduce hail damage to crops (producing many small hail stones rather than a few large, damaging ones) and to suppress lightning discharges to reduce the number of wildfires. (In this last case,

---

[2] http://www.latimes.com/news/nationworld/world/la-fg-rain31jan31,0,39372.story#axzz2uqfLW1MA; http://usatoday30.usatoday.com/weather/research/2008-02-29-china-weather_N.htm; http://www.theguardian.com/sport/2008/aug/08/olympics20081?guni=Article:in%20body%20link.

[3] For some comments on effectiveness, see http://www.independent.co.uk/sport/olympics/how-beijing-used-rockets-to-keep-opening-ceremony-dry-890294.html and http://www.universetoday.com/16728/the-chinese-weather-manipulation-missile-olympics/.

[4] See, for example, http://www.weathermodification.org/projectlocations.php.

[5] See http://www.weathermodification.org/index.php.

[6] See http://www.weathermodification.org/publications/index.php/JWM.

[7] See, for example, the Society's position statement, "Planned Weather Modification through Cloud Seeding," available at https://www.ametsoc.org/policy/2010plannedweathermod_cloudseeding_amsstatement.html.

APPENDIX C

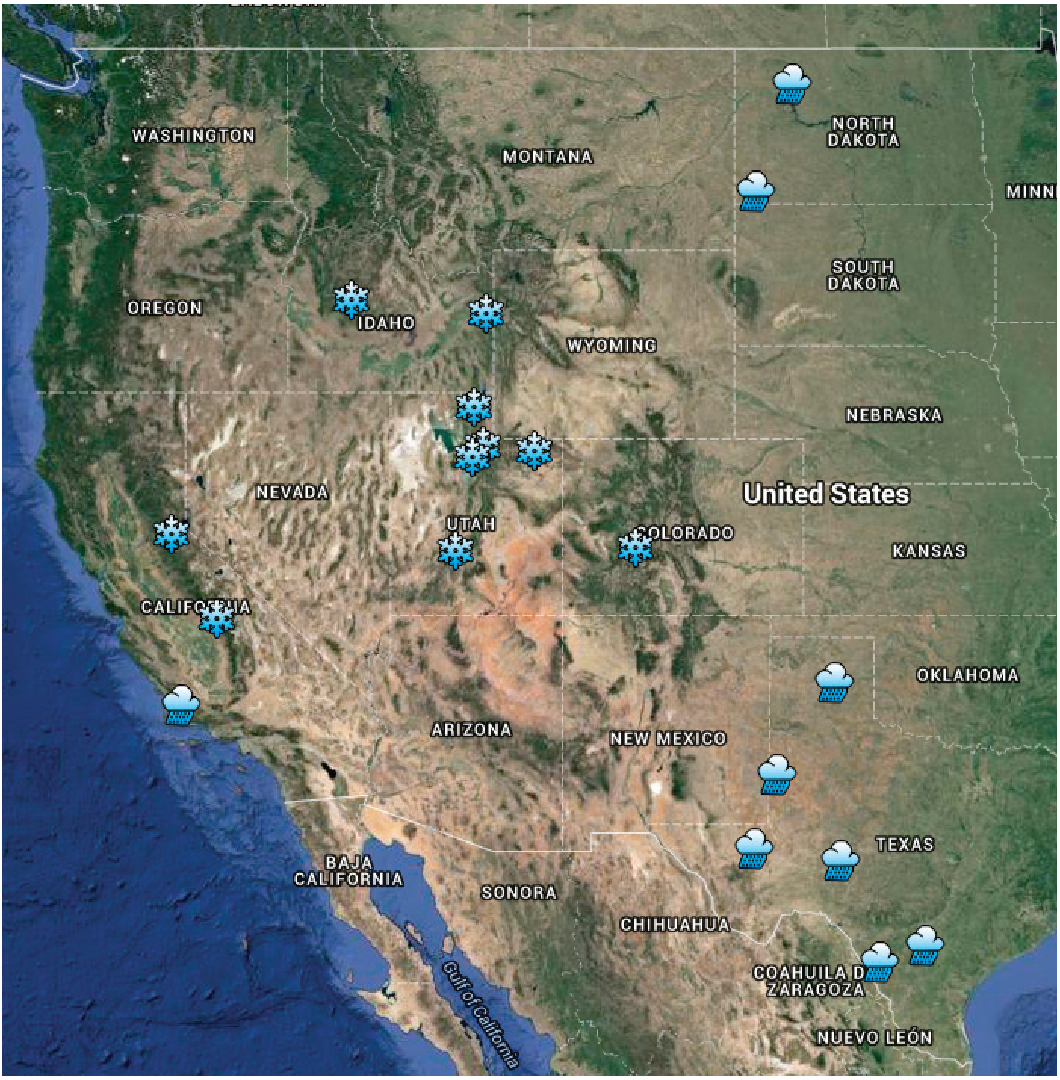

FIGURE C.1 Self-reported recent and ongoing weather modification project locations on the Great Plains and in the western mountain regions of the United States. SOURCE: Weather Modification Association, https://maps.google.com/maps/ms?ie=UTF8&hl=en&msa=0&msid=210263860280044943005.00047f6342c83772ab091&ll=36.575469,-106.867725&spn=15.220428,16.763863&source=embed&dg=feature.

thin strips of aluminum foil or "chaff" are used as the seeding agent; they short circuit the natural electrical charging process within the storm.) Seeding of wintertime stratiform clouds has been shown to significantly increase snowpack on mountain ridges (Huggins, 2006; Super and Heimbach, 1983).

Given the threat posed by tropical cyclones in general and hurricanes in particular to the Atlantic and Gulf coasts of the United States, numerous ideas have been advanced for modifying such large weather systems. As examples of these proposals, it has been suggested that soot be used to absorb sunlight and so change the air temperature in such a way that convection currents are reduced.[8] Another suggestion is to spread environmentally friendly oil slicks to separate the warm ocean water (the energy source) from the atmosphere (where the energy is released), but maintaining an effective slick in the face of hurricane-force winds would be a challenge.

Despite previous calls for a national research program in hurricane modification or suppression, there is currently no government-funded research effort in this area (NRC, 2003). Both numerical and field explorations—funded by a diverse group of federal agencies including the National Oceanic and Atmospheric Administration (NOAA), the National Aeronautics and Space Administration (NASA), the Office of Naval Research (ONR), and the Department of Homeland Security (DHS)—continue to examine the basic physics underlying the functioning of hurricanes. The field programs include piggy-back experiments on operational NOAA and U.S. Air Force (USAF) "hurricane hunter" flights in the Atlantic and research flights in the eastern and western Pacific by U.S. university researchers using funding from NSF, ONR, and elsewhere.

Such efforts could provide a firm basis on how such systems might be modified. Present-day numerical models incorporating the best-available physical knowledge are capable of simulating many features of both tropical cyclones at different stages of intensity and the likely impact various modification strategies might have on such systems. The most recent comprehensive effort was the Hurricane Aerosol and Microphysics Program (HAMP; Cotton et al., 2011),[9,10] which was supported by DHS, Science

---

[8] See http://www.itwire.com/science-news/climate/15149-boston-area-scientists-study-controlling-hurricanes-with-soot; this notion was investigated in the Hurricane Aerosol and Microphysics Program, described in following text.

[9] See http://earth.huji.ac.il/data/file/danny/126_Cotton_JWM_2011.PDF. See also the briefing "The Rise and Fall of the Hurricane Aerosol and Microphysics Program (HAMP)," by J. Golden, W. Woodley, W. Cotton, D. Rosenfeld, A. Khain, and I. Ginis. See http://weathermodification.org/Park%20City%20Presentations/DC%20Program%20Review.pdf.

[10] Hurricane Aerosol and Microphysics Program (HAMP): Improving Hurricane Forecasts by Evaluating the Effects of Aerosols on Hurricane Intensity – Final Report, by William L. Woodley. See http://saive.com/911/DOCS/DHS-Final-Report-Operation-HAMP.pdf.

and Technology Directorate, Homeland Security Advanced Research Projects Agency/Infrastructure and Geophysical Division. HAMP was discontinued in 2010 after only about 1 year of active research, though publication of results has continued. Similar but smaller-scale investigations by university researchers continue with support from the National Science Foundation[11] and the Office of Naval Research.[12] Both NOAA and NASA continue such research in their in-house research centers and support modest university studies.

The current position of NOAA on efforts to modify hurricanes was stated by Dr. Richard Spinard, then head of NOAA's Office of Oceanic and Atmospheric Research:[13]

> NOAA does not support research that entails efforts to modify hurricanes. NOAA, and its predecessor agency, once supported and conducted research into hurricane modification through Project STORMFURY from 1962 to 1983. Project STORMFURY was discontinued as the result of: 1) inconclusive scientific results, and 2) the inability to separate the difference between what happens when a hurricane is modified by human intervention versus a hurricane's natural behavior. Since Project STORMFURY's end 26 years ago, NOAA scientists have gained substantial insight on the complicated and interconnected processes within the overall hurricane environment. Yet, it remains unclear if enough knowledge has been gained to make any new modification attempts practicable.

Regulation and Oversight of Weather Modification Programs

There is a patchwork of regulations and oversight of weather modification programs at the international, federal, and state levels. Some climate intervention strategies face a similar scenario with respect to existing treaties and laws.

International

In 1975, the U.S. and Canadian governments entered into an "Agreement Relating to the Exchange of Information on Weather Modification Activities." This provided only

---

[11] See, for example, https://www.nsf.gov/news/news_summ.jsp?cntn_id=104474; http://www.nsf.gov/news/news_summ.jsp?cntn_id=117388.

[12] http://www.defensenews.com/article/20130701/TSJ01/307010016/Navy-Scientists-Predict-Killer-Hurricanes.

[13] Letter, R. Spinrad, NOAA, to W. Laska, DHS. Subject: Response to Statement of Work - Hurricane Aerosol and Microphysics Program. Dated July 29, 2009. See http://voices.washingtonpost.com/capitalweathergang/noaa_letter_dhs_hurricane_modification.pdf.

for the exchange of information where weather modification activities being carried out by one nation might impact the weather in the other.[14]

Responding to a U.S.-U.S.S.R. initiative, weather modification in support of military operations—weather warfare[15]—was effectively banned by the United Nations in "UN General Assembly Resolution 31/72, TIAS 9614 - Convention on the Prohibition of Military or Any Other Hostile Use of Environmental Modification Techniques."[16],[17] This Convention was signed in Geneva on May 18, 1977, and came into force on October 5, 1978. The U.S. Senate gave its advice and consent to ratification on November 28, 1979, by a vote of 98-0. The Convention was then signed by U.S. President Jimmy Carter on December 13, 1979; the U.S. ratification was deposited at New York on January 17, 1980.[18] Although there does not appear to be any active program on weather warfare within the U.S. military, discussions (perhaps better called speculations) continue as to the possibilities for weather warfare in the future.[19]

Federal

In the United States, routine weather modification (typically cloud seeding) is loosely regulated. At the federal level, several legislative efforts have been made since the 1940s in regard to weather modification. Initially, these were focused on promoting research and development (R&D) on weather modification techniques, reflecting the optimistic views of the time. In recent years, given the lack of significant progress in the 1960s and 1970s, federal efforts to advance weather modification R&D have

---

[14] See copy of this treaty at http://iea.uoregon.edu/pages/view_treaty.php?t=1975-RelatingExchangeInformationWeatherModificationActivities.EN.txt&par=view_treaty_html.

[15] The U.S. military carried out a number of "weather warfare" activities in Vietnam. The most extensive was Operation Popeye, a massive cloud seeding effort over the Ho Chi Minh Trail that had the goal of reducing infiltration down this trail. This USAF effort was reported to have increased rainfall in the seeded areas by an estimated 30% during 1967 and 1968. For details, see Weather Modification: Hearings before the Subcommittee on Oceans and International Environment of the Committee on Foreign Relations, United States Senate, 1974, Folder 01, Box 06, Douglas Pike Collection: Unit 11 - Monographs, The Vietnam Center and Archive, Texas Tech University. http://www.vietnam.ttu.edu/virtualarchive/items.php?item=2390601002.

[16] For the text of the Convention, see http://www.fas.org/nuke/control/enmod/text/environ2.htm.

[17] It appears that the U.S. military's position is that the language of the Convention applies only to modification activities that produce permanent changes in the environment, with local, nonpermanent changes still being allowed. See Enclosure D at http://www.dtic.mil/cjcs_directives/cdata/unlimit/3810_01.pdf.

[18] For the history of the U.S. involvement in this Convention, see the U.S. Department of State document at http://web.archive.org/web/20070914081350/http://www.state.gov/t/ac/trt/4783.htm.

[19] A good example of such speculations is provided by the research paper at http://csat.au.af.mil/2025/volume3/vol3ch15.pdf.

generally not been supported by the Congress or the Administration. As will be seen, currently there is only a reporting requirement for weather modification activities.

In 1971, the U.S. Congress passed and the President signed Public Law 92-205. This resulted in the establishment of reporting requirement in Title 15, Chapter 9A—Weather Modification Activities or Attempts; Reporting Requirement. This act requires individuals conducting weather modification activities in the United States to report them to NOAA, which keeps records of such projects on behalf of the Secretary of Commerce. (This authorizing legislation laid out a research program in addition to this reporting requirement, but that program was never funded.)

In 2005 (U.S. Senate Bill 517 and U.S. House Bill 2995) and again in 2007(2007 U.S. Senate Bill 1807 and U.S. House Bill 3445), bills were introduced in the Congress which would have established a program of expanded experimental weather modification in the United States, set up a Weather Modification Operations and Research Board, and implemented a national weather modification policy. Over the past 20 years, several other bills addressing weather modification have been proposed in the House and the Senate. None of these proposed bills made it into law.

State

It is at the state level, where weather modification is treated as a commercial endeavor, that one finds some oversight and regulation. Standler (2006) reviews many of the state laws in place and related court cases as of the date of his paper.[20]

As discussed by Standler (2006), many states have some form of statute for regulation and oversight of weather modification activities. Many, perhaps all, of the resulting regulations and procedures are now posted to the Internet. A good example of these state regulations is provided by the State of Texas Department of Licensing and Regulation—Weather Modification.[21]

Reviewing several of these both indicates some common themes and suggests that the lack of a common federal statute is a potential issue since weather modification activities could easily impact more than one state (recall the U.S.-Canada treaty mentioned above; see also the recent paper by DeFelice et al. (2014) on downstream effects of seeding). Standler (2006) has identified the two features common to most state regulations:

---

[20] Standler, Ronald B. 2006. Weather Modification Law in the USA. 33 pp. Available at www.rbs2.com/weather.pdf.

[21] See http://www.tdlr.state.tx.us/weather/weathermod.htm#url.

> “1. ensure that commercial weather modification companies are competent (e.g., states often require cloud seeders to have earned at least a bachelor’s degree in meteorology or a related field, plus have experience in weather modification); and
>
> 2. require companies to have the resources to compensate those harmed by their weather modification (‘so-called proof of financial responsibility’).”

If these two conditions are satisfied, then the commercial entity may be licensed to do business in the state. As a second step, once a specific weather modification project is identified, then the licensed weather modification company must seek a permit to conduct specific operations at designated times and places. Some states require public notices of such efforts and the holding of public meetings prior to issuing of a permit. An environmental impact statement or documentation that the seeding technique to be used is environmentally safe may need to be provided by the weather modification company.

In some states, the local county government and/or sponsoring agricultural cooperative may be involved in the permitting process and may also assume some of the legal liability.

Lessons from Public Reactions to Weather Modification Activities

Contrail formations from routine airplane activities are ubiquitous. They are from the formation of ice crystals high in the troposphere through inadvertent seeding with jet engine exhaust particles. As such they are a consequence of air pollution. Contrails may have minor impacts on the climate in regions where jet planes are common, such as over Europe and the United States.

The history of weather modification—especially its military applications during the Vietnam War—has led some skeptical individuals to believe that contrails are visible signs of some nefarious plot. This skepticism has led to the notion of “chemtrails”—a widely publicized conspiracy theory (see Box C.1). Supporters of the chemtrail conspiracy believe that some, perhaps all, the contrails left by aircraft are really chemical or biological agents deliberately sprayed at high altitudes by a government agency for purposes undisclosed to the general public. They have speculated that the purpose of these releases may be for weather modification climate intervention through solar radiation management or Earth radiation management, psychological manipulation, human population control, or biological or chemical warfare. Furthermore, they hold contrails responsible for a wide range of respiratory illnesses and other health problems.

BOX C.1 CHEMTRAIL CONSPIRACY THEORIES

When aircraft travel through the upper troposphere, the water vapor emitted in the engine exhaust can condense on other exhaust particles to form cirrus clouds. The results are the familiar contrails that can be seen in the upper troposphere trailing behind the generating aircraft. Chemtrail conspiracy believers speculate that contrails are formed by deliberate chemical releases for the purposes of albedo modification, psychological manipulation, population control, weather modification, or biological or chemical warfare, and are the cause of respiratory and other illnesses. Although this conspiracy has been repeatedly debunked,[a] which has shown that the sometimes persistent high-altitude contrails are simply normal water-based condensation trails from the exhausts of the engines of high-flying aircraft under certain atmospheric conditions in which the crystals and supercooled droplets are very slow to evaporate, this myth persists. Relevant to the topic of this report, Kuhn (1970), Lee et al. (2009), Frömming et al. (2011), and Schumann and Graf (2013) found that contrails have a similar effect as cirrus clouds and therefore, averaged over the globe, increasing the number of contrails would warm the planet.

---

[a] See, for example, http://contrailscience.com/how-to-debunk-chemtrails/; http://sleet.aos.wisc.edu/~gpetty/wp/?p=989; http://conspiracies.skepticproject.com/articles/chemtrails/; http://irishweatheronline.wordpress.com/2013/09/08/contrails-v-chemtrails-the-science-that-debunks-the-conspiracy/.

This chemtrails theory persists in spite of numerous efforts by members of the scientific community around the world to explain that what is being seen are just artificial clouds produced by normal condensation processes. People demanding explanations have sent thousands of complaint letters to various government agencies, showing the popularity of the chemtrail conspiracy theory and illustrating the possible type of reaction from a portion of the public when and if a climate intervention effort is undertaken.

Most of the state-level regulations related to weather modification foster openness and transparency (public notices, public meetings, and environmental impact statements). Any federal policy related to albedo modification would likely benefit from similar policies. In addition, the involvement of private contractors rather than the military services would likely help promote international buy-in and help minimize conspiracy theories.

APPENDIX D

Volcanic Eruptions as Analogues for Albedo Modification

Considerable progress has been made in understanding the volcanic response problem, but the attempts to reconcile simulations with observations underscore clearly that the present capability for simulating stratospheric aerosols and the climate response to the associated radiative forcing is in a relatively primitive state. As discussed in Chapter 5, the current understanding of albedo modification is insufficient to permit accurate assessment of the likely effects of climate intervention by deliberate alteration of stratospheric aerosols, let alone to plan for deployment. This section highlights some recent work on understanding the climate's response to volcanic eruptions and discusses prospects for future research directions.

OBSERVATION AND SIMULATION OF RESPONSE TO VOLCANIC ERUPTIONS: PAST STUDIES

There are many different approaches to simulation of volcanic response, which can be used to shed light on the processes involved. The approaches differ in the choice of what is calculated in the model versus what is imposed as boundary conditions based on observations. At the extreme end of the spectrum of forcing models with observations, one can specify the sea surface temperature and sea ice patterns and impose observed volcanic radiative perturbations to the atmosphere, and then see how well the observed changes in land surface temperature and atmospheric circulation patterns can be simulated (as in Graf et al., 1993). As a variant on this approach, different sea surface temperature patterns (e.g., El Niño vs La Niña) or initial circulation states of the stratosphere can be imposed in order to assess which aspects of the observed posteruption climate are due to the aerosol-related radiative forcing versus natural variability which may or may not have been influenced by the eruption (Kirchner et al., 1999; Stenchikov et al., 2004; Thomas et al., 2009a, b). If one is interested primarily in testing aerosol chemistry and microphysics, one can instead impose the observed stratospheric temperature and circulation pattern and see how well the observed aerosol properties can be modeled. At the opposite limit of simulation approaches, models can be driven by estimates of the observed injection of volcanic sulfur dioxide and other substances; both the resulting aerosol and ozone distribution and the ocean-atmosphere circulation and associated sea ice changes are simulated using a fully coupled model. This approach requires a coupled ocean-atmosphere model with a full representation of stratospheric dynamics and chemistry and is very demanding. It is the kind of simulation that most closely mimics what would be required for assessment of climate intervention actions, but very few simulations of this type have so far been conducted in the context of volcanic response. Various intermediate combinations of the approaches have appeared in the literature.

The complexity of the atmosphere's response to volcanic eruptions serves as a stark reminder of the challenges confronting any attempt to engineer the climate through deliberate modification of stratospheric aerosols. Aerosol characteristics and the length of time the aerosols remain in the atmosphere depend on the latitude at which the volcanic sulfur dioxide is injected. The aerosols absorb incoming solar infrared and thermal infrared upwelling from below, in addition to keeping some sunlight from reaching the surface, and the infrared effects lead to stratospheric heating that warms the stratosphere. This heating affects stratospheric circulations, which via a range of complex fluid mechanical processes affect the climate of the lower parts of the atmosphere, including surface temperature. The character of the response to the aerosol-induced stratospheric heating is sensitive to interannual variations in the state of the stratosphere at the time the injection occurs, in particular to the state of the Quasi-Biennial Oscillation (Stenchikov et al., 2004; Thomas et al., 2009a). Most attempts to simulate the effects of stratosphere-based climate intervention crudely represent the effect of the engineered aerosols by simply reducing the amount of solar energy hitting the top of the atmosphere; simulations of this sort do not represent the important dynamical and chemical effects of the aerosol-induced stratospheric heating and can lead to severe distortions of the climate response (Tilmes et al., 2009).

As a result, the volcanic response is not a simple cooling of the planet. Large eruptions lead to severe reductions in rainfall over land, especially in the tropics (Trenberth and Dai, 2007). Furthermore, though eruptions cool the following summers, the first winter following an eruption exhibits pronounced high-latitude warming (Robock and Mao, 1992). This winter warming, as well as many other regional aspects of the volcanic response, cannot be accounted for as a response to the blocking of sunlight but instead results as an indirect effect of stratospheric heating; it requires accurate calculation of the aerosol and radiative processes leading to the heating, a well-resolved stratosphere, and a good representation of the interaction between the stratosphere and the lower parts of the atmosphere. Models that incorporate stratospheric heating, either by calculation or by imposing it from observations, can yield a winter warming pattern that has some resemblance to observations, but accurately reproducing the magnitude of the response has proved problematic.

The discussion in Chapter 3 ("Observations and Field Experiments of Relevance to SAAM") summarizes a recent assessment of the ability of coupled ocean-atmosphere models to reproduce the winter volcanic response as found in the study by Driscoll et al. (2012); see Figure 3.11. There have also been a number of simulation studies aimed at testing models of aerosol evolution rather than climate response (English et al., 2013; Kravitz et al., 2010, 2011b), and these highlight the considerable remaining difficulties both in observing and modeling aerosol properties. Arfeuille et al. (2013) argued that even with accurate observationally based specification of aerosol properties, existing radiative transfer codes could not accurately reproduce the stratospheric heating.

VOLCANIC RESPONSE IS FAR FROM AN EXACT ANALOGY FOR CLIMATE INTERVENTION BY STRATOSPHERIC AEROSOL MODIFICATION

It has been argued that the climate response to engineered stratospheric aerosol modification would have much in common with that from volcanic eruptions, but the volcanic response should nonetheless not be taken as an exact analogue for climate intervention (Robock et al., 2010, 2013). From a microphysical standpoint, the key difference is that eruptions inject sulfur dioxide into a relatively clean stratosphere, whereas engineered injections would add sulfur dioxide to a stratosphere that already has a considerable burden of aerosols. This changes various aspects of the physics determining droplet size growth and coalescence of smaller droplets to form larger ones, both of which affect the residence time of aerosols and their effects on albedo. Engineered injection may also involve a different range of altitudes, and the latitudinal distribution would probably also be different; it is generally assumed that climate intervention would produce a more spatially uniform distribution of aerosols than point-source volcanic eruptions, but it is not yet known how well the actual distribution of aerosols can be controlled. Furthermore, volcanic eruptions inject a range of substances, such as ash, that would not be present in an engineered injection.

From the standpoint of climate response, the chief difference between volcanic and engineered injection is that volcanic eruptions give rise to a short-lived radiative forcing perturbation (at most a few years), which is sufficient to yield a strong climate response over land in the case of large eruptions but does not last long enough for the ocean temperature to be much affected, and insofar as the ocean is affected at all it is only the uppermost layers of the ocean that are involved; sustained aerosol forcing due to climate intervention action would involve a considerably deeper part of the ocean, and a larger ocean response. The probable difference in land-sea temperature contrast between engineered and volcanic stratospheric aerosol injection has implications for all atmospheric circulations driven by land-sea thermal contrast, notably monsoons and diversions of the midlatitude jet streams. Response of sea ice is sensitive to subtle changes in the ocean circulation, and probably cannot be adequately tested by examination of volcanic response. This is a particular concern, since there are indications that multiple closely spaced eruptions—a rare occurrence such as happened at the time of the Little Ice Age—which approximate the sustained cooling resulting from engineered aerosol modification, can switch the North Atlantic over into an icy mode that can persist for centuries (Miller et al., 2012).

Despite these shortcomings of the volcanic analogue vis-à-vis engineered modification of stratospheric aerosols, the volcanic response engages almost all of the same aspects of atmospheric chemistry, physics, and dynamics as does the climate intervention problem and, therefore, serves as a useful test of the simulation capabilities that would be needed to assess the effects of deployment of climate intervention schemes involving stratospheric aerosol modification.

APPENDIX E

Discussion of Feasibility of Albedo Modification Technologies

Assessing an albedo modification strategy's feasibility (ignoring the extremely important need for appropriate governance issues dealt with elsewhere in this document) hinges upon

- Developing a theoretical and conceptual framework for a particular strategy for producing an albedo modification and
- Identifying system components and means that are critical to testing the scientific and physical concepts important to the strategy, and the technology necessary for implementing those strategies.

It is worth noting that the implementation details, and costs needed to test the underlying concept, would differ significantly from those that would be employed if the strategy were to be used at a larger scale. Assessing the conceptual feasibility of a strategy need not initially use the same implementation methods that would be considered feasible for a larger-scale implementation. So it is necessary to distinguish between assessing the "scientific feasibility" of a strategy (e.g., what calculations, instrument developments, laboratory and field experiments are needed to demonstrate an understanding of underlying physics to produce an intended perturbation to albedo in a particular region and time) and the "practical feasibility" issues associated with a larger deployment (e.g., Is it possible? And what would the cost be for a deployment intended to affect the planetary albedo sufficiently to counter some fraction the radiative forcing arising from increasing greenhouse gases?).

Understanding both types of feasibility studies is important and they can be considered in parallel. The scientific feasibility studies would provide better information for more realistic estimates of costs and practical strategies to produce a measurable effect on the climate processes. These studies would also examine local impacts to radiative forcing, quantify the intended changes, and assess whether models are capable (or not) of simulating and predicting the statistical characteristics of those changes to the climate processes to demonstrate some physical understanding of the climate process being manipulated. The process is necessarily iterative. The first step uses theory, existing analogues in the real world (e.g., volcanoes and ship tracks), and both process and climate models to provide a "zero-order guess" at the amplitude of the induced perturbation to component processes and the "fast" response of the climate system (the so-called "adjusted radiative forcing"). These modeling studies and analyses of existing analogues provide basic estimates of relevant forcing, as well as the local responses guiding estimates of costs, and implementation details, but there is a limit to their utility. There can easily be flaws in physical understanding expressed in models or overlooked issues that were not considered. At some point more stringent assessments would require that laboratory and field experiments would be needed to make sure that initial estimates are realistic and robust across location, climate regimes, and seasons.

If exploratory field experiments were successful in producing the desired effect on the component behavior, they would (a) provide information needed to characterize the potential for a particular strategy (perhaps for only a subset of important regimes or seasons) to produce a significant radiative perturbation; (b) provide a mechanism for estimating the cost of inducing such a change; and (c) identify the immediate, local impact of those changes on that component of the climate system. Exploration of albedo modification to other regimes, locations, and season might then be considered to identify their potential to produce radiative forcing, and eventually consideration of slower feedbacks, and consequences to the climate system become important considerations.

Feasibility estimates should thus be contingent upon (1) first-guess estimates based on models and measured analogues found in our current environment; (2) staged series of laboratory and de minimus field experiments designed to test basic understanding and components important to the strategy, and the overall robustness, of the models; (3) updated estimates of feasibility produced by improved knowledge from the de minimus field experiments; and (4) testing of the robustness of the mechanisms as the amplitude of forcing and temporal and areal extent are increased, where nonlinearities become important. Eventually, as the amplitude of the forcing is increased, assessing the feasibility of the strategy becomes primarily a signature detection problem—that of teasing out a signal (the climate response to a perturbation) in the presence of the background "noise" of natural climate variability (MacMynowski et al., 2011).

APPENDIX F

Acronyms and Abbreviations

AGU	American Geophysical Union
AOD	aerosol optical depth
AVHRR	Advanced Very High Resolution Radiometer
BECCS	bioenergy with carbon capture and sequestration
BPC	Bipartisan Policy Center
CALIOP	Cloud-Aerosol Lidar with Orthogonal Polarization
CALIPSO	Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation
CARMA	Cloud Aerosol Research in the Marine Atmosphere experiment
CBD	Convention on Biological Diversity
CCN	cloud condensation nuclei
CCS	carbon capture and sequestration
CDN	cloud droplet number
CDR	carbon dioxide removal
CERES	Clouds and the Earth's Radiant Energy System
CIFEX	Cloud Indirect Forcing Experiment
CIRPAS	Center for Interdisciplinary Remotely-Piloted Aircraft Studies
CLRTAP	Convention on Long-Range Transboundary Air Pollution
CMIP5	Coupled Model Intercomparison Project
CN	condensation nuclei
CRM	cloud-resolving model
DACS	direct air capture and sequestration
DECS	Drizzle and Entrainment Cloud Study
DHS	U.S. Department of Homeland Security

DIC	dissolved inorganic carbon
DOE	U.S. Department of Energy
DYCOMS II	Second Dynamics and Chemistry of Marine Stratocumulus experiment
ENMOD	Convention on the Prohibition of Military or Any Other Hostile Use of Environmental Modification Techniques
ENSO	El Niño–Southern Oscillation
EOP	Executive Office of the President
E-PEACE	Eastern Pacific Emitted Aerosol Cloud Experiment
ERF	effective radiative forcing
GCAM	Global Change Assessment Model
GCM	general circulation model
GeoMIP	Geoengineering Modeling Intercomparison Project
GHG	greenhouse gas
IASS	Institute for Advanced Sustainability Studies
ICSU	International Council for Science
IPCC	Intergovernmental Panel on Climate Change
IPSL-CM5a	Institut Pierre Simon Laplace Climate Model
ISS	International Space Station
JPSS	Joint Polar Satellite System
LES	large eddy simulation
LWC	liquid water content
LWP	liquid water path
MAGIC	Marine ARM GPCI Investigation of Clouds
MASE	Marine Stratus/Stratocumulus Experiment
MAST	Monterey Area Ship Track experiment

MCB	marine cloud brightening
MESSAGE	Model for Energy Supply Strategy Alternatives and their General Environmental Impact
MIROC-ESM-CHEM	Model for Interdisciplinary Research on Climate—Earth System Model—Chemistry
MISR	Multi-angle Imaging SpectroRadiometer
MODIS	Moderate Resolution Imaging Spectroradiometer
MPI-ESM	Max Planck Institute for Meteorology Earth System Model
MSU	microwave sounding unit
Mtoe	million tons oil equivalent
NASA	National Aeronautics and Space Administration
NEPA	National Environmental Policy Act
NH	Northern Hemisphere
NOAA	National Oceanic and Atmospheric Administration
NorESM	Norwegian Earth System Model
NPP	NPOESS (National Polar-orbiting Operational Environmental Satellite System) Preparatory Project
OMPS	Ozone Mapping Profiler Suite
ONR	Office of Naval Research
OSIRIS	Optical Spectrograph and Infrared Imaging System
OSTP	Office of Science and Technology Policy
PACE	Pre-Aerosol, Clouds, and ocean Ecosystem
PDO	Pacific Decadal Oscillation
POC	pocket of open cells
PSAC	President's Science Advisory Committee
ReMIND	Regional Model of Investments and Development
SAAM	Stratospheric Aerosol Albedo Modification

SAGE	Stratospheric Aerosol and Gas Experiment
SH	Southern Hemisphere
SMAP	soil moisture active and passive
SOLEDAD	Stratocumulus Observation of Los Angeles Emission Derived Aerosol-Droplets
SPICE	Stratospheric Particle Injection for Climate Engineering
SRM	solar radiation management or sunlight reflection methods
SRMGI	Solar Radiation Management Governance Initiative
TOA	top of atmosphere
UNFCCC	United Nations Framework Convention on Climate Change
USGS	U.S. Geological Survey
UV-B	Ultraviolet-B
VIIRS	Visible Infrared Imaging Radiometer Suite
VOCALS-REx	VAMOS Ocean-Cloud-Atmosphere-Land Study Regional Experiment.